Understanding which biomechanical and neuromuscular variables are important in improving discus, shot put and hammer throwing performance.

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Abstract

Athletics has been a prominent feature in the Olympic programme for decades, within which rotational throwing events, discus, shot put, and hammer, comprise three of the four throwing events. Given the competitive nature of throwing, coaches and athletes are constantly seeking methods to enhance performance. In general, coaches and athletes look to improve either biomechanical (throwing technique) or neuromuscular (e.g. strength and power) abilities in an effort to improve performance. In isolation, both biomechanical and neuromuscular variables have been related to performance enhancement. However, conjecture exists as to the causal effect adapting neuromuscular variables has on enhancing performance, and changes in biomechanical variables over longitudinal periods have not been reported. Thus, the overall purpose of this Thesis was to understand which biomechanical and neuromuscular variables are important to improving discus, shot put and hammer throwing performance. While trying to address the current gaps in the literature with scientific rigour, this Thesis was designed in an applied manner as to be embedded within, and directly influence, coaching and resistance training practises. A paucity of resistance training literature to enhance rotational throwing performance was identified; as such, a conceptual model of resistance training to enhance neuromuscular drivers of throwing biomechanics was developed. It was found that biomechanical phenomena are underpinned by multiple neuromuscular factors. Therefore, a comprehensive assessment battery was needed to determine the neuromuscular variables associated with throwing performance, specifically, the appropriate sections of the force – time and force – velocity curves. Furthermore, metrics associated with muscular and tendinous qualities would provide additional adaptive information.

It remains difficult to assess tendinous stiffness of upper and lower body tissues, and rotational ability in an applied setting. Thus, three assessment protocols were assessed: two were adapted from the literature and one was a novel protocol specific to shot put. The first assessment of musculoarticular stiffness derived from the perturbation method demonstrated poor test – retest reliability. More specifically, it was found that bench press and bench pull musculoarticular stiffness was unreliable [change in mean: -35.1 to 15.8%; coefficient of variation (CV): 7.1 to 111%; intra-class correlation (ICC): -0.58 to 0.89] and squat musculoarticular stiffness was not quantifiable in a group (n = 8) of experienced power trained athletes. The second and third assessments, seated cable rotation and cable put, were found to be reliable between days in a group (n = 9) of resistance trained men. Reliability was observed in the kinematic variables (cable put: ICC = 0.92 to 0.99, CV = 3.1 to 8.6%; cable seated rotation: ICC = 0.76 to 0.99, CV = -1.7 to 16.1%), but not the kinetic variables.

Establishing the relationship between biomechanical and neuromuscular variables relies on reliable neuromuscular data being correlated to reliable biomechanical data. More specifically, the role of pulling musculature in throwing is not well understood. Thus, to understand the role of pulling type movements and throwing performance, kinematic measures from a throwing

movement need to be reliable prior to performing correlations between such throwing kinematic measures and neuromuscular measures. Therefore, two investigations were performed: 1) the reliability of kinematics from a seated shot put, and 2), the relationship between seated shot put kinematics and bench throw and bench pull kinematics in a group of resistance trained athletes (n = 9). Firstly, seated medicine ball kinematics derived from manual digitisation were found to be reliable (CV = 2.75 to 8.38%, ICC = 0.82 to 0.95) between days. Furthermore, such kinematics were highly repeatable between digitisation occasions (CV = 0.12 to 4.98%, ICC = 0.92 to 1.00) and no difference in kinematics were observed when the number of digitised views was reduced from three to two. Secondly, bench pull bar velocity was highly related to seated shot put peak velocity, as was bench press (r = 0.71 to 0.89, $p < 0.05$). However, light load bench pull was highly related to seated shot put acceleration variables (r = 0.67 to 0.83, $p < 0.05$), whereas bench press was not. The differing association suggests that pressing and pulling musculature play different roles in putting ability and that both should be included in a comprehensive test battery of shot putters' neuromuscular qualities.

The last four investigations quantified changes in competition performance, throwing biomechanical variables, and neuromuscular variables over a longitudinal period in four throwers (shot put: n = 1 female, discus; n = 1 male; hammer throw; n = 2, 1 female 1 male) ranging in ability from sub elite to elite. All athletes were highly trained and were competitive athletes ranked in the top three in each discipline based on national rankings. Throwing biomechanics were assessed using video digitisation (hammer throw) or infra-red marker tracking and automated modelling (shot put and discus). The tracked neuromuscular variables remained constant between participants and included force-velocity profiling [countermovement jump, bench throw, bench pull, and cable rotation (hammer throw and discus) or cable put (shot put)], vertical jump, and inertial load ergometer testing. Over the tracking period, fluctuations in both biomechanical and neuromuscular variables were observed and the association between performance change and change in biomechanical or neuromuscular variables was specific to the athlete. For both the discus and shot put investigations, no biomechanical or neuromuscular variables changed concurrently with the criterion performance variable (release velocity); however, the female hammer thrower's release velocity tended to change with change in velocity through the preceding turns, but not with any singular neuromuscular variable. Furthermore, many force velocity measures declined while release velocity increased. In contrast, the male hammer thrower showed a strong association between release velocity and changes in late eccentric squat ability, but not with changes in any biomechanical variables. It was proposed that the predictive ability of neuromuscular and biomechanical measures is athlete specific and should be treated as such.

In summary, this Thesis identified that biomechanical and neuromuscular variables in isolation are not predictive of performance. However, all variables – both biomechanical and neuromuscular – should be enhanced, with much more research needed to determine whether predicting performance change from biomechanical and neuromuscular variables is viable in and valid for rotational throwing athletes.

Attestation of authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

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List of co-authored publications

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(Schofield 85%, Neville 4%, Hébert-Losier, K 5%, Cronin 3%, , Uthoff 3%)

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List of common abbreviations

2D	Two dimensional	m	Mass
3D	Three dimensional	M	Male
BM	Body mass	M ECC	Moderate velocity eccentric
BS	Back swing	m/s	Meters per second
Cf	Cable force	m/s^2	Meters per second per second
CM	Change in mean	MAV	Mean amplitude voltage
CMJ	Counter movement Jump	MTU	Muscle tendon unit
COM	Center of mass	MVC	Maximal voluntary contraction
CON	Concentric	MVT	Maximal voluntary torque
CON100	Maximum bar velocity reached during the first 100 ms of the concentric movement	N	Newtons
COR	Center of rotation	N·s	Newton seconds
CSA	Cross-sectional area	NA	Not applicable
CV	Coefficient of variation	Nm	Newton meter
DLT	Direct linear transformation	Nm/s	Newton meters per second
DOMS	Delayed onset muscle soreness	NS	Not stated
DS	Double support	OC	Oral contraceptive
ECC	Eccentric	PA	Pennation angle
ECC100	Maximum bar velocity during the 100 ms prior to concentric onset	Plyo	Plyometric
EMG	Electromyography	PV	Peak velocity
f	Female	Pwr	Power
F ECC	Fast velocity eccentric	r	Radius
FL	Fascicle length	RD	Right foot down
Fr	Radial component of cable force	REL	Release
FSH	Follicular stimulating hormone	RFD	Rate of force development
FT	Fibre type	RM	Repetition maximum
GRF	Ground reaction force	RO	Right foot off
Ho	Hammers orbital path	Rpm	Revolutions per minute
Hz	Hertz	S ECC	Slow velocity eccentric
ICC	Intra-class correlation coefficient	SD	Standard deviation
Iso	Isometric	SS	Single support
k	Stiffness	STA	Soft tissue artifact
$kg.m^2$	Kilograms per meter squared	T	Testosterone
kg·m/s	Kilogram meters per second	Tcf	Tangential component of cable force
L/s	Lengths per second	Tv	Tangential velocity
LH	Luteinizing hormone	W	Watts
LPT	Linear position transducer		
2D	Two dimensional		

Chapter 1

Introduction

1.1 Background

Discus, shot put and hammer throw are three of the four throwing events within the Olympic programme. The event winner is decided by the greatest official distance registered (measured from the inner point of the circle to the first point where the implement lands). To register as an official result, the implement must land within the confines of the sector and the athlete must stay within the confines of the throwing circle (1). Throwing circle size varies between discus (2.5 m), and hammer and shot put (2.135 m). The shot put circle also has an additional stop board that extends up from the front edge of the circle.

Official distance in hammer and shot put is dictated by the laws of projectile motion (angle, height, and velocity at release) and the release distance (the distance from the release point to the inner most portion of the circle) (2-4). Discus performance, in addition to projectile motion and release distance, is affected by aerodynamic properties (i.e., lift and drag) that are a function of disc orientation and spin relative to atmospheric conditions and laws of projectile motion. Of the variables that relate to performance, release velocity is the primary predictor of performance across all events (2, 5, 6). Thus, athletes and coaches involved in discus, shot put, and hammer throw seek methods to enhance release velocity to enhance throwing performance.

Regardless of throw discipline, two different (but related) areas play a role in increasing distance: biomechanics and neuromuscular performance (see Figure 1.1). Biomechanics refers to the kinematic and kinetic events that occur during the throwing motion, whereas neuromuscular performance is the quantification of physiological qualities (e.g. force – time, force – velocity capabilities) that can be trained via various forms of resistance training. Variables related to either biomechanics or neuromuscular performance are commonly reported independently; however, coaches consider both concurrently to enhance release velocity and performance.

Biomechanically, enhancing release velocity across throws relies on optimising the magnitude, duration, and direction of force applied to the implement (4, 7). As such, coaches are interested in biomechanical occurrences that underpin high release velocities. Relationships between kinematic and kinetics variables relevant to increasing force – either magnitude, duration, or direction – have been reported in elite and sub-elite throwers (7-9). However, how biomechanical adaptations relate to changes in throwing performance over longitudinal training periods and neuromuscular adaptations relate to these changes in biomechanics are not well documented.

While optimisation of throwing biomechanics is imperative to performance, enhancing select neuromuscular variables that relate to biomechanical variables provide further performance advantage. Coaches have integrated strength training adhering to traditional methodologies to enhance absolute neuromuscular force expression in athletes (10, 11). Although performance enhancements have supported the inclusion of traditional methodologies (12, 13), researchers have shown that a decrease in performance can occur with an increase in peak force (14) and that a quadratic relationship between neuromuscular variables and throwing performance may exist (15, 16). As such, the effectiveness of these traditional training methodologies on performance is questionable.

The value of neuromuscular adaptation from resistance training for throwing performance depends on its ability to enhance throwing kinetic and kinematic qualities that lead to greater release velocities (see Figure 1.1). It is well accepted that the ability to produce force quickly (early force – time) and apply force at high velocities is required in throwing sports. Within a physiological context, a considerable amount of research has been directed at understanding related mechanisms (*Figure 1.1*, athlete physiology). Mechanisms such as peak force, fibre type, tendon kinetics, and neural factors underpin early force – time and high velocity force application (17-19). Moreover, resistance training that enhances one of these aspects (e.g., strength training to enhance peak force) can result in an adverse adaptation to another aspect (e.g., strength training supresses fast fibre types) (20, 21). Given this complexity, concurrent consideration of all training requirements and adaptive responses are required when planning resistance training to enhance throwing performance. As yet, no research has been undertaken to investigate the longitudinal effects of resistance training directed at enhancing neuromuscular mechanisms on biomechanical determinants and performance of throwing.

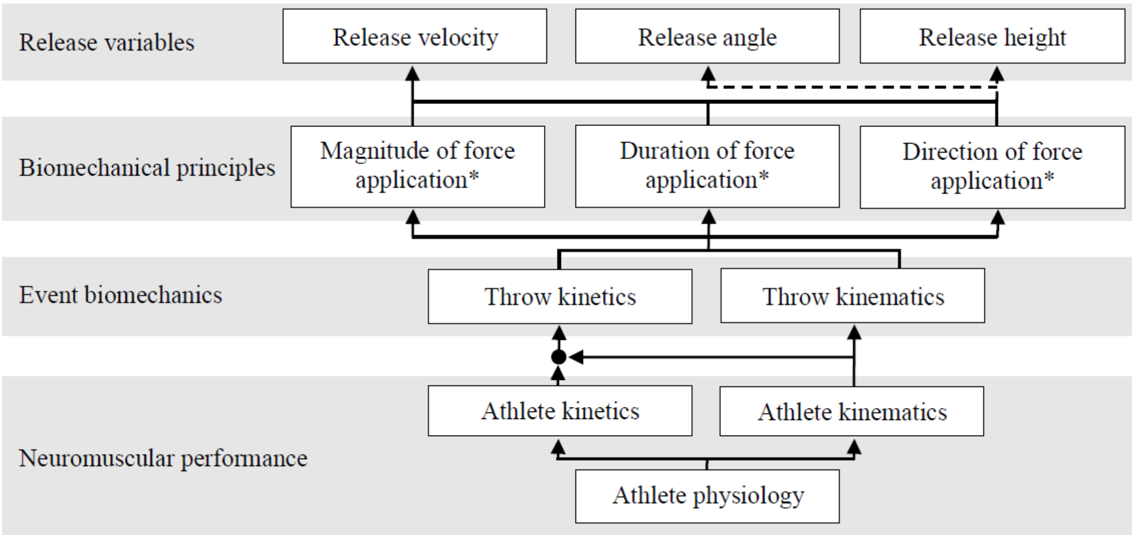

Figure 1. 1. Pathways for neuromuscular performance and event biomechanics to enhance throwing performance. Note. *Application to the implement, thick line denotes direction of thesis. Dashed line denotes areas not directly addressed in this Thesis.

1.2 Rationale

Understanding the relationship between biomechanics, neuromuscular adaptation, and performance has considerable implications for coaches and strength coaches seeking to enhance throwing performance. In addition to addressing identified gaps in the literature, this research was directed by coaches' needs, both technical and strength coaches, to influence practise within the

High Performance Sport New Zealand system. Therefore, research directives were derived from both academic and practical bodies of knowledge. Specifically these were:

1) Resistance training directed at enhancing performance in throws is largely historically driven. Previous literature, although sparse, has demonstrated mixed results following traditional training methods (14, 16, 22). Logically, performance enhancement is more likely when neuromuscular adaptation is specific to event biomechanics. Therefore, understanding those methods of resistance training to induce adaptation related to enhancing event biomechanics would seem important for athletes and coaches.

2) Using valid and reliable measures to track neuromuscular adaptation alongside performance change is of fundamental importance; however, there is a paucity of evidence based practise in this area. Therefore, tracking numerous neuromuscular qualities that are both sports-specific and non-specific is required. It has been identified that repetition maximums in the squat, bench press, and power clean are related to throwing performance (14, 15). However, it is less clear how more specific neuromuscular assessments relate to performance. Prior to integrating new methods to track neuromuscular adaptations in athletes, the assessment itself needs to be established and its reliability quantified. Research is therefore needed to develop and understand the reliability and value of new kinematic and kinetic measures/movements specific to throwing performance.

3) The effect of novel resistance training methods that enhance neuromuscular qualities related to throwing have been investigated in isolation from actual throwing performance (20, 23, 24). As such, the effects of novel resistance training methods on rotational throwing performance are unknown. Biomechanical variables related to throwing performance have been identified in each rotational throwing event; however, changes in biomechanical and neuromuscular determinants have not been mapped longitudinally alongside performance change. Enhancing elite throwing performance involves improving the neuromuscular system specific to event biomechanics by promoting greater or longer force application to the implement. Research is required to understand how resistance training over long periods affects specific neuromuscular and biomechanical qualities in elite throwers.

1.3 Purpose

The overall purpose of this thesis was to investigate variables, both biomechanical and neuromuscular, that enhance performance over longitudinal periods. The overarching question of interest was: “Which biomechanical and neuromuscular variables are important in improving discus, shot put and hammer throwing performance?” The research was specifically aimed at enhancing technical coaching and resistance training practices associated with discus, shot put and hammer. As such, this thesis was intended to directly influence practise within the Athletics

New Zealand and High Performance Sport New Zealand systems. The specific objectives of this thesis were:

1) Develop a theoretical model of resistance training that is associated with enhancing neuromuscular qualities associated with throwing performance.

2) Develop methods to assess neuromuscular qualities that are specific to throwing performance.

3) Investigate the changes in biomechanical and neuromuscular variables that occur over longitudinal periods in response to resistance training and throwing periodisation.

1.4 Significance of research

There is considerable interest in understanding potential means of enhancing throwing performance in discus, shot put, and hammer through resistance training, given the Olympic status of these sports. Understanding resistance training methodologies that adapt neuromuscular variables related to throwing biomechanics is important to performance. The literature provides insight into how resistance training can enhance neuromuscular adaptation (e.g., fibre type, tendon stiffness) that will theoretically enhance the kinematics (e.g., increase elbow angular velocity) associated with throwing (25-27). Synthesising such literature into a theoretical model provides guidance regarding how we might train throwers.

Specificity is critical to transference of resistance training adaptation to sport-specific performance (14). However, there is little available research demonstrating the reliability of throwing specific neuromuscular testing methods. It is well documented that the final phase of shot put and rotational ability across discus and hammer is important to throwing performance. Nonetheless, neuromuscular testing methods specific to these qualities have yet to be established. Furthermore, the contribution of elastic ability in a stretch shortening cycle phenomena has been demonstrated to aid throwing performance, but few assessment methodologies exist that are specific to throwing kinematics. The development and repeatability of specific testing methods for throwers provide ecologically valid and kinematically specific neuromuscular tracking options to coaches. As a result, it becomes possible to monitor training adaptations that are more specific to throwing.

Finally, there is a paucity of longitudinal biomechanics and resistance training literature in rotational throwing. Thus, the integration of a theoretical model into a practical setting can provide information as to its applicability to performance. Moreover, tracking biomechanical and neuromuscular adaptations regularly through a training cycle provides information on the primary contributors to performance. This abundance of data provides an opportunity to quantify variables important to throwing performance, provide an evidence-based approach to enhance throwing performance, as well as inform future research directions.

1.5 Thesis organisation

This thesis is comprised of four sections (Figure 1.2) that aim to answer the over-arching question "Which biomechanical and neuromuscular variables are important in improving discus, shot put and hammer throwing performance?". The first section includes four literature reviews. Chapters 2, 3, and 4 are narrative reviews describing the biomechanical characteristics of discus, shot put, and hammer throwing, respectively. Chapter 5 is a narrative review on current strength and conditioning protocols employed within track and field rotational throwing. These Chapters set the foundational knowledge and identify the gaps in the literature related to the biomechanics and resistance training of throwers. The second section (Chapter 6) includes one current opinion piece that outlines a novel approach to resistance training for rotational throws that hinges on the biomechanics of throwing outlined in previous Chapters. In this Chapter 6, the theoretical model that guides subsequent Chapters is outlined. Section three investigates the reliability of novel assessments that are technically, physically, and/or ecologically valid within rotational throwing. From this section, the assessment methods that will be used going forward are established. Chapter 7 describes the reliability of assessing muscular-articular stiffness derived from the oscillation technique in novel postures. Chapter 8 investigates the reliability of two novel cable based neuromuscular assessments that are ecologically valid to throwing performance. Chapter 9 describes the reliability of kinematics derived from a putting-based assessment that was manually digitised. The comparability of camera set-ups commonly used in track and field was also included. Chapter 10 quantifies the relationship between pulling movements and throwing as to provide rationale for the inclusion of pulling motions in subsequent Chapters. The fourth section includes four single subject longitudinal case studies. Chapters 11, 12, 13, and 14 describe changes in biomechanical and neuromuscular variables in response to a longitudinal training programme that was outlined in Chapter 6. Single subject designs were thought to be more valid and relatable to high performance settings given the limited number of semi-elite and elite throwers in New Zealand. Furthermore, given the embargoed status of this thesis, there was little opportunity to recruit a larger sample size from around the world. The final section (Chapter 15) provides a summary, practical recommendations, limitations and future research direction. This thesis was embargoed; however, Chapters 3, 7 and 8 have been accepted by peer-reviewed journals. Note that all Chapters are presented in a journal type structure, except for Chapter 16.

Which biomechanical and neuromuscular variables are important in improving shotput, discus, and hammer throwing performance?

Chapter 1: Introduction.

Section 1: Literature reviews

Chapter 2: Current biomechanical knowledge of the discus: A narrative review

Chapter 3: Rotational shot put: A phase analysis of current kinematic knowledge
Sports Biomechanics

Chapter 4: Biomechanical characteristics of the Hammer throw: A narrative review

Chapter 5: Resistance training in track and field rotational throws: A commentary of the current literature

Section 2: Current opinions

Chapter 6: Periodisation to enhance early force – time and high velocity force application: A conceptual model for throwing events

Section 3: Assessing kinematics

Chapter 7: Multi-joint musculoarticular stiffness derived from perturbation is highly variable
Journal of Strength and Conditioning Research

Chapter 8: Kinematic and kinetic variability associated with the cable put and seated rotation assessment
Journal of Sport Sciences

Chapter 9: Reliability of manual digitisation of seated shotput kinematics with reduced camera numbers

Chapter 10: Brief report: Seated medicine ball put kinematics are related to both bench press and bench pull bar velocities across multiple loads

Section 4: Understanding the change in kinematics and kinetics in elite athletes

Chapter 11: The integration of biomechanics and resistance training in male hammer throwing: A case study

Chapter 12: The integration of biomechanics and resistance training in female hammer throwing: A case study

Chapter 13: The integration of biomechanics and resistance training in male discus throwing: A case study

Chapter 14: The integration of biomechanics and resistance training in female shot putting: A case study

Chapter 15: Summary, practical recommendations, limitations and future research

Figure 1. 2. Thesis chapter structure.

Chapter 2

Current biomechanical knowledge of the discus: A narrative review

2.0 Prelude

The biomechanical determinants of sporting movements directly determine performance. Thus, understanding the biomechanics of the event is crucial for coaches trying to affect performance via technical change, biomechanists trying to quantify key variables, and strength coaches trying to enhance performance through neuromuscular training and adaptation. The discus throw is one of the four throwing events in a track and field programme. Given the integral role of biomechanics within this performance context, the purpose of this Chapter was to provide a comprehensive summary of the literature pertaining to discus throwing biomechanics. This information provides important insight as to the kinematic and kinetic variables driving performance. Coaches, athletes, and support staff can use this information to enhance performance as it relates to their specified fields. Most importantly, the information in this Chapter provides foundational knowledge that will guide understanding of best practice assessment methods and training methods for discus throwers, which will be used to guide and underpin the ensuing Chapters in this thesis.

2.1 Introduction

The discus throw is one of the four throwing events in the track and field Olympic programme. The winner of the discus throwing event is the athlete who is able to throw the discus the furthest within the sector (competition landing area) while staying within the confines of the throwing circle. Circle dimensions (diameter 2.5 m, see Figure 2.1) and sector width (projected out at 34.92° relative to the centre of the circle, see Figure 2.1) are constant between competitions and sex, as specified by the International Association of Athletics Federations. At a senior level, between-sex differences in the mass and geometry of the discus differ. Males throw a 2 kg discus and females throw a 1 kg discus (see Figure 2.1B, Table 2.1).

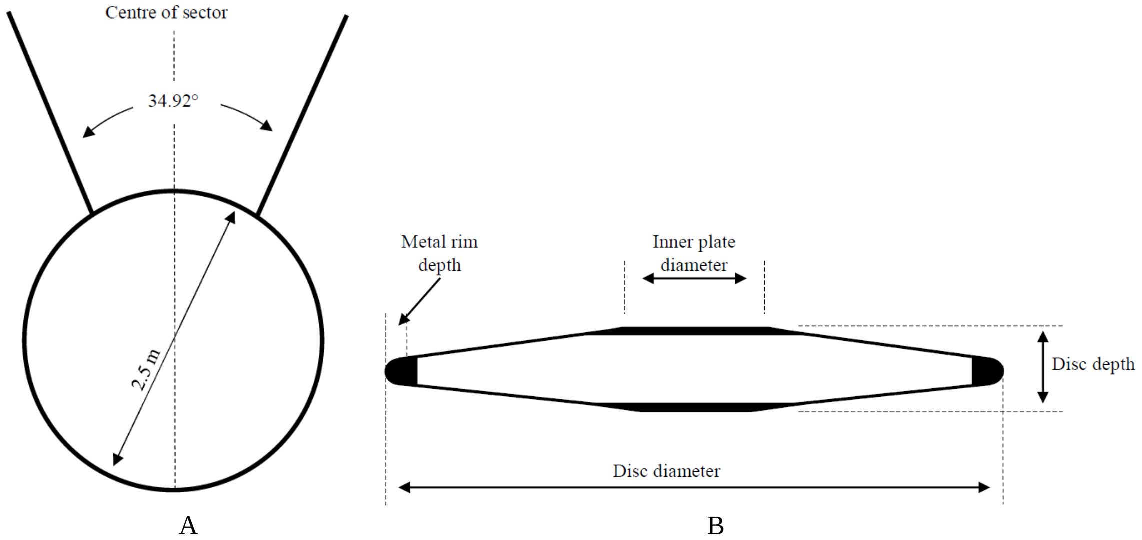

Figure 2. 1. A) Discus circle and sector dimensions. B) Discus dimensions.

In sports biomechanics, kinetics and kinematics provide important information on movement that can be useful in optimising performance. Biomechanics is crucial in throwing events where release velocity (determined by the impulse applied to the discus) and disc parameters at release (release angle, height, and disc orientation) determine performance according to projectile motion principles. Disc parameters refer to the orientation of the discus relative to atmospheric conditions and the launch angle of the discus in such a way that the aerodynamic properties are optimised (6, 28). Optimisation of discus orientation has received considerable attention within the literature (6, 28, 29) and achieving optimal discus orientation at release is believed to be skill based and learned over time (see Bartlett (29) for full review on this topic).

Table 2. 1. Discus dimensions range (minimum to maximum) for female and male events.

	Female (1 kg)	Male (2 kg)
Disc diameter (mm)	180 – 182	219 – 221
Disc depth (mm)	37 – 39	44 – 46
Inner plate diameter (mm)	50 – 57	50 – 57
Metal rim depth (mm)	12 – 13	12 – 13

Release velocity, which is the primary contributor to performance, is directly related to the impulse applied to the discus, which is generated through one and a half rotations of the athlete-disc system before release. Increasing the magnitude of impulse applied to the discus and the way in which it is applied is a function of kinematic and kinetic patterns (4, 30, 31). Current literature has sought to understand the relationship between select kinetic and kinematic variables and performance (8, 32), or documented kinematic variables exhibited by elite performers (33, 34). Nonetheless, how select variables interact with one another and or additional variables of interest has not been reported. A synthesis and review of current literature can aid to clarify this interaction and provide information regarding events and patterns that promote increased force production, increased time of force application, and more efficient orientation of force. These data would provide valuable insight into performance as these are the constituent parts of impulse, which contribute to release velocity.

Thus, a synthesis and review of current discus throwing biomechanical literature is necessary to determine kinematic and kinetic patterns that promote force application on the discus to enhance release velocity. The objective of this article was hence to review and synthesise biomechanical literature with a focus on strategies to enhance release velocity during discus throwing.

2.2 Methods

This review was limited to investigations analysing full discus performance using competition implements. A full discus throw was defined as one that is used in a competition involving approximately one and a half rotations before release. Derivatives of this movement (standings throws, side starts, etc.) were excluded. Due to the lack of literature retrieved (n = 31), methodological variance between studies, and broad scope of this review, a narrative style review was deemed the most appropriate. SportDiscus^{TM} via EBSCO and Google Scholar were searched for articles analysing the biomechanics of discus throwing. The following search terms were used 'discus', 'discus throwing', 'track and field', and 'biomechanics'. Also, the reference lists of all studies included for review were searched manually for studies of relevance missed during the initial electronic search. Titles, abstracts, and full-texts of retrieved documents were sequentially reviewed to determine their relevance to the topic. Relevance was established by the following inclusion criteria: 1) published in the English language; 2) addressed biomechanics or expert opinions specific to the full discus throwing motion; and, 3) have reference to increasing either release velocity or throwing distance. The articles were categorised as "Biomechanics" or "Expert Opinion" based on the content and design of the articles. The search for relevant literature was initiated in June 2016 and continued until there was a saturation of information and no additional literature of relevance could be sourced (search ended in July 2018). A total of 43 articles were reviewed for relevance, from which 12 did not fulfil the inclusion criteria. A total of 31 articles remained, 23 related to biomechanical analysis and 8 related to expert opinion.

2.3 Results

Participant descriptive data from the 23 biomechanical investigations are summarised in Table 2.2. A total of 528 throwers were represented in these studies, 308 males (58%) and 220 females (42%). Biomechanical analysis of both male and female throwers were undertaken at both elite and sub-elite levels. The majority of investigations analysed elite performers either in isolation or concurrently with sub-elite performers. Elite and sub-elite performers within these studies were defined based on distance thrown (elite > 57 m and sub-elite < 57m).

Table 2. 2. Participant information of biomechanical investigations meeting inclusion for review.

	Sample size (*n*)			Characteristics		
	Male	Female	Total	Level	Release velocity (m/s)	Distance measured (m)
Vodicková (35)	4		4	Elite	M: 24.21 – 24.75	M: 64.15 – 24.75
Gregor, Whiting, and McCoy (36)	3	3	6	Elite	M: 24.0 – 25.3 F: 23.9 – 26.0	M: 64.68 – 66.60 F: 60.68 – 65.36
Knicker (37)	3		3	Elite	M: 23.9 – 26.0	M: 59.16 – 67.40
Knicker (38)	8	8	16	Elite	M: 23.8 – 26.8 F: 22.2 – 24.4	M: 61.26 – 67.34 F: 60.16 – 67.40
Knicker (33)	8	8	16	Elite	M: 23.8 – 26.8 F; 22.2 – 24.5	M: 60.16 – 67.40 F: 61.26 – 67.34
Hay and Yu (39)	14	15	29	Varying	M: 21.68 – 25.39 F: 20.67 – 25.85	M: 53.20 – 67.14 F: 43.10 – 68.08
Ariel, Finch, and Penny (40)	4		4	Elite	M: 24.98 – 30.80	M: 65.4 – 69.4
Dapena and Anderst (34)	24		24	Elite		M: 58.44 ± 2.98
Finch, Ariel, and Penny (41)	4		4	Elite	22.69 – 33.43	M: 59.7 – 69.4
Miyanishi and Sakurai (42)	25		25	Varying	NS	M: 47.21 – 67.09
Tong, Xie, Teh, and Yu (43)	57	52	109	Varying	NS	NS
Yu et al. (30)		8	8	Varying	NS	F: 51.83 – 61.65
Dinu, Levêque, Natta, Vandewalle, and Portero (44)	4		4	Sub-elite	M: 19.62 ± 0.46	M: 42.66 ± 2.88
Leigh and Yu (8)	51	42	93	Varying	M: 22.8 ± 1.3 – 25.0 ± 0.8 F: 22.5 ± 1.1 – 24.3 ± 1.1	M: 52.3 ± 2.2 – 66.5 ± 0.7 F: 50.8 ± 3.6 – 66.6 ± 1.2
Leigh and Yu (32)			NS	Varying	NS	NS
Leigh et al. (4)	51	53	104	Varying	M, F: 20.7 – 26.2	M, F: 48.9 – 67.4
Badura (45)	8	8	16	Elite	M: 23.9 – 24.9 F: 23.1 – 24.2	M: 63.17 – 69.43 F: 57.71 – 65.44
Nemtsev (46)		4	4	Sub-elite	NS	36.3±2.08
Panoutsakopoulos and Kollias (47)	8		8	Varying	NS	M: 48.61 – 67.63
Monsef et al. (48)	1		1	Elite	NS	M: 64.76
Dai, Leigh, Li, Mercer, and Yu (49)	8	15	23	Sub-elite	NS	M: 56.7±2.7 F: 54.1±5.7
Maeda, Byun, Hirose, and Ogata (50)	22		22	Varying	NS	M: 31.92 – 59.21
Junming, Jihe, and Ting (51)		4	4	Elite	F: 22.57 – 23.65	F: 60.75 – 61.47
Chen, Zhou, and Chen (52)	1		1	Elite	M: 23.72	M: 58.10

M = Male, F = Female, *Sex of participants not reported, ** Estimated distance, not stated (NS) by authors, [c] Cross-sectional investigation, [i] interventional/longitudinal investigation, varying = Elite and sub-elite combined.

Table 2.3 summarises the data collection methods and associated outcome measures derived from each study. The majority of the literature analysed competition throwing performance (three to six throws in competition) and the best performance was analysed (4, 8, 34, 39, 40, 42, 43, 45, 47, 50, 52, 53). The best throwing performance (i.e., maximal distance) is not often associated with the greatest release velocity of a set of throws due to the atmospheric conditions and relative aerodynamic orientation of the discus (45). Therefore, the best performance may not have been the throw with the greater release velocity or optimal kinematic performance with respect to release velocity. The majority of studies manually digitised video capture images taken with 2 – 3 cameras operating at 50 – 60 Hz (4, 8, 33-35, 38-40, 42-45, 48, 49, 51, 52), except for three studies that employed higher frame rates or infrared systems (36, 46, 50) (see Table 2.3). Kinematics have been reported at the beginning and end of phases, with only a few authors reporting kinematic waveforms (42). In conjunction with certain time points, the majority of literature reported only a select number of kinematic parameters (e.g., temporal analysis or kinematics in separate phases) (43, 47, 51). For clarity, the results presented are in reference to right-handed throwers.

After reviewing the literature, it was evident that the discus throw is comprised of six phases defined by foot contacts and release. For a right-handed thrower, these phases are: 1) Backswing (BS), defined by bilateral foot contact and discus movement opposite the throwing direction; 2) First double support (1DS), defined by bilateral foot contact at the back of the circle; 3) First single support (1SS), starting at right foot off and is characterised by single foot contact at the back of the circle; 4) Flight (F), begins with left foot off and is defined as the absence of ground contact; 5) Second single support (2SS), starting at right foot touch down and is characterised by single foot contact in the middle of the circle; 6) Second double support (2DS), starting with left foot touch down and is defined by bilateral foot contact at the front (nearest to sector) of the circle; and, 7) Release of the discus (REL), when the implement leaves the throwers hand. Of note is that there are two main release techniques observed: supported and unsupported. Supported, often referred to as blocking, refers to a release with the throwers feet in contact with the ground. Unsupported, often referred to as reversing, refers to a release without the throwers feet in contact with the ground. Accordingly, this review discusses the literature in relation to the six phases, with the addition of discus velocities and phase durations (see section 4.1) and release parameters (see section 4.8).

Table 2. 3. Methods and information from the selected investigations organised by publication date.

Author	Performance descriptions	Method of analysis	Phases analysed: BS	1DS	1SS	F	2SS	2DS	REL	Summary of results
Vodicková (35)	1 competitive throw (performance NS)	Capture: 2 orthogonal cinematographic cameras (50 Hz) Analysis: Manual digitisation and analysis in SimiMotion.							X	- Discus and selected kinematics were reported at release.
Gregor et al. (36)	1 competitive throw (best performance)	Capture: 2 orthogonal cinematographic cameras (120 Hz) Analysis: Manual digitisation.		X	X	X	X	X	X	- Females release the discus at a lower relative body height than males. - Trunk angle becomes more reclined with increasing release angle.
Knicker (37)	NS	NS			X	X	X	X	X	- Inter athlete variations in discus velocity and axial separation through each phase exist.
Knicker (38)	NS	Capture: 2 orthogonal cinematographic cameras (50 Hz) Analysis: Manual Digitisation performed in Peak Performance V5.			X	X	X	X	X	- Inter athlete variation in temporal patterns and discus velocity through each phase exist. - Females tend to spend more time in the delivery phase than males.
Knicker (33)	NS	Capture: 2 orthogonal cinematographic cameras (50 Hz) Analysis: NS			X	X	X	X	X	- As the level of performance increases, the correlation between release velocity and distance decreases. Inter athlete variation in discus velocity through each phase exist.
Hay and Yu (39)	1 competitive throw (best performance)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: Manual digitisation (DLT)		X	X	X	X	X	X	- Significant correlations between changes in, and the absolute discus velocity during phases and performance. - Angular momentum relates to increased distance.
Ariel et al. (40)	1 competitive throw (best performance)	Capture: 3 cinematographic cameras (60 Hz) 2 orthogonally orientated Analysis: Manual digitisation (DLT)							X	- Release kinematics reported.

Dapena and Anderst (34)	1 competitive throw (best performance)	Capture: 2 orthogonal cinematographic cameras (50 Hz) Analysis: NS	X	X	X	X	X	X	- Angular momentum is essential to discus performance, and numerous combinations of segment momentum generate elite performance.
Finch et al. (41)	2 competitive throws (best and worst performance)	Capture: 3 cinematographic cameras. 2 orthogonal (sampling rate NS) Analysis: Manual digitisation (DLT)						X	- Comparison of release kinematics between good and bad throws.
Miyanishi and Sakurai (42)	1 competitive throw (best performance)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: Manual digitisation (DLT)	X	X	X	X	X	X	- Angular momentum about the vertical axis is predominantly generated during first single support.
Tong et al. (43)	1 competitive throw (best performance)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: NS				X	X	X	- Males tended towards decreasing vertical velocity during second single support - Males and females tended towards increasing vertical velocity during release.
Yu et al. (30)	3 maximal performances in two starting positions	Capture: 3 cinematographic cameras (60 Hz), synchronised with 3 force plates sampling at 1000 Hz. Analysis: Motion Soft 4.0		X	X	X	X	X	- Right foot forward and lateral and left foot vertical and backward left foot GRF relate to performance during the second single support and delivery. - Normalised right foot, right hip and left knee kinetics related to performance during second single support and delivery.
Dinu et al. (44)	12 throws collected, only performances above 80% of season’s best analysed.	Capture: 3 cinematographic cameras (50 Hz), synchronised EMG over nine muscles converted to 1000hz. Analysis: Motion Soft 4.0 used for analysis.	X	X	X	X	X	X	- Changes in EMG during phases observed. - Inter athlete variation in EMG magnitudes observed.

Leigh and Yu (8)	1 competition throw (best performance)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: Manual digitisation and analysis performed in custom-written software (MotionSoft).	X	X	X	X	X	X	X	- Hip – shoulder, shoulder – arm, and trunk tilt are related to performance at varying instances in female and male throwers.
Leigh and Yu (32)	Competition throws, (performance NS)	Capture: 2 cinematographic cameras (sampling rate NS) Analysis: Manual digitisation and analysis performed in Peak Motus 6.1.			X	X	X	X	X	- Hip-shoulder and shoulder-arm separation at varying instances tend to increase with female throwing distance. - Hip-shoulder separation at left foot off has a decreasing trend with increasing distance in male throwers. - Release characteristics (angle, height, and speed of release) all have a positive association with distance.
Leigh et al. (4)	1 competition throw (best performance)	Capture: 2 orthogonal cinematographic cameras (60 Hz, shutter speed 1/1000) Analysis: Manual digitisation (DLT) with analysis performed in custom written software.	X	X	X	X	X	X	X	- Hip-shoulder separation, trunk tilt, throwing arm elevation, and second single support phase duration related to female throwing performance. - Hip-shoulder separation is related to males throwing performance. - Release velocity highly related to male and female throwing performance.
Badura (45)	1 competition throw (performance NS)	Capture: 2 cinematographic cameras (50 Hz) Analysis: NS		X	X	X	X	X	X	- Release velocity related to performance - Participant kinematic data reported
Nemtsev (46)	3 throws	Capture: 6 Qualisys infrared cameras (120 Hz) Analysis: NS						X	X	- Only release data reported
Panoutsakopoulos and Kollias (47)	1 competition throw (best performance)	Capture: 1 cinematographic camera (300 Hz) Analysis: V1 home 2.02.54		X	X	X	X	X	X	- Phase durations vary between elite throwers and phase duration does not relate to performance.

Monsef et al. (48)	3 competition throws (3 best performances of six)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: DARTFISH TEAM PRO 4	X	X	X	X	X	X	-	Fluctuations in joint and discus kinematics through each phase exist.
Dai et al. (49)	3 competition throws (performances NS)	Capture: 2 orthogonal cinematographic cameras (60 Hz) Analysis: Manual digitisation (DLT), analysis performed in MATLAB.	X	X	X	X	X	X	-	Kinematic variability is correlated with performance, more so in males than females.
Maeda et al. (50)	1 competition throw (best performance)	Capture: 3 cinematographic cameras, (2 orthogonal) (300 Hz, shutter speed 1/1000 or 1/1200) Analysis: Manual digitisation (DLT).	X	X	X	X	X	X	-	Center of gravity velocity and linear momentum relate to performance level.
Junming et al. (51)	NS	Capture: 2 orthogonal cinematographic cameras (50 Hz) Analysis: SignaltEC3D.					X	X	-	Large hip-shoulder and shoulder-arm separations reported in elite female throwers.
Chen et al. (52)	1 competition throw (best performance)	Capture: 2 orthogonal cinematographic cameras (50 Hz). Analysis: High titanium 3-D Signal TEC V1.OC software for processing.	X	X	X	X	X	X	-	Kinematic and release parameters for a single participant reported.

Abbreviations: NS = Not stated, GRF = ground reaction force, EMG = electromyography, DLT = direct linear transformation, BS = backswing, 1DS = first double support, 1SS = first single support, F = flight, 2SS = second single support, 2DS = second double support, REL = release

2.4 Discussion

2.4.1 Phase durations and discus velocity

Varying phase durations are reported at an elite level (Table 2.4) (29, 37, 47, 54). Weak non-significant correlations between durations and throwing distance have been reported for the first double support phase ($r = 0.23$, $p > 0.05$) (47).

Table 2. 4. Elite throwers phase durations.

	Males	Females
Distance (m)	56.82 – 69.02	55.8 – 69.78
1st double support (s)	0.36 – 0.70	0.48 – 1.12
1st single support (s)	0.25 – 0.44	0.33 – 0.49
Flight (s)	0.00 – 0.18	0.02 – 0.14
2nd single support (s)	0.09 – 0.28	0.13 – 0.33
2nd double support (s)	0.10 – 0.26	0.11 – 0.22

Values adapted from Bartlett (29).

Release velocity is the most critical variable to throwing performance. It is well accepted that the majority (62 to 73%) of final release velocity is gained during the final phase of the discus throw (i.e., second double support to release) (29, 37). In theory, increasing velocity from the beginning to the end of the throw is logical when aiming to achieve the greatest release velocity. However, increases (38), decreases (29, 34), and no change in discus velocity have been reported during first single support, flight, and second single support at an elite level (see Table 2.5) (29, 37-39). The most efficient velocity pattern preceding release has not been identified, and likely will not be recognised due to between thrower differences in anthropometrics, biomechanics, and stylistic trait variations that determine discus velocity. Hay et al. (39) reported a strong correlation between change in discus velocity during flight and distance thrown by female throwers ($r = 0.76$, $P \leq 0.01$), but the same strength of association was not evident in male throwers. The discrepancy between sexes is likely a result of the differing weights thrown that future investigations should look to understand.

Table 2. 5. Change in discus velocity during a phase and absolute velocity at the end of a phase of discus throwing.

	Males (Throw distance = 59.07 – 67.40 m)		Females (Throw distance = 57.90 ± 7.51 m)	
	Change (m/s)	Absolute (m/s)	Change (m/s)	Absolute (m/s)
1st Double support	2.34 – 9.44	3.90 – 6.80	4.85 ± 1.26	4.85 ± 1.26
1st single support	-2.05 – 7.60	7.60 – 12.8	2.19 ± 1.46	7.03 ± 0.78
Flight	-3.00 – 3.80	7.64 – 16.3	-0.44 ± 1.52	6.59 ± 1.48
2nd single support	-4.60 – 11.8	7.64 – 13.1	1.30 ± 1.15	7.89 ± 1.30
2nd double support	3.16 – 19.38	23.8 – 26.0	15.34 ± 1.39	23.22 ± 1.49

Values adapted from Bartlett (29), Knicker (38), Knicker (37) and Hay and Yu (39). Change (m/s) = change in velocity during phase; Absolute (m/s) = velocity at the end of the associated phase.

2.4.2 Backswing

The backswing encompasses the starting position and movement of the athlete-discus system away from the throwing direction. Monsef (48) observed stance width to range from 37 to 41% of an athlete's height in one elite male thrower, but did not explore how stance width related to throwing distance. Despite both Knowles (55) and Tidow (54) theorising that starting in a wide, slightly externally rotated foot position facing away from the sector produces greater right hip pre-stretch, a prolonged acceleration path, and a more significant weight shift during the ensuing phase. There is currently no quantitative data available supporting this theory or defining the most advantageous starting position (29).

Coach-driven feedback encourages controlled movement and weight shift to the right foot as the athlete pivots on the left foot during backswing. Concurrently, large hip to shoulder and shoulder to discus separations are generated with the discus carried at shoulder height at maximal backswing (4, 32, 54, 56). Researchers have yet to report ground reaction force (GRF) data during the backswing phase (30). Leigh et al. (4) observed weak associations between trunk forward lean ($r = 0.35$, $p < 0.05$, range: – 73 to 63°), throwing arm elevation ($r = 0.28$, $p < 0.05$, range: 2 to 54°) and performance in elite females, but not male throwers at maximal backswing. Few researchers have reported kinematic data through the backswing phase. A few studies indicate that a wide stance, forward lean, and high discus position is a preferential biomechanical pattern (4, 32, 54, 56); but due to the lack of data, further research is required to understand backswing kinematics that optimise performance.

2.4.3 First double support

From maximum backswing, elite throwers linearly shift over the left foot and rotate towards the throwing direction, maintaining hip to shoulder separation, shoulder to arm separation, and forward trunk lean with flexed knees (4, 34, 48, 52). The act of shifting and rotating increases both linear momentum and angular momentum about the vertical axis (34, 42, 50). Maeda et al. (50) found that the magnitude of linear momentum differentiated elite and sub-elite throwers (>

80 kg·m/s) from novices (< 60 kg·m/s), but not elite and sub-elite (note: direction of linear momentum not stated). Angular momentum begins to be generated in first double support, the magnitude of which coaches believe dictates how the discus is orientated (palm down or up) (57). Dapena and Anderst (34) observed elite male throwers to generate 78 ± 10% of their total angular momentum before right foot off and accredited 94% of their horizontal release velocity to their angular momentum. In the process of generating angular momentum, consideration should be given to the magnitude of discus acceleration as it relates to acceleration of the discus during ensuing phases ($r = -0.85$, $p < 0.01$) (39). In summary, during the first double support phase, elite throwers generate high angular momentum concurrently with sufficient linear momentum to shift over the left foot laterally. If further discus acceleration in flight is a goal, momentum should predominantly come from the width of the system and not its change in velocity.

2.4.4 First single support

During the first single support phase, the right leg rotates in a counter clockwise path (referred to as a sweep) while the left knee flexes and the thrower pivots on the left foot. The centre of mass (COM) continues to move laterally over the left foot before starting its projection obliquely left across the circle relative to the centre of the sector. Concurrently, elite throwers maintain forward trunk lean with reference to a vertical axis (18 ± 7 and 22 ± 7° in male and 17 ± 7 and 24 ± 8° in female throwers at right and left foot off, respectively) while the hip to shoulder and shoulder to arm separations decrease (females: -12° to 60°, males: -19° to 60°) and the lead arm swings in the direction of rotation (4, 8, 32, 34, 39, 42, 48, 50, 52).

Greater hip to shoulder separation was thought to enhance performance through the generation of torque during the first single support (55). However, Leigh et al. (4) reported a weak negative correlation between hip to shoulder separation during first single support and distance thrown in female athletes ($r = -0.35$, $p \leq 0.05$). Similarly, Leigh et al. (8) found that athletes who threw more than 65 m exhibited significantly smaller hip to shoulder separation than those who threw less than 55 m. Given the ranges reported in this measure (11 to 74°) by Leigh et al. (4), it can be concluded that maintaining a small magnitude of hip to shoulder separation during first single support might be beneficial; however, considerable individual variations exist (4, 8, 55). Shifting the COM left increases linear momentum, which has been shown to distinguish elite from novice throwers (50). Linear momentum depends on the application and orientation of the ground reaction force (GRF), with Yu et al. (30) observing that vertical, but not horizontal, left foot impulse relates to distance ($r = 0.70$, $p = 0.05$). Collectively, these results suggest that a certain amount of linear momentum and horizontal impulse are required, combined with a vertical impulse, to project the athlete across the circle in flight (30, 50).

The rotary action of the left arm, sweeping of the right leg, and application of force from the left leg laterally to the centre of rotation all contribute to the observed increase in angular momentum

(30, 34, 42, 58). An area of coaching contention is the width of right leg sweep, where both wide (29, 54, 55) and narrow (29, 54) sweeps are proposed to enhance performance. A wide leg sweep is most often encouraged by coaches as it is thought to increase angular momentum (29, 34, 39, 55). Dapena and Anderst (34) documented sweep leg width concurrently with angular momentum, but did not investigate the relationship between the two. Hay and Yu (39) observed a close to significant correlation ($r = 0.60$, $p > 0.05$) between angular momentum at left foot off and distance thrown, but relevant limb kinematics were not reported. With regards to lead arm movement and GRF timing relative to axis orientation, sparse kinematic and kinetic data have been reported. Hence, the primary determinants of increased angular momentum remain largely undetermined. To summarise, during first single support, elite athletes adopt both wide and narrow sweep leg radius's concurrently with a swinging lead arm to increase angular momentum. Kinematically, both hip to shoulder and shoulder to arm separations decrease, but remain positive, indicating some degree of separation. Further research should seek to understand definitively how kinetic and kinematics influence linear momentum through single support.

2.4.5 Flight

At left foot off, the magnitude of linear and angular momentum and the trajectory through which the athlete will move in flight are established (34, 39). Elite athletes manipulate their limb orientation in flight, increasing throwing arm elevation (i.e., shoulder abduction), hip to shoulder separation, and shoulder to arm separation (4, 8, 34, 45, 48). The principle of conservation of momentum is essential to an effective flight phase and has implications for landing orientation, hip to shoulder separation, shoulder to discus separation, and discus velocity (34). Increases in hip to shoulder separation of varying magnitudes (0 to 89°) during the flight phase have been reported (4, 8, 45). Hay and Yu (39) suggested that narrowing the sweep leg resulted in isolated hip acceleration when upper body radius was maintained. Badura (45) later corroborated these findings, but did not report upper body radii. Dapena and Anderst (34) observed elite throwers to narrow the right leg radii in flight and simultaneous decrease left arm radii. Much of the literature has focused on describing the effects of the sweep leg (29, 39, 45, 54); however, the movement of the left leg in flight affects the lower body radius and thus should be considered concurrently with the sweep leg. Coaches advocate narrowing the space between the thighs in flight (57). Although Dapena and Anderst (34) reported a narrower radius of rotation from the left leg compared to the right, kinematic data in support of coaching cues to narrow thigh space in flight are limited.

With regard to the upper body, maintaining the shoulder to arm separation, "winding" into a stationary free arm, and increasing discus height (part of establishing an orbit) are key technical considerations supported by empirical evidence (4, 8, 45, 48, 54, 55). Elite throwers increase the magnitude of shoulder to arm separation in flight (4, 8, 52), which has been related to performance. More specifically, shoulder to arm separation magnitude at right foot down weakly relates ($r = 0.34$, $p < 0.01$) to throwing distance in female throwers of varying abilities (32) and is a trait of elite male performers (45). Tidow (54) suggested that the lead arm works against the direction of rotation. In support, Dapena and Anderst (34) observed elite throwers to decrease left arm radii and velocity during the flight phase. The authors speculated that the motion of the left arm helped increased the velocity at which the left leg rotated, but did not provide supporting evidence.

Leigh and Yu (8) and Leigh et al. (4) reported mean trunk to arm elevation (greater shoulder abduction) to increase from left foot off to right foot down. Monsef et al. (48) also observed discus height to increase during flight. Coaches advocate the establishment of a “good” orbit, i.e., a qualitative measure of discus height (55). From the literature it seems that discus height increases in flight (48); however, large ranges and standard deviations have been reported. Therefore, there likely exists a broad bandwidth associated with high-level performance for this particular metric (4, 8). In summary, the development of hip to shoulder separation is a function of narrowing the lower body radii while the lead arm slows or works against the direction of rotation. However, significant inter-athlete variations in hip to shoulder separation occur, indicating that a one-size-fits-all approach is not appropriate. Finally, the maintenance of or increase in shoulder to arm separation should be observed, concurrently with an increase in discus height.

2.4.6 Second single support

On right foot touch down, internal rotation of the foot is observed concurrently with high landing forces (30, 45). Throwers will then pivot through single support on the right foot while horizontally abducting the left shoulder and actively trying to plant the left leg at the front of the circle (34, 54). The degree of right foot rotation required may depend on release style. Badura (45) observed the right foot to be more internally rotated in non-reversing releasers when compared to those using a reversing technique. Regardless of release style, the orientation of GRF at right foot down is largely and significantly correlated (driving impulse, $r = 0.81$; leftward impulse, $r = -0.75$) to throwing performance (30). Propulsive GRF aids in maintaining or increasing angular momentum and linear momentum, which has been observed in elite and sub-elite throwers (30, 34, 42, 50). Linear momentum at left foot down has specifically been shown to differentiate elite from novice throwers (50).

Although angular momentum about a vertical axis is maintained or increased through single support, elite throwers demonstrate a shift in angular momentum from positive to negative about a medio-lateral axis and an increase in negative angular momentum about the anterior-posterior axis (34, 42). The shift from positive to negative angular momentum about a medio-lateral axis occurs concurrently with the decreasing trunk tilt towards 0° observed in both female and male throwers across levels (4, 8). Attaining a rearward lean at release, which is a function of the second single support phase kinematics, is important for performance in female throwers, but not so in males (8). Coaches should therefore encourage rearward lean at release, especially in females.

Coaches have suggested that a purpose of the second single support is to increase hip to shoulder separation that, in principle, increases the time over which force can be applied to the discus during ensuing phases (34, 45, 54, 57). The magnitude of hip to shoulder separation at left foot down has been shown to relate to performance ($r = 0.31$, $p = 0.045$) in female throwers (8). However, decreases (30, 45, 52), maintenance of (4, 8, 34), and increases (34, 45) in hip to shoulder separation through second single support have been reported. When displayed graphically over the course of the second single support, ascending and descending patterns exist (34, 45). Coaches have speculated that the ability to maintain or increase hip to shoulder separation is related to disc velocity and left leg kinematics (29, 54), but no quantitative data support a relationship between left leg kinematics and hip to shoulder separation.

With regard to the upper limbs and discus, the majority of the literature has observed increases in shoulder to arm separation, decreases in throwing arm elevation, and increases in lead arm momentum in the direction of the throw during second single support (4, 8, 34, 45). Increases in shoulder to arm separations of differing magnitudes across sexes and throwing abilities have been reported, the magnitude of which at left foot down has been related to performance in female throwers [$r = 0.34$, $p < 0.01$, (32); $r = 0.43$, $p = 0.005$ (8)], but not in male throwers (4, 8, 45, 48). Increases in shoulder to arm separation are proposed to result from an active lower-body drive that pre-stretches the chest musculature (30, 44, 59). Further research understanding the drivers of shoulder to arm separation would provide insight into the discrepancies between sexes and varying magnitudes of change reported.

Decreasing throwing arm elevation occurs concurrently with increasing shoulder to arm separation. Both Leigh and Yu (8) and Leigh et al. (4) observed throwing arm elevation to decrease between right and left foot down in male and female throwers of ranging abilities. Changing throwing arm elevation affects disc orbit (29), with the thrower actively influencing the disc orbit or moving their body away from the direction of the discus (4, 8, 43, 48). Only Dapena and Anderst (34) have investigated lead arm kinematics during second single support, reporting increased maximal angular momentum arising from increased velocity and radius. The authors suggested that the lead arm contributes to increasing right foot GRF and angular momentum; but again, no supporting data were provided. In summary, elite throwers maintain or increase both hip to shoulder and shoulder to arm separation through second single support by effective GRF orientation and holding the discus in a horizontally abducted position. The role of the left leg is unclear: It could aid in achieving both hip to shoulder and shoulder to arm separation. The orbit of the discus has been schematically represented and suggested as an essential consideration in throwing performance.

2.4.7 Second double support

The purpose of second double support is to enhance discus velocity by further gaining and transferring momentum to the discus at the point of release (34, 39). Increasing and transferring momentum arise from propulsive right leg force (30), left leg and arm kinetics and kinematics (referred to as "the block") (30, 55, 57), and using the previously generated hip to shoulder and shoulder to arm separations (4, 8, 34). Coaches believe an effective block is characterised by the left leg being firm on landing and the left arm simultaneously slowing and narrowing in radius (55, 57). The orientation of the left foot depends on release style. Typically, a "blocking release" refers to a throwing style where the athlete releases the discus from second double support, whereas a "reversing release" refers to a throwing style where the thrower releases from the flight phase following second double support and lands facing away from the sector. Blocking releasers tend to plant the left foot in a relatively more open position (i.e., pointing towards the sector) than reversing releasers (45). The magnitudes of the vertical ($r = 0.75$, $p = 0.03$) and backward-directed ($r = 0.90$, $p = 0.00$) force upon left foot contact have been correlated to throwing distance (29, 30). Increased GRF at left foot down is likely a function of elite throwers transferring horizontal linear system momentum into horizontal and vertical discus velocity (34, 50). Slowing and narrowing of the left arm occur simultaneously with a strong blocking leg to transfer the momentum of the to the discus (34).

Along with a strong left-side block, coaches promote the development of high propulsive and rotary forces from the right leg to increase angular momentum and provide a strong base for momentum transfer (34, 57, 59). In support, Yu et al. (30) observed forward ($r = 0.81$, $p = 0.02$) and right GRF impulse ($r = 0.75$, $p = 0.03$) and right hip internal rotation moments ($r = 0.84$, $p = 0.01$) to be related to official distance thrown. Furthermore, Dapena and Anderst (34) observed elite throwers to increase angular momentum early in second double support. Only GRF were reported by Yu et al. (30), thus the effects of GRF on angular momentum and discus velocity are yet to be quantified. The GRF generated allow the thrower to use the hip to shoulder and shoulder to arm separations in a propulsive manner. In theory, to maximise performance according to the impulse-momentum relationship, high magnitudes of separation from both hip to shoulder and shoulder to arm at the start of second double support, and angles closer to zero at release, indicate increased time over which force was applied (impulse). This theory is supported by both coaching observations (54, 57) and biomechanical data (4, 8, 34, 37, 45, 51). The large hip to shoulder (males: 10 to 89°, females: -3 to 90°) and shoulder to arm separations (males: 3 to 60°, females: 16 to 86°, relationship to performance in female's $r = 0.43$, $p = 0.005$ (8)) at left foot down have been observed to decrease leading into release (4, 8, 33, 34, 45). At the instant of release, it has been proposed that both hip to shoulder and shoulder to arm separation should correspond to zero, with trailing angles at release indicative of a technical flaw (29, 51).

Kinematic data are variable and show both overtaking and trailing of the shoulders over the hips and arm over the shoulder in second double support (4, 8, 34, 45, 52). At release, only shoulder to arm separation has been associated with performance in female throwers ($r = 0.38$, $p = 0.01$) with the group throwing more than 65 m displaying shoulder to arm separation closer to zero (8). Thus, the body of evidence support generating large hip to shoulder and shoulder to arm separations at left foot down and decreasing these angles throughout second double support until release. To attain the optimal angle of release, it would seem that increasing angular momentum of the discus about an anterior-posterior axis (34, 53), leaning the trunk rearwards (4), and increasing the COM vertical velocity (34) are desired technical traits. Increased discus angular momentum about an anterior-posterior axis (4, 8, 34, 53) and a reclined trunk position at release have been observed in both elite male (86 to 124°) (4, 8, 35, 36) and female (81 to 120°) (4, 8, 36) throwers, with only the magnitude of trunk lean being related to performance in female throwers ($r = -0.39$, $p < 0.05$). The sex differences observed can be attributed to disparities in release styles, as females are predominantly blocking releasers and males, reversing releasers (34, 45, 54). The reversing style generates vertical velocity through vertical leg drive, whereas the blocking style favours a rearward trunk lean to enhance the vertical discus velocity (57). The most effective release style remains undetermined. Overall, it appears that large separations (i.e., hip to shoulder and shoulder to discus) and the production of large GRF are essential to apply force to the discus through second double support. The translation of force to release velocity and distance likely relies on trunk position and blocking kinetics and kinematics. However, researchers have not investigated the relationship between linear momentum, GRF, and discus velocity.

2.4.8 Release parameters

Release parameters are crucial for maximising official throwing distance (45) and differ slightly between male (2 kg) and female (1 kg) discus throwers. The vertical and resultant speed of the discus are the release parameters exhibiting the greatest correlations to official distance ($r = 0.63$ and 0.53, respectively) and explain 28 and 36% of the variation in distance, respectively (4, 39). Using modelling techniques, Chiu (28) determined that a release velocity of 26.66 m/s, release angle of 36.5°, attack angle of -10.3° (see Figure 2.2), and disc attitude of 26.3° were required for men to throw the current World Record distance of 74.08 m in the absence of wind. The corresponding values for women to match the World Record of 76.80 m were 27.04 m/s, 32.75°, -9.25°, and 23.50°. Windy conditions require a change in release angle, disc attitude, and disc roll (i.e., lateral disc axis tilt) to achieve comparable throwing distances (6, 28). When release parameters are manipulated to suit atmospheric conditions, distance thrown can increase into a headwind (wind speeds of up to 17 m/s with a 2 kg disc and 13 m/s with a 1 kg disc) when release and attitude angles are decreased (28). Similar increases in distance in tailwinds (wind speeds exceeding 7 m/s with a 2 kg disc and 12 m/s with a 1 kg disc) when the release and attitude angles are increased (28) have been noted. It has been suggested that disc release speed is dictated by physical qualities, whereas disc launch conditions (i.e., release, attack, and attitude angles) are skill based (4, 28, 55). To throw long distances, throwers need to be able to modify their release parameters according to environmental conditions. The use of technology in training and competition to quantify release parameters should aid throwers and their coaches to better comprehend changes in release parameters that influence distance thrown in different environmental conditions.

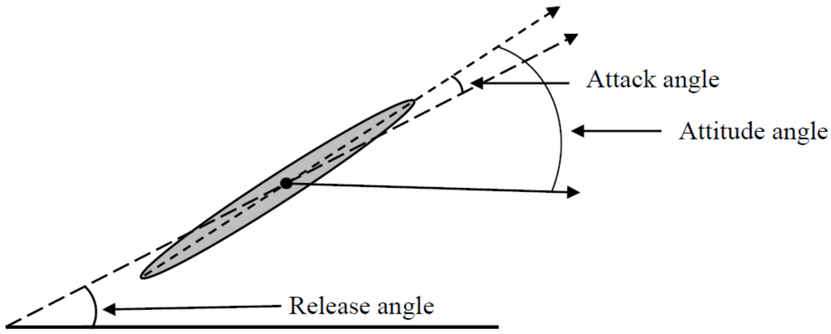

Figure 2. 2. Discus release parameters.

2.5 Conclusions

The purpose of this review was to highlight the current research, participants, methods of data capture, analysis, and resultant biomechanical data associated with performance in each phase of discus throwing. Discus performance is underpinned by release parameters (velocity, height, and angle of release with the appropriate attitude and tilt angles). Although release angle, height, and attitude angle are important, the primary predictor of performance is release velocity. Release velocity is increased by increasing the magnitude of force applied to the discus or the time over which it acts (i.e., impulse-momentum relationship). As such increasing thrower-discus momentum, both angular and linear, and translating it into the discus at the point of release are of practical importance. However, research reporting the transfer of this momentum with corresponding kinetic and kinematic data from maximal backswing to release is sparse. There is a need to understand both kinematics and kinetics that enhance momentum, including system radius, moment of inertia, angular velocity, and linear velocity. Literature reporting these variables in a comprehensive manner would provide coaches with an evidence base from which performance enhancing technique changes can be applied.

Multiple kinematics and kinetics parameters in isolation have been related to throwing performance. Throwing performance itself is a composite of multiple kinematics and kinetics working in harmony to accelerate the discus. Therefore, adapting a single parameter will affect the system as a whole, which should be kept in mind by practitioners. Future research needs to quantify the effects of kinematic parameters on release velocity to provide coaches with quantitative data on determinants of poor and optimal throwing performance.

Chapter 3

Rotational shot put: A phase analysis of current kinematic knowledge

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3.0 Prelude

The literature review in the previous Chapter described the biomechanics of the discus throw. A comprehensive search revealed a paucity of literature, specifically on biomechanical changes over time in both elite and sub-elite populations. Similar to discus throwing, the biomechanics of shot put are critical to performance. Given the integral role of biomechanics within shot put performance, the purpose of this Chapter was to provide a comprehensive summary of the literature pertaining to shot put biomechanics. This information provides important insight as to the kinematic and kinetic variables driving performance. Coaches, athletes, and support staff can use this information to enhance performance as it relates to their specified fields. Most importantly, the information in this Chapter provides foundational knowledge that will guide understanding of best practice assessment methods and training methods for shot putters, which will be used to guide and underpin the ensuing Chapters in this thesis.

3.1 Introduction

Shot put has been a permanent fixture within the summer Olympic programme since its inception in 1896. Shot putters aim to generate maximal displacement of the shot (men's shot: mass 7.26 kg, diameter: 110 to 130 mm; women's shot: mass 4 kg, diameter: 95 to 110 mm) within the confines of the sector, while maintaining foot contact within the throwing circle. The rules of shot put stipulate that the thrower can contact the inside of the rim or top of the rim during the first rotation provided no propulsion is gained, as well as contact the inside, but not top, of the stop board. Circle, sector, and stop board dimensions are shown in Figure 3.1.

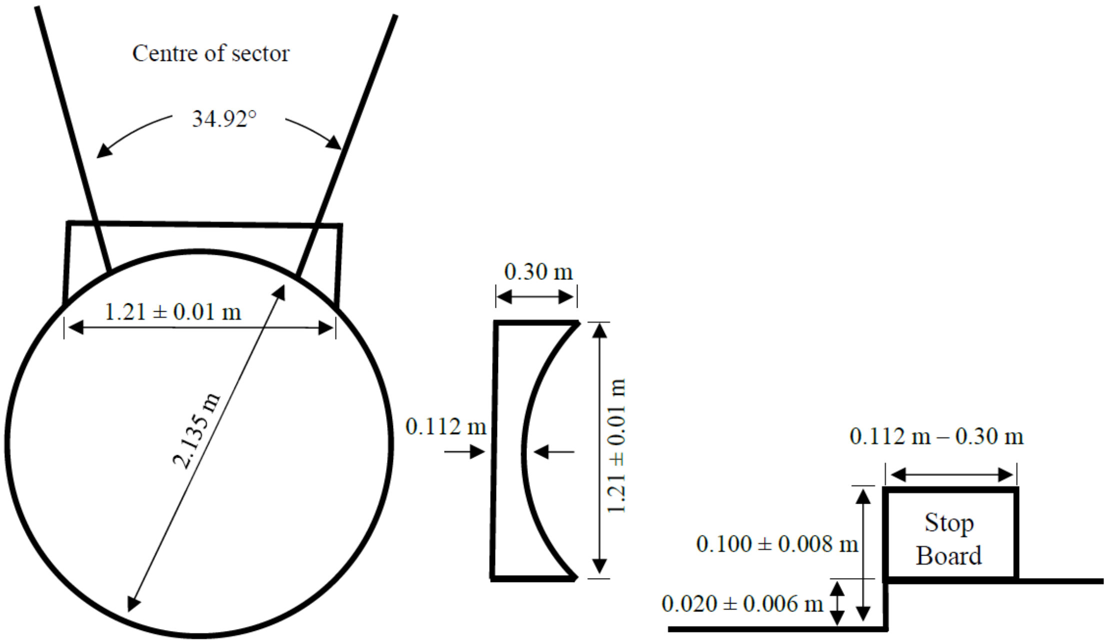


Figure 3. 1. Shot put circle (left) and stop board (right) dimensions, adapted from IAAF (1).

Several throwing style variations have been trialled over the years. The gliding technique was introduced in the 1950s and was the technique of choice for many years. The gliding technique involves a linear push out of the back to the front of the circle while facing away from the sector. Throwers then rotate towards the sector, putting the ball for maximum distance. The rotational style appeared in the 1970s and is the most prevalent nowadays (60). The rotational style technique is traditionally separated in to six phases and involves approximately 1.5 – 2 rotations of the body before implement release, during which the athlete generates large forces within short time frames to project the shot into the sector. Large forces arise from both technique and physical factors during shot putting and consideration of both these factors are needed to enhance performance. Consequently, both coaches and biomechanists quantify kinematics and kinetics when working with a shot putter to enhance performance (5, 25, 61-64).

Researchers have identified select variables that are important to performance in isolation (e.g., hip to shoulder separation, angular velocity, and linear and angular momentum) (5, 9, 25, 61, 63-66). The main criteria traditionally used for evaluating the quality of a track and field throwing performance include the variables of release velocity, angle, and height of release (3). During athletic events, special reports are prepared that provide a detailed analysis of the best athletes in every discipline in terms of these variables (5), which have the advantage of being easy to measure, even during a live performance. To the authors' knowledge, however, a synthesis of the kinematic literature in shot putting has not been undertaken. The outcome of such a literature review would be a valuable resource for athletes and coaches, in addition to providing future direction for kinematic research. Therefore, the objective of this review was to synthesise and critically evaluate current kinematic literature relevant to rotational shot put. Specifically, this review aimed to address the critical kinematic variables within each of the six phases of the rotational technique that relate to increased shot put distance and release velocity.

3.2 Methods

A narrative style review was deemed most appropriate due to the broad scope, limited data available, and the variability in the methodologies of the reviewed literature. The literature review process was continued until there was a saturation of information and no additional research of relevance was sourced. This review was limited to studies analysing full rotational shot putting (i.e., athlete starts at the back of the circle and uses rotational movement to displace the shot). SportDiscus^{TM}, Google Scholar, and PubMed databases were searched between June 2016 and June 2018 to identify biomechanical literature on shot put using the search terms 'shot put', 'biomechanics of', and 'track and field throwing'. A total of 41 articles were found across databases. Titles, abstracts, and full-texts of retrieved documents were sequentially reviewed to determine their relevance to the topic. Also, the reference lists of all studies included for review were searched manually for additional studies of relevance. The inclusion criteria were: 1) published in the English language; 2) addressed biomechanics, muscular kinetics, or expert opinions specific on shot put biomechanics; and, 3) referred to increasing either throwing distance (i.e., key performance outcome) or release velocity (i.e., main kinematic determinant of throwing distance). Exclusion criteria were: 1) articles including standing throws or derivatives of the full movements; and, 2) studies not stating throwing style. The articles were categorised as "Biomechanics" or "Expert Opinion" based on the content and design of the articles. A total of 20 articles met inclusion.

3.3 Mechanical terminology

The main mechanical terminology used in the included studies is summarised here to limit possible ambiguity. For clarity, the results presented are in reference to right-handed throwers.

Global reference frame. The global reference frame refers to a fixed coordinate system and reference point that defines the movement within a calibrated space. Different global reference frames have been used in the shot put literature (5, 9, 25). This review considers the z axis as being orientated vertically (positive upward), the y axis as being oriented horizontally bisecting the centre of the sector (positive in the throwing direction), and x axis oriented orthogonally to the z and y axis (positive pointing towards the right hand side when viewed from behind).

Hip to shoulder separation. Hip to shoulder separation describes the relative angle of the pelvis axis in relation to the shoulder axis in the transverse plane (5, 9, 25, 62). Positive angles represent the shoulders leading the hip, negative angles represent the hip leading the shoulders.

Angular and linear momentum. Angular momentum is the product of the moment of inertia and angular velocity of a segment, object, or system about an axis (67). Linear momentum is the product of mass and velocity of a segment, object, or system. Both angular and linear momentum are vector quantities that possess a magnitude and a direction in 3D space. Only two investigations have reported angular and linear momentum, both of which used the same body segment parameters and model for prediction (5, 68).

Velocity and speed. Velocity is a vector quantity that has a magnitude and a direction in 3D space. Speed on the other hand is a scalar quantified by magnitude only. All investigations reporting release velocity have also provided release angle (25, 61, 62, 66, 69-71) with the exception of Dinu, Natta, Huiban, and Houel (72) who reported shot speed only with no directional information. Several authors have presented speed, but not velocity, between first double support and second double support phases (9, 65). A few authors graphically reported x - y and y - z shot movements, providing a direction to the magnitude of velocities (5, 25, 73). For simplicity, the magnitudes of velocity metrics are pooled. Therefore, the values reported are representative of shot speed within phases and are not directionally specific.

3.4 Results

Table 3.1 summarises the participant characteristics from the 20 biomechanical investigations meeting inclusion. A total of 102 participants were represented across these studies. Most investigations included male participants (95 participants in total, 93%) ranging in skill level from novice to elite. Few studies involved female participants (7 participants in total, 7%), the majority of which were classified as elite competing at a world championship level (9, 61).

Data collection methods, phases analysed, and key results of each investigation are summarised in Table 3.2. The majority of 3D data has been collected by digitising cinematographic video collected at 50 – 196 Hz (5, 9, 25, 61-63, 65, 66, 68-71, 73, 74), with only three investigations using optoelectronic systems (64, 72, 75).

Table 3. 1. Participant information from all studies reviewed.

	Sample size (*n*)			Characteristics		
	Male	Female	Total	Level	Release velocity (m/s)	Distance (m)
Stepanek (71)	2		2	Elite	NS	M: 22.39 – 22.47
Luthanen (65)	1		1	Varying	M: 12.30 – 13.32	M: 18.65 – 20.66
Ariel et al. (69)	3		3	Elite	M: 13.60 – 13.95	M: 21.07 – 21.16
Coh and Jost (70) and Čoh and Štuhec (66)	1		1	Elite	12.94	19.58
Peng, Peng, and Huang (76)	7		7	Sub-elite	M: 9.68 ± 0.13	M: 11.57 ± 2.42
Peng, Peng, and Huang (77)	3		3	Sub-elite	NS	M: 12.88 - 16.86
Byun et al. (5)	6		6	Elite	M: 13.18 – 14.07	M: 20.23 – 22.04
Čoh et al. (25)	2		2	Elite	M: 12.60 – 13.95	M: 19.06 – 20.30
Gutierrez-Davila et al. (9)	6	1	7	Elite	M: 13.38 – 14.13 F: 12.90	M: 20.05 – 21.77 F: 18.68
Stepanek (73)		1	1	Sub-elite	NS	F: 16.50*
Harasin et al. (63)	8		8	Varying	NS	M: 18.24 – 20.94
Schaa (61)	5		5	Elite	M: 13.7 – 14.0	M: 20.50 – 22.03
Lipovesk et al. (62)	13		13	Varying	M: 12.52 – 13.58	M: 17.70 – 20.77
Williams (64)	8		8	Sub-elite	NS	M: 16.05 ± 2.12
Arrhenius (74)	8		8	Varying	NS	M: 16.11 ± 2.11*
Dinu et al. (72)	3		3	Sub-elite	M: 9.30 ± 0.21	NS
Urita et al. (75)	7		7	Novice	NS	M: 12.99 ± 1.39
Kapur and Devi (78)		5	5	Novice	NS	F: 7.94 ± 1.27
Kato et al. (68)	12		12	Sub-elite	NS	M: 15.63 ± 1.51

M = Male, F = Female, NS = Not stated. * Estimated distance.

Kinematics within phases have been related to those observed in prior phases (5, 68). Most of the biomechanical literature focused on the second double support and release phases (see Table 3.2), with some authors addressing phases preceding release (5, 65, 66, 68, 70-73), but not always (9, 61-64, 69, 74-76, 78). Furthermore, kinematics were often described at specific events (e.g., hip to shoulder separation at left foot down) rather than throughout the complete motion, which would be required to examine the interdependency of biomechanical parameters within and across phases.

Table 3. 2. Methods and descriptive information of phases and results from the selected investigations.

Reference	Trial descriptions	Method of analysis	Phases analysed.						Key results
			1DS	1SS	FP	2SS	2DS	REL	
Stepanek (71)	1 competition throw (best attempt)	Capture: 2 cinematographic cameras (196 Hz) Analysis: NS	X	X	X	X	X	X	- Select kinematics (shot put, right and left foot, and left hand) of Randy Barnes' best attempt during the Seoul Olympics.
Luthanen (65)	3 competition throw per year	Capture: 2 cinematographic cameras (50 – 60 Hz) Analysis: Conducted in Ariel Performance Analysis Systems	X	X	X	X	X	X	- Shot put velocity and performance increased between years. Changes in phase durations also reported.
Ariel et al. (69)	Competition throws (attempt analyzed NS)	Capture: 2 cinematographic cameras (60 Hz) Analysis: Conducted in Ariel Performance Analysis Systems						X	- Release kinematics of the top 3 performers. Selected kinematics through each phase graphically represented.
Coh and Jost (70) and Čoh and Štuhec (66)	1 competition throws (best attempt analyzed)	Capture: 3 cinematographic orthogonal cameras (50 Hz) Analysis: Conducted in Ariel Performance Analysis Systems	X	X	X	X	X	X	- Selected kinematics of one elite thrower.
Peng et al. (77)	3 laboratory-based trials	Capture: 2 Kistler force plates (1250 Hz) Analysis: Performed in Kwon GRF.				X	X	X	- Right left GRF tended to decrease during landing with performance. Propulsion time tended to increase with performance.
Byun et al. (5)	1 competition throws (best attempt analyzed)	Capture: 2 cinematographic cameras (60 Hz) Analysis: Manual digitised analysis method NS.	X	X	X	X	X	X	- Selected kinematics (release, trunk tilt, and hip to shoulder separation) and kinetics (linear and angular momentum) of the top 10 performers.
Čoh et al. (25)	1 competition throw (best attempt analyzed)	Capture: 2 cinematographic orthogonal cameras (50 Hz) Analysis: Conducted in Ariel Performance Analysis Systems.	X	X	X	X	X	X	- Selected kinematics reported and compared between two elite throwers.

Gutierrez-Davila et al. (9)	1 competition throws (best attempt analyzed)	Capture: 2 cinematographic cameras (100 Hz) Analysis: Manual digitised analysis method NS.					X	X	-	Release kinematics and selected kinematics during double support and at release. Shot put and centre of mass velocity represented graphically.
Stepanek (73)	1 competition throw (foul throw analyzed)	Capture: 2 cinematographic cameras (100-200 Hz) Analysis: Manual digitization analysis programme NS.	X	X	X	X	X	X	-	Rotary shot put is biomechanically more demanding in comparison to linear shot put. Shot kinematics and temporal data reported.
Harasin et al. (63)	1 – 3 trials per person (based on a distance)	Capture: 2 cinematographic cameras (50 Hz) Analysis: Conducted in Ariel Performance Analysis Systems					X	X	-	Angular displacement of the lead arm observed to be twice as large in elite vs sub-elite throwers.
Schaa (61)	1 competition throw (best attempt analyzed)	Capture: 2 cinematographic cameras (50 Hz) Analysis:				X	X	X	-	Release kinematics and foot contact displacements.
Lipovesk et al. (62)	1 competition throw (best attempt)	Capture: 2 cinematographic cameras (50 Hz) Analysis: Conducted in Ariel Performance Analysis Systems					X	X	-	Release velocity was the most significant predictor of performance. However, right knee joint and hip to shoulder velocities, and release height and angle also determined performance.
Williams (64)	3 throws in laboratory	Capture: 6 Vicon Nexus optoelectronic cameras (240 Hz) Analysis: Analysis performed in Vicon Nexus.					X	X	-	Lower body energy was related to performance.
Arrhenius (74)	3 legal throws	Capture: 2 cinematographic cameras (120 Hz) and 2 AMTI force plates (960 Hz) Analysis: Video digitization performed in Vicon Motus.				X	X	X	-	Peak force from the right foot and left foot time on the ground related to performance.

Dinu et al. (72)	≈ 9 – 10 laboratory-based trials	Capture: 6 optoelectronic cameras (200 Hz) Analysis: NS	X	X	X	X	X	X	-	Centre of mass velocity was not significantly different when throwing underweight vs normal weight shots. Shot velocity was higher with underweight shots.
Urita et al. (75)	10 – 18 maximal trials	Capture: Mac3D optoelectronic cameras (300 Hz) Analysis: performed in Cortex motion analysis software			X	X	X	X	-	Direction of the throwers centre of mass through the circle relative to foot position related to performance.
Kapur and Devi (78)	Competition simulation attempts NS.	Capture: 1x cinematographic camera, sampling rate NS. Analysis: Performed in Kinovea.					X	X	-	Decreased right shoulder abduction and greater right elbow joint angles relate to distance.
Kato et al. (68)	Competition throws analysed (attempt NS)	Capture: 2-3 cinematographic cameras (60 Hz, shutter speed 1/1000 s). Analysis: NS	X	X	X	X	X	X	-	Linear and angular momentum were significantly related to performance. Right elbow and left heel related to angular momentum.

1DS = First double support, 1SS = First single support, FP = Flight phase, 2SS = Second double support, 2DS = Second double support, REL = Release.

Shot put phases have been divided into six phases in the scientific literature according to foot contacts and key events. For a right-handed thrower, these phases are: 1) First double support, defined by bilateral foot contact at the back of the circle; 2) First single support, starts at right foot off and is characterised by single foot contact at the back of the circle; 3) Flight, starts with left foot off and is defined as the absence of ground contact; 4) Second single support, starts at right foot down and is characterised by single foot contact in the middle of the circle; 5) Second double support, starts with left foot down and is defined by bilateral foot contact at the front of the circle close to the stopping board, and, 6) Flight release, characterised by the absence of foot contact at the front of the circle until loss of contact with the shot. This review addresses these six phases, with additional sections specifically addressing shot put velocities or speeds, phase durations, and release parameters.

3.5 Discussion and implication

3.5.1 Phase durations and shot velocities

The duration of each phase and shot velocity within each phase of rotational shot putting varies within elite populations (Table 3.3). Historically coaches have recommended reducing flight and second single support durations (79); however, currently, no empirical data are available to support decreasing duration of these phases to enhance performance. Phase durations are a function of limb kinematics and kinetics and therefore, kinematics should be more closely inspected to identify the source of longer or shorter durations than those advocated (79, 80).

Table 3. 3. The duration of phases and shot velocities reached at the end of each phase in elite throwers.

Phase	Duration (s)	Shot velocity (m/s)
First double support	0.28 - 0.70	2.24 - 2.93
First single support	0.40 - 0.58	1.67 - 2.51
Flight	0.04 - 0.14	0.80 - 1.46
Second single support	0.17 - 0.25	1.45 - 2.95
Second double support	0.10 - 0.20	7.02 - 13.32
Release	0.02 - 0.07	12.30 - 14.13

Notes. Velocity data is the magnitude of the velocity vector and is not directionally specific. Data sourced from: (5, 9, 25, 61, 65, 66, 69, 70, 73).

Substantial variability can be observed in shot velocity (see Table 3.3) at the end of each phase in elite throwers that throw the shot more than 19 m (65, 66). To adhere to the summation of speed principle, it would make sense to increase velocity successively through each phase; however, this pattern is not observed at an elite level. Byun et al. (5) reported fluctuating patterns of shot velocity in the periods leading up to double support, and ~86% of the final release velocity to be gained from second double support onwards (3). A representative shot velocity profile can be observed in Figure 3.2. The deceleration of the shot during the flight phase is noteworthy and consistent with current literature (5, 61, 66). This deceleration pattern is a trait of elite throwers (5, 61, 65, 66). Deceleration of the shot corresponds with the development of hip to shoulder separation that is likely conducive to increased shot velocity through proceeding phases due to increased time of force application, the use of the summation of force principle, and stretch shortening cycle phenomena (5). However, the relationship between the magnitude of this deceleration to biomechanical variables essential to performance is unknown and would benefit from further investigation.

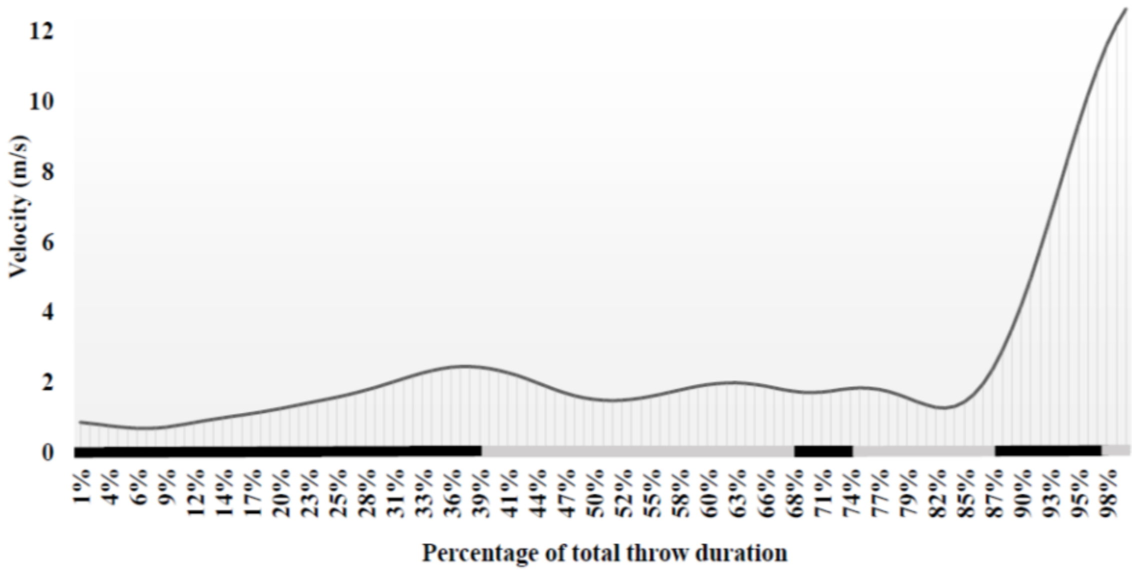


Figure 3. 2. Velocity trace of the shot as a percentage of throw duration. Shaded lines along the bottom represent the phases. Dark lines (from left to right) represent first double support, flight and second double support, respectively. Light lines represent first single support, second single support and release, respectively.

3.5.2 First double support

First double support is the first shot putting phase and is defined by bilateral foot contact at the back of the circle. Bartonietz (79) suggested a low starting position with 90 to 120° of knee flexion to promote a continued elevation of the shot throughout the throwing motion. However, Čoh et al. (66) observed the lowest position of shot to occur during the second double support phase, contradicting the former suggestion. Byun et al. (5) observed trunk forward lean (relative to the horizontal) in first double support, favouring low starting positions; although large variability between throwers was noted.

As the thrower moves through first double support, high magnitudes of thrower – shot angular momentum (> 70 kg-m²/s) and linear momentum (> 250 kg-m/s) have been observed in two elite throwers (5). Stepanek (71) recorded high lead arm angular velocity in one elite thrower that agrees with the generation of high thrower – shot angular momentum, although angular momentum values were not reported. Kato et al. (68) reported linear momentum to relate to performance ($r = 0.64$ to 0.79, $p \leq 0.05$) within a group of sub-elite throwers, which was in agreement with Bartonietz (79) who suggested that the timing of the weight shift (from right to left) and external rotation of the left leg were important. Although no empirical GRF data have been reported, Čoh et al. (25) observed the COM to move laterally left during double support. Similarly, the shot put moves laterally in a anticlockwise circular path (that continues until second single support): The shape and radius of which varies between athletes (5, 25, 71, 73).

Due to the limited segment kinematic data available, the most effective positions and movement patterns through first double support remain unknown. That said, elite throwers generate high magnitudes of angular with some linear momentum during this phase, with both the shot put and centre of mass moving left. Thus, segment kinematics promoting such kinetics should be encouraged. Future research should investigate the kinematic determinants of increased angular and linear momentum, leftward COM and shot movement, and kinematic patterns leading to an effective first double support.

3.5.3 First single support

First single support begins with right foot off and finishes when the left foot loses ground contact. A wide sweep of the right leg is thought to be the most effective movement strategy in this phase as it increases the athlete – shot system's angular momentum, which has been related to performance within sub-elite shot putters ($r = 0.61$, $p < 0.05$) (66, 68, 81). Byun et al. (5) reported decreased athlete momentum simultaneously with increases in angular momentum of the right and left leg throughout first single support; however, lower limb kinematics were not reported. In contrast, Stepanek (71) reported increasing right foot velocity, but not its moment arm; thus, the determinants of angular momentum remain unclear. Expert opinions advocate laterally shifting the COM from right to left while simultaneously externally rotating the left foot and hip in preparation to drive into the middle of the circle (79). However, biomechanists have not yet quantified such kinematic patterns.

Bartonietz (79) proposed that the hip to shoulder separation attained during first single support resulted from athletes "holding back" the left side alongside a well-timed push with the left leg. In support of these propositions, Byun et al. (5) and Čoh et al. (25) observed an increase in hip to shoulder separation with the hip axis leading the shoulder axis (when viewed in a transverse plane) in elite shot putters. Byun et al. (5) also reported increases in linear momentum (i.e., indicative of a left leg push) to increase with hip to shoulder separation.

Concerning the upper body, fluctuations in upper body momentum within the first single support was reported by Byun et al. (5) in two elite shot putters, but limb kinematics were not. Stepanek (71) observed decreasing left hand velocity in an elite shot putter through single support. As with the lower limbs, providing recommendations in terms of the most effective kinematics or determinants of angular momentum for single support is challenging given the relatively limited amount of data available on elite shot putters. The magnitude of angular momentum appears to be essential to performance; thus, the athlete – shot system angular velocity and momentum, segmental angular velocities, and moment arms should be considered in trying to optimise shot put performance.

3.5.4 Flight

The absence of ground contact characterises the flight phase; thus, it begins with left foot off and finishes on right foot contact. Due to the lack of ground contact and laws of physics, thrower - shot angular momentum remains constant through flight. The magnitude of angular momentum about the global vertical axis at the end of the flight phase has been shown to correlate with performance in sub-elite throwers ($r = 0.72$, $p < 0.05$) (68). Byun et al. (5) observed a redistribution of momentum in the flight phase where lower body angular momentum increased, and upper body angular momentum decreased. More specifically, left leg angular momentum graphically increased in the two elite throwers analysed. Similarly, Stepanek (71) observed increased left foot and decreased left hand velocity throughout the flight phase, with Kato et al. (68) reporting a significant positive relationship between left foot velocity and angular momentum at right foot down ($r = 0.77$, $p < 0.01$). Collectively, these data suggest that momentum is reoriented in flight from the upper to lower body, which results in the lower body leading the upper body. Indeed, hip to shoulder separation has been observed to increase during the flight phase, which is thought a function of sweep leg mechanics (5, 66, 79, 82).

The COM in flight (when viewed from above) moves slightly leftwards and forward (25, 66). Urita et al. (75) reported center of gravity (COG) direction to be related to the variability in angular momentum in subsequent phases in most throwers ($r = -0.58$ to -0.92, $p \leq 0.05$). Large magnitudes of angular momentum (i.e. > 55 kg-m^2/sec) through the phases proceeding flight have been reported (5) and associated with shot put performance [$r = 0.58 – 0.72$, $p < 0.05$ (68)]. In summary, the COM should travel down the centre of the sector during the flight phase and slightly towards the left, but not excessively. Concurrently, the athlete should transfer angular momentum from the upper to the lower body and increase hip to shoulder separation. That said, the kinematics associated with an effective transfer of momentum remain undetermined and warrant further investigation. Additionally, movement kinematics and kinetics that determine the athletes' optimal trajectory should be investigated.

3.5.5 Second single support

Second single support begins with right foot contact. The position of the right foot at contact should be in line with the centre of the circle when viewed from the rear and past the centre of the circle when viewed from the side (61, 75). Urita et al. (75) reported right foot placement to be related to COM direction in flight ($r = 0.73$ to 0.97, $p < 0.05$). Thus, lateral foot placement is likely a reflection of the COM projection generated through first single support and carried through flight. An amortization phase follows the planting of the right foot where upward and forward linear momentum decrease concurrently with increasing trunk tilt (i.e., a reclined position viewed from the side) (5, 77, 79, 80). Peng et al. (77) observed that when right foot vertical and horizontal impulse decreased on ground contact, better performance was observed. Actively planting the right foot minimises deceleration, whereby an active plant is likely the result of the right foot turning in a manner to decrease braking forces (77, 79). However, further quantification of the kinematics that indicate an active plant is required as evidence is anecdotal, with a right knee angle of 100° suggested as optimal for performance (82).

Byun et al. (5) observed a trend towards an increase in angular momentum through single support in two elite shot putters, the magnitude of which ($r = 0.58$ to 0.72, $p < 0.05$) and direction in flight ($r = -0.58$ to -0.92, $p < 0.05$) have been related to performance (68). The maintenance or increase in angular momentum during second single support is likely related to left leg kinematics given that the velocity of the foot has been reported to increase in an elite thrower (71) and shown to relate to angular momentum [$r = 0.61$, $p < 0.01$ (68)]. Left leg (hip, knee, and ankle) angular kinematics have, however, not been specifically reported. Upper body angular momentum has also been shown to increase from 15 – 35 kg-m²/s to over 50 kg-m²/s during late single support concurrent with a decrease in lower body momentum. Horizontally flexing the left arm to decrease the moment of inertia and increase rotational velocity likely aids in the transference of momentum (63, 71, 79). Alongside the patterns of angular momentum are changes in hip to shoulder separations throughout second single support, where an initial increase in separation is followed by a decrease in separation in elite male throwers (5, 66). This pattern of hip to shoulder separation is likely the result of the timing of left leg and left hand velocity (with decreased left hand radius) during early and late single support, respectively, that follows the principle of conservation and reorientation of momentum (5, 71, 79). However, this contention is speculative given segmental kinematics and kinetics have not been quantified during this phase.

In summary, braking forces on ground contact should be minimised by an active right leg plant, with elite throwers observed to increase trunk tilt (throughout) and hip to shoulder separation before increasing upper body and vertical momentum during late single support. Kinematic analyses of this phase are scarce. Therefore, methods to decrease braking forces and manipulate momentum are unknown. Future research should seek to quantify associated limb kinematics.

3.5.6 Second double support

The planting of the left leg indicates the beginning of the second double support phase, also referred to as the power position, with the end of second double support and start of flight release defined by a loss of ground contact. The left foot contact position has marked implications for shot put performance. Lipovšek et al. (62) reported deviations from the "ideal foot placement" (described as approximately 20 cm of the z-axis width) negatively impacted throwing performance ($r = -0.65$, $p < 0.05$). In a few throwers, left foot placement has been related to the projection of the COM in flight ($r = 0.79$ to 1.0, $p < 0.01$) (75). In elite male shot putters throwing ~19.5 m, 86% of the release velocity was gained from left foot down to the instance of release (3). Therefore, increasing the time of force application by increasing the acceleration path of the shot and amount of force applied to the shot in second double support is essential to performance. The acceleration path ranges between 1.41 to 1.69 m in elite male throwers (9, 25, 66, 70, 73) and is mostly linear (when viewed from above) (5, 9, 80) and vertically inclined (when viewed from the side) meaning the majority of shot height and vertical velocity is gained through second double support (5, 25, 66). The length of the acceleration path is suggested to be a function of body position (i.e., trunk tilt and shoulder axis held back) and anthropometric characteristics (9, 25, 61); however, there is an absence of empirical data supporting these suggestions.

Throwers should seek to apply large propulsive forces from the right side and large braking forces from the left side for as long as possible during second double support (5, 62, 64, 74, 77). Peng et al. (77) observed better shot put performances tended to exhibit longer right foot contact times and larger left leg vertical and horizontal impulses. In a latter investigation, Arrhenius (74) observed right leg peak propulsive force ($r^2 = 0.45$, $p = 0.001$) and left leg time on the ground ($r^2 = 0.52$, $p < 0.001$) to relate to performance. To generate large GRF, the right leg should rapidly extend to increase vertical momentum together with the application of large left leg GRF (5, 25, 62). Shot put adheres to the law of conservation of momentum: upper body momentum decreases as hip to shoulder separation decreases and distal limbs begin to extend to accelerate the shot (5, 63, 66). The left arm horizontally extends quickly during early double support and slows through the latter stages (25, 66, 71), with greater angular displacement noted in elite when compared to sub-elite throwers ($p = 0.02$) (63). Lead arm horizontal extension prior to the putting action is thought to pre-stretch the chest musculature; whether this is the case is unknown (63). Following the lead arm, the shoulder of the putting side rapidly flexes horizontally with putting elbow extension velocities reaching 1881 to 2030 °/s in elite throwers (25, 66, 70). Byun et al. (5) also observed a decrease in trunk tilt in two elite shot putters, which likely assists in increasing the time and magnitude of force application on the shot.

In summary, the majority of release velocity is generated in second double support. The magnitude and orientation of force application are essential to performance, which are the result of the preceding phases. Coaches should promote the maintenance of ground contact with the production of large propulsive forces from the right leg concurrently with large braking and vertical left leg forces. Although little data exists, researchers have suggested that elite throwers move the left shoulder rapidly through a large range of motion (horizontal flexion to extension) slightly prior to extending the trail arm. Future research should seek to quantify both lead and trail side mechanics and their interrelationships.

3.5.7 Flight release

Rotational shot putters have a short flight phase prior to release during which approximately 25 cm of vertical lift can be observed (79). During this phase, the right elbow continues to extend while trunk tilt, left hand velocity, and angular and linear momentum continue to decrease (5, 25). The throwers ability to align their segments to the desired angle of put, fully extend the right elbow, and rotate while in flight contributes to performance (9, 62, 78). The force applied in flight increases shot velocity by ~5 m/s (5, 79). The ability to develop large forces rapidly in flight, such as those observed at the right elbow (25, 70), relates to the percentage of type II fibres and cross sectional area of muscles (26, 83), as well as body composition. Specifically, total lean body mass ($r = 0.92$, $p < 0.01$) (84) and fat-free mass ($r = 0.66$ to 0.75, $p \leq 0.05$) (85) are related to shot put performance. Therefore, training should aim to increase lean muscle mass and body composition qualities of shot putters, and emphasise the development of faster fibre types.

In summary, a powerful release exhibits high elbow extension velocities with resultant forces applied through the acceleration path of the shot, which occurs off an unsupported freely rotating body. The foundation for an effective putting action from the right arm is the inertia of the body and the supporting musculatures composition. Specifically, high lean mass is important for explosive performance; thus coaches should promote the development of muscle cross sectional area and use methods that target fast twitch muscle fibre properties.

3.5.8 Release parameters

The critical variables during release are velocity, angle, and height, and the horizontal release distance (i.e., the last point of contact with the shot over the inner most point of the stopping board) (86). Height of release in elite shot putters varies between 2.20 to 2.35 m, with release velocities ranging from 12.5 to 14.5 m/s (3, 66). The most critical variable for increasing distance is release velocity; however, the interaction between release angle, height, and horizontal release distance needs consideration. Simulation based investigations have suggested that a release angle of 42° is required to throw a World Record distance from a release height of 2.14 m (3, 86). Hubbard et al. (86) described the relationship between the release variables as a constrained relationship, with release velocities observed to decrease with increasing release angles by 0.03 m/s per degree and increasing release height by 0.8 m/s per m. Additionally, horizontal release distance decreases with increasing release angles by 0.03 m per degree and with release height by 1.3 m per m. The decrease in release velocity with increasing release angle relates to the effect of gravity and the biological changes in muscular output with increasing shoulder flexion (3). Changes in release angle have significantly less impact on official shot put distances (± 3° from optimal affects shot put distance by less than 0.10 m) than changes in release velocity, which can affect shot put distance by up to 2 m. Therefore, coaches should primarily focus on increasing release velocity, while bearing in mind the interaction between variables when analysing release data (3).

3.5.9 Participant considerations

Homogeneity of participants across research enables pooling of data, cross-study comparisons, and stronger inferences from science. The latter is of particular relevance in high performance and individual-based technical sport research where sample sizes are relatively small (i.e., 1 to 13 participants per sex in this current review) as small sample sizes inflate effect sizes (87). Most of the shot put literature published to date (i.e., 93%) has focused on male athletes (61, 63, 65, 66, 70, 71, 74), with females being vastly underrepresented (73, 78). The lower proportion of females that use the rotational technique than males is likely a contributing factor to this disparity (9, 61). Even though the kinematic principles likely transfer to female shot putters, the sex difference noted suggests that the kinematic parameters linked with performance and throwing distance in rotational shot put identified in this literature review are most applicable to male athletes.

Of note was the varied performance standards of athletes investigated in the 20 articles reviewed, with a total of 26 elite (9, 25, 61, 66, 69-71), 34 sub-elite (64, 68, 72, 73, 76, 77), 12 novice (75, 78), and 30 athletes of varying levels (sub-elite to elite) (62, 63, 65, 74). Caution is advised in terms of extrapolating study findings across performance levels given that established relationships are specific to the population. That said, differences in biomechanical movement strategies between levels of performance is practically important for coaches to understand.

3.5.10 Methodological considerations

The data collection environment needs consideration as this can affect the resulting data and interpretation. While laboratory based studies are more controlled and can provide a greater amount of data due to the use of more advanced technology, they lack in ecological validity. In contrast, competition data are ecologically valid, but often need to rely on less accurate and extensive data collection methods and equipment. At present, a mix of competition (5, 9, 25, 61, 62, 65, 66, 69, 71) and laboratory (63, 77) based data collection methods have been used to better our understanding of shot put performance. It is unknown how comparable laboratory and competition based shot put performance and biomechanics data are; thus, whether findings from laboratory (72, 77) and competition (5, 66) are interchangeable requires further research. In golf, which is another rotational based activity, kinematic patterns are similar when comparing 2D to 3D methods; however, there are considerable differences in terms of the magnitude (e.g., ~16° in x-factor) between methods (88).

Infrared marker based data collection methods are considered the gold standard for generating kinematic data in spite of recognised limitations in terms of skin artefacts, movement errors, and variability in outputs due to marker sets (89, 90). Within the current literature, only three investigations used infrared systems (64, 72, 75). Marker set configurations have been observed to significantly affect kinematic outputs, with best practice being cluster based tracking that minimizes soft tissue artefact movement and the placement of markers away from sites highly affected by these artefacts. While Urita et al. (75) and Williams (64) used a more extensive marker set than Dinu et al. (72), no investigation has employed cluster based segment tracking, which might improve the accuracy of kinematic data in future studies.

Infrared systems are not practical or permitted in competition due to the International Association of Athletics Federations (IAAF) rules and on-field constraints. The majority of the shot put literature has therefore used manual digitisation of cinematographic video methods for in-competition kinematic analyses. Manual digitisation relies on the subjective determination of a point in space (91). This method has shown good agreement with optoeletronic methods (91, 92) and may even be superior to optoelectonic in inadequate lighting conditions (91).

To derive accurate 3D data from manual digitisation of 2D videos, landmarks of interest must be identified in two non-collinear fields of view and the frame rates must exceed twice that of the movement frequency (Nyquist theorem) (93). The majority of the shot put literature reviewed collected cinematographic video using two cameras with a minimum sampling rate of 50 Hz (5, 9, 25, 61-63, 65, 66, 68-71, 73, 74), which likely satisfies the Nyquist theorem. However, occlusion of landmarks of interest is likely during shot put performance if using only two cameras to record the rotational movement. Landmark occlusion is a possible reason Byun et al. (5) reporting fluctuating angular momentum in flight, which is not possible due to the principle of conservation of momentum. To overcome occlusion, additional cameras are required to improve the determination of points in space using the least squares determination approach (93).

Field of view (i.e., along the movement plane) and camera resolution are important for digitisation accuracy, thus camera distance and focal length need to be considered (91). Dividing camera resolution by the field of view provides an indication of movement range within a singular pixel. In competition, camera placement is often restricted to the grandstand, which can be 70 to 100 meters away (61). In such circumstance, focal length can be used to modulate the field of view. Camera resolution, field of view, and focal length are important parameters to report to compare kinematic data or understand the variance in reported values (91). Few authors have reported camera distance (25, 61, 66) and resolution (25, 62, 66, 70). Schaa (61) reported camera distances of 70 to 100 m making telephoto lenses necessary; however, focal length and field of view were unreported. Čoh and Štuhec (66) and Coh and Jost (70) reported the distance of the overhead camera and its resolution, but not for the other two cameras used. Reported camera resolution has been 720 x 576 pixels (25, 62, 66, 70) that can lead to kinematic noise at the velocities reported in shot put depending on field of view. Taking a field of view of five meters with a 720 pixel camera (assuming square pixels) gives 1.44 cm of movement per pixel. At a frame rate of 60 Hz and actual speed of 10 m/s (values above this threshold are commonly reported in shot put), speed derived from digitisation can theoretically range from 8.2 to 11.8 m/s due to a 5 cm range of movement within consecutive pixels.

3.6 Conclusions

The primary determinant of shot put performance is release velocity. Generating high release velocities stems from the development and transference of momentum through each phase. Kinematics and kinetics within each phase are co-dependent; therefore, athletes and coaches should consider the biomechanics of an athlete through preceding phases when addressing kinematic changes within given phases. Biomechanists within the field would benefit from quantifying angular momentum, linear momentum, and COG/COM patterns in athletes. If a baseline and evidence-based database exist, then technical errors can be addressed against gold-standard performances.

Globally, a paucity of kinematic and kinetic data relating to shot put performance exists and varying capture and reporting methods have been used. To generate comparable elite performer competition data, researchers should look to standardise field of view and camera resolution, as well as use multiple cameras (>3) to avoid occlusion and increase accuracy of data capture in a field environment. Where possible, these data should be compared to laboratory based performance to understand the accuracy of competition data and the validity of laboratory based assessments. The use of wearable technology (e.g., inertial measurement units) may provide researchers with technological bridge between laboratory and field testing, although the validity and accuracy of such units in rotational shot put will need to be investigated.

The current literature has reported a select number of variables through the motion or at specific events. Therefore, understanding and coaching the movement between set events is difficult, notably given the interdependency between body segments and events. Future research should aim to report kinematic and kinetic data waveforms of all segments and variables (e.g., mechanical energy) to inform best practice.

Chapter 4

Biomechanical characteristics of the Hammer throw: A narrative review

4.0 Prelude

The literature reviews comprising the previous two Chapters have described the biomechanics of the discus throw and shot put. Both Chapters have highlighted the paucity of longitudinal literature documenting biomechanical change over longitudinal periods across sexes and performance levels. The third and final rotational throw is the hammer throw that provides the focus for this chapter. As stated earlier, competition performance is determined by the biomechanics of the movement. A comprehensive understanding of hammer throwing biomechanics is therefore of seminal importance in high performance sports and athlete development. The purpose of this Chapter was therefore to provide a comprehensive summary of the literature pertaining to hammer throw biomechanics. This information provides important insight as to the kinematic and kinetic variables driving performance. Coaches, athletes, and support staff can use this information to enhance performance as it relates to their specified fields. Most importantly, the information in this Chapter provides foundational knowledge that will guide understanding of best practice assessment methods and training methods for hammer throwers, which will be used to guide and underpin the ensuing Chapters in this thesis.

4.1 Introduction

The hammer throw is one of four throwing disciplines in the track and field athletics programmes. The winner of the hammer throw event is the athlete who can throw the hammer the furthest distance, measured from the innermost point of the circle to the nearest mark on the ground the implement makes within the sector in line with the centre of the circle, while staying within the throwing circle. In senior competitions, males throw a 7.26 kg hammer (length 1215 mm, head diameter 110 to 130 mm) and females a 4 kg hammer (length 1195 mm, head diameter 95 to 110 mm), where hammer length is taken from the inside of the handle to the bottom of the ball. Throws are performed within a throwing circle (2.135 m diameter), and the throw is deemed a foul if it lands on or outside the sector lines (projected out at 34.92° from the centre of the circle) or the thrower steps outside the front half of the throwing circle (1). Circle diameter and sector width are constant between competitions and sexes as specified by the International Association of Athletics Federations (IAAF) rules (1). The hammer throw adheres to the laws of projectile motion where flight distance is a composite of release velocity, release height, release angle, and air resistance, with release velocity being the most reliable predictor of performance (94). In generating the final release velocity, one to three preliminary swings and three to four turns are performed depending on the thrower’s style. The initial swings take place with minimal rotation and change in physical orientation of the body (95). For right handed throwers during the turns, the left foot remains in contact with the ground and the right foot is lifted and planted periodically resulting in an alternating single and double support pattern (95). As the right foot is lifted and planted, the left foot remains in contact with the ground and rotates around in a way that the hammer thrower progresses forward through the circle.

Advancing technical knowledge of coaches and athletes requires an understanding of hammer throwing biomechanics. Therefore, a review of existing biomechanics research is necessary to determine strategies employed by throwers, and methods that can be used to enhance propulsion and reduce deceleration to enhance performance. The objective of this review was to synthesize and evaluate current biomechanical literature relevant to hammer throwing. Specifically, this review aimed to identify the critical biomechanical variables within each phase of hammer throwing that relate to throwing distance and release velocity.

4.2 Methods

This narrative review investigated full hammer throwing performance using outdoor competition implements. Hammer throw performance was defined as throws using three to four turns performed with either 4 kg (women) or 7.26 kg (men) implements. SportDiscus^{TM} via EBSCO and Google Scholar, were searched for articles that analysed the biomechanics of hammer throw performance, with the last search conducted in May 2018. The following search terms were used ‘hammer throw’, ‘biomechanics’, and ‘track and field throwing’. Additionally, the reference lists of all studies included for review were searched manually for additional studies of relevance. A total of 70 articles were initially found. Titles, abstracts, and full-texts of retrieved articles were sequentially reviewed to determine their relevance to the topic based on the following inclusion criteria: 1) published in the English language; 2) addressed biomechanics, muscular kinetics, or expert opinions specific to hammer throwing; and, 3) referred to increasing either release velocity or throwing distance. Articles on weight throw (a derivative of the hammer throw) were excluded due to differences in implement weight and length. For clarity, the results presented are in reference to right-handed throwers. After screening, 15 articles remained.

4.3 Results

Participant descriptive data from the 15 articles are summarised in Table 4.1. A total of 124 male and female throwers of varying levels were represented, although one study did not specify how many participants were involved. Most of this literature investigated elite populations or world championship level performers exclusively (n = 72, 58%), with female throwers clearly underrepresented (n = 27, 22%). Elite and sub-elite were defined as throwers competing at a world championship or Olympic level. The other throwers were considered trained, but not of world championship or Olympic level (registering distances < 70m). Four studies did not specify participant sex but reported past and present men’s world record holders to be involved in the investigations (95-98).

Table 4. 1. Participant information from all studies reviewed.

	Sample size (*n*)			Characteristics		
Study design	Male	Female	Total	Level	Release velocity (m/s)	Distance measured (m)
Dapena (95)			8*	Elite	NS	73.30 (61.02 – 80.46)
Dapena (96)			8*	Elite	NS	NS
Dapena and Feltner (97)			8*	Elite	NS	73.30 (61.02 – 80.46)
Dapena and Mcdonald (98)			8*	Elite	NS	73.30 (61.02 – 80.46)
Bartonietz and Borgstom (99)	4		4	Elite	NS	M: 80.7±1.1
Gutierrez-Davila, Soto, and Rojas (100)	6	7	13	Elite	NS	M: 79.1 ± 0.6 F: 67.8 ± 4.4
Dapena, Gutierrez-Davila, Soto, and Rojas (101)			NS	Elite	NS	M: 72.8 ± 7.4 F: 67.8 ± 4.0
Murofushi et al. (7)	3		3	Variable	M: 19.6 – 27.2	M: 39.5 – 75.3
Mercadante, Menezes, Martini, Trabanco, and De Barros (102)	3	3	6	Sub-elite	M: 24.6±0.9 F: 23.6±1.6	M: 55.4 ± 3.01 F: 52.05 ± 4.91
Susanka, Stepanek, Miskos, and Terauds (103)	4		4	Elite	NS	M: 72.9 ± 9.7
Rojas-Ruiz and Gutierrez-Davila (104)			29*	Variable	NS	67.3±8.6
Isele and Nixdorf (94)	8	8	16	Elite	M: 27.6±0.3 F: 27.1±2.7	M: 77.4 ± 1.7 F: 73.8 ± 2.7
Ohta, Umegaki, Murofushi, and Luo (105)	1		1	Elite	NS	Modelled
Brice et al. (2)	5	5	10	Variable	M: 23.7±1.8 F: 24.1±0.7	M: 54 ± 7.6 F: 53.9 ± 3.2
Brice, Ness, Everingham, Rosemond, and Judge (106)	2	4	6	Sub-elite	M: 24.7±0.08 F: 24.1±0.41	M: 58.2±0.4 F: 54.43±1.3

M = Male, F = Female, NS = Not stated. *Sex of participants not reported, ** Estimated distance, [c] Cross-sectional investigation.

The data collection methods and associated outcome measures are summarised in Table 4.2. The majority of the literature used cinematographic video capture with sampling rates of 25 to 50 Hz, though three investigations used infrared camera systems (250 Hz) and high speed cinematographic video cameras (250 Hz) (2, 7, 106). Cinematographic film analysis requires manual digitisation of two dimensional videos prior to extracting data using direct linear transformation methods or using the methods developed by Dapena, Harman, and Miller (107) in which athlete and hammer models are reconstructed. In contrast, infrared systems track retroreflective markers and have been used to reconstruct rigid-body positions in space by one group of researchers only (2, 106). The accuracy of both methods have previously been reported (99, 107, 108); however, concerning the 2D video-based methods, Winter (93) suggested that errors increase with camera distance. Only Isele and Nixdorf (94) clearly reported camera position, situating the cameras in the first row of the grandstand in a stadium.

Table 4. 2. Methods and information from the selected investigations.

Studies	Trial description	Analysis method	Outcome measures	Key results
Dapena (95)	2 maximal outdoor competition trials per athlete	Capture: 2 cinematographic cameras capturing at 50hz. Analysis: Manual digitization with Dapena et al. (107) methods.	Hammer speed and height Single and double support phases	- Gravity affected hammer speed. - Hammer accelerated predominantly in double support.
Dapena (96)	NS	Capture: 2 cinematographic cameras, NS Hz. Analysis: Manual digitization with Dapena et al. (107) methods.	Hammer – athlete system COM path Hammer COM path Athlete COM path	- Vertical hammer and athlete COM functioned cyclically through the throw in an asynchronous pattern. - Hammer accelerated in double support. - Hammer and athlete COM translated and are diametrically opposed about a common COR.
Dapena and Feltner (97)	2 maximal competition or simulated competition trials per athlete	Capture: 2 cinematographic, NS Hz. Analysis: Manual digitization with Dapena et al. (107) methods.	Calculated hammer wire forces Hammer – athlete system COM path Hammer speed Hammer radius	- Hammer speed fluctuations related to horizontal athlete COM displacement and gravity. - Hammer speed fluctuations related to changes in pull direction of cable. - Hammer radius shortened with turn progression.
Dapena and Mcdonald (98)	2 maximal competition or simulated competition trials per athlete	Capture: 2 cinematographic cameras capturing at 50 – 64 Hz. Analysis: Manual digitization with Dapena et al. (107) methods.	Hammer – athlete system momentum Hammer angular momentum Athlete angular momentum	- Angular momentum increased and became more vertical with each turn. - Hammer and athlete momentum followed a conical path that was half phase asynchronous. - Athlete momentum followed a conical path that was related to body configuration.
Bartonietz and Borgstom (99)	Video recordings from the 1995 world championships. Trial numbers NS	Capture: 2 (side and rear) cinematographic cameras capturing at 50 Hz. Analysis: Qualitative kinematic observations and temporal analysis.	Qualitative kinematic analysis Temporal foot contact analysis	- Kinematics important to performance were an early catch and maintenance of a wide radius.
Gutierrez-Davila et al. (100)	1 throw in competition	Capture: 2 video cameras capturing at 50 Hz. Analysis: Manual digitization with DLT.	Temporal analysis Hammer angular momentum and radius Catch and toe off azimuth angles	- Variable double:single support ratios. - Variable azimuth angles and radius of rotations. - Angular momentum and hammer velocity increased in double support and decreased in single support.

Dapena et al. (101)	Modelled data	Analysis: Computer simulation.	Predicted distance in a vacuum Predicted distance using hammers COM Predicted distance using hammerhead COM	- Air resistance decreased distance thrown. - Predicting distance using the hammerheads COM over estimated distance. - Predicting distance using true hammer COM was more accurate. - Female hammers were more affected by wind and COM used.
Mercadante et al. (102)	1 throw (best performance) in competition	Capture: 2 video cameras capturing at 60 Hz. Analysis: Automated hammer tracking, methods NS.	Hammer kinematics	- Hammer launch of 3 male and female reported. - Hammer velocity increased from turn to turn and increased and decreased in double and single support respectively.
Murofushi et al. (7)	3 throws indoors	Capture: 3 video cameras capturing at 250 Hz synchronized with a load cell (in hammer wire) and 8 force plates capturing at 500 Hz.	Hammer velocity and azimuth angles Wire tensile and ground reaction forces	- Hammer speed increased in double support. - Wire tensile forces increased with each turn. - High GRF and a transfer from right to left of vertical GRF in elite but not sub-elite. - Asynchronous hammer and athlete COM pattern in elite but not sub-elite.
Susanka et al. (103)	1983 World championship or international competition throws	Capture: 2 cinematographic cameras capturing at 200 Hz. Analysis: Manual digitization.	Temporal characteristics Segment kinematics Hammer kinetics	- Hammer acceleration occurred before double support. - Velocity increased 6 to 9 m/s per turn. - Hammer accelerated when the angle between shoulders and hammer wire exceeded 90°. - Hammer – shoulder and shoulder – pelvis separations fluctuated through each turn.
Rojas-Ruiz and Gutierrez-Davila (104)	Best performance of competition	Capture: 2 video cameras capturing at 50 Hz.	Angular displacement of the hammer Velocity of the hammer	- As average velocity increased, angular displacement decreased in antepenultimate but not penultimate turn.
Isele and Nixdorf (94)	Best performance at 2009 world championships	Capture: 2 video cameras operating at 25 Hz. Analysis: Manual digitization with DLT.	Temporal and path parameters Athlete and hammer kinematics	- Release velocity related to distance. - Duration of turns negatively related to distance thrown. - Variability in spatial and angular parameters. - Positive relationship between velocity at the end of turns and distance thrown.
Ohta et al. (105)	Modelled data	NA	NA	- Hammer – athlete system can operate as a parametric oscillator.
Brice et al. (2)	10 outdoor throws	Capture: 21 infra-red cameras sampling at 250 Hz.	Hammer cable forces and kinematics	- Cable force related to distance thrown. - Negative and positive tangential forces coincided with single and double support and hammer deceleration and acceleration respectively.

		Analysis: Automated point reconstruction in Vicon Nexus suite and MatLab.		
Brice et al. (106)	10 outdoor throws	Capture: 21 infra-red cameras sampling at 250 Hz. Analysis: Automated point reconstruction in Vicon Nexus suite and MatLab.	Thorax to pelvis kinematics	- Hip to shoulder separation positive. - Negative correlation between hip to shoulder separation magnitude and distance.

Abbreviations: COM = Centre of motion; COR = Centre of rotation; NA = Not applicable; NS = Not stated; DLT: Direct linear transformation; GRF: Ground reaction force.

It was recognised that propulsive and deceleration patterns remain relatively constant between turns and sexes, and each turn can be split into double and single support that are defined by azimuth angles. Azimuth angles provide spatial context to the start and end positions of the different phases (7, 100). Azimuth angles (Figure 4. 1) correspond to a position (0 to 360°) of the throwing circle in relation to a reference frame that moves with the throwers linear displacement (100). In addition to phases, changes in kinematics were observed from first to last turn. As such, the discussion is broken into kinematic changes with turn progression, double support, single support, and release parameters.

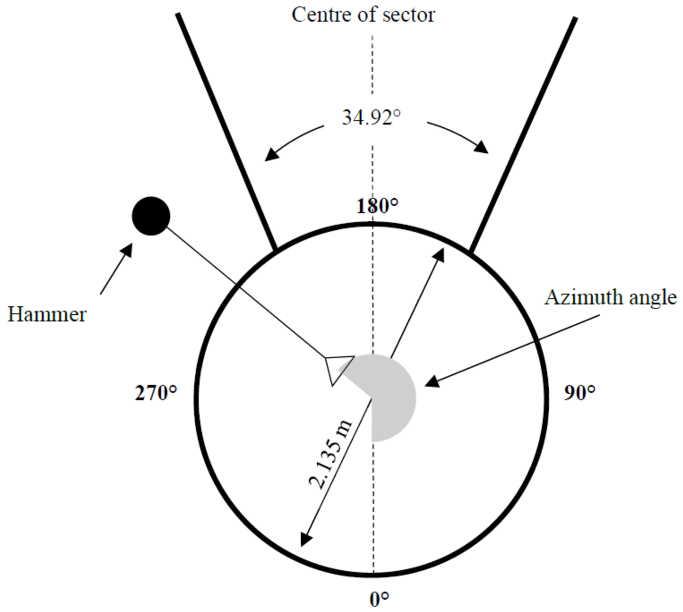


Figure 4. 1. The calculation of azimuth angles, sector, and circle geometry in hammer throws.

4.4 Discussion and implications

4.4.1 Kinematic changes with turn progression

Propulsive and deceleration patterns remain constant between turns. However, subtle changes in countering [movements of the centre of mass (COM) of the hammer relative to the COM of the thrower] magnitude, hammer orbit inclination, phase start and end azimuth angles, and turn durations were observed in elite throwers alongside increasing hammer velocity (Figure 4.2). Countering, the half phasic asynchronous hammer and athlete COM height change relationship, has been suggested to be associated with hammer acceleration (105). Murofushi et al. (7) and Dapena (96) observed a pattern of increasing vertical hammer and athlete COM displacement as elite throwers progressed through each turn. The progressive increase in the amplitude of vertical COM movement has been observed to occur in parallel, although in a half phasic and asynchronous manner (i.e., thrower COM is low when the hammer COM is high). In conjunction, there is a progressive increase in hammer orbit incline and velocity (2, 7, 96). This relationship is not surprising as an increasing vertical displacement and velocity of the hammer COM requires equal decrease in the athlete COM displacement to oppose it and increase velocity as a function of parametric oscillation (105, 109).

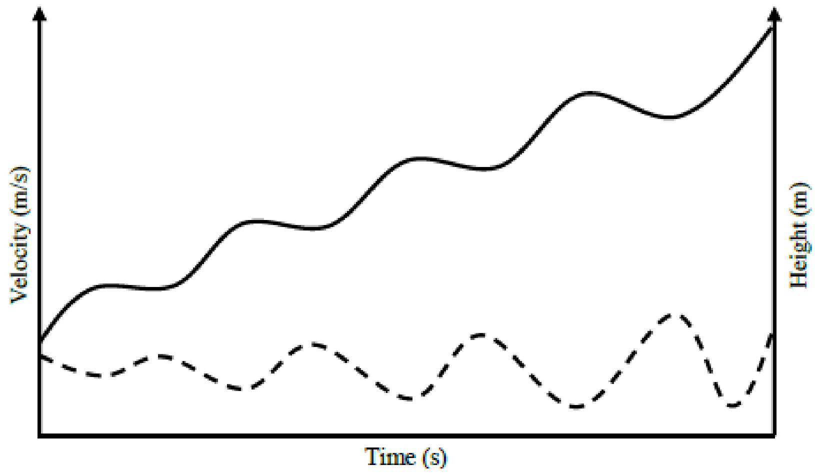


Figure 4. 2. Representative patterns of hammer velocity (solid line) and height (dashed lines) fluctuations through a four-turn hammer throw.

A progressive inclination of the orbit has been noted by several authors (2, 7, 95, 96). The orbit initially begins flat and then gradually inclines to approximately 40° at release (110), which corresponds to the release angles observed in elite performers (100). A gradual inclination of the hammer plane through the turns towards an optimal launch angle is, logically, the most efficient pattern overall for most athletes.

Azimuth angles define spatially where double and single support occur (Table 4.3). A progression with turn number towards greater azimuth angles at right foot down can be observed in both male and female hammer throwers (94, 100). The azimuth angles reported by Isele and Nixdorf (94) and Gutierrez-Davila et al. (100) found that the azimuth angles differed significantly between sexes at right foot down during turns one (mean difference = 33.9°, $p = 0.04$), two (mean difference = 19.8°, $p = 0.01$), and three (mean difference = 21.2°, $p = 0.01$), with females having smaller azimuth angles (Table 4.3). However, significantly smaller azimuth angles at right foot off in females were observed in turns one (mean difference = 25.6°, $p = 0.04$) and two (mean difference = 27°, $p = 0.01$) only, with no significant difference in the sum of angular displacements in double support between sexes ($p > 0.05$). These findings suggest that the technical model used by males and females differ, where males plant the right foot earlier and use more of the descending phase of the hammer orbit, and thus the effects of gravity. Further research should look to understand the between sex differences and the underpinning reasoning for such differences.

Table 4. 3. Azimuth angles in elite female (64.93 to 77.96 m) and male (78.31 to 82.05 m) throwers.

		Azimuth angle (°)	
Phase	Event	Female	Male
Turn 1	0° - Right foot off	41 - 115	21 - 88
	Catch - 0°	221 - 256	170 - 250
Turn 2	0° - Right foot off	37 - 112	28 - 76
	Catch - 0°	223 - 267	219 - 269
Turn 3	0° - Right foot off	23 - 97	34 - 74
	Catch - 0°	237 - 286	223 - 265
Turn 4	0° - Right foot off	33 - 85	17 - 66
	Catch - 0°	250 - 284	223 - 288
Release	0° - Implement release	98 - 130	90 - 135

Azimuth angle data from Isele and Nixdorf (94) and Gutierrez-Davila et al. (100).

The magnitude of deceleration within each turn is an important determinant of throwing performance, with the magnitude of deceleration corresponding to the duration of single support (2, 94, 100, 111). The ranges of phase durations for elite female and male hammer throwers are reported in Table 4.4. There is an observable tendency for the duration of the double support phase to decrease from turns 1 to 3, whereas single support duration remains relatively constant, which are likely a function of hammer velocity and the time needed to reposition for the subsequent double support phase. The increased double support time during the fourth turn is a function of double support angular displacement as it encompasses release (0° to release azimuth angle, the larger displacement of any turn, see Table 4.3) (94, 100). Bartonietz et al. (111) suggested that greater throwing distances are attained when the ratio of single to double support time favours double support, but the supporting data were equivocal. Currently, temporal data do not validate this concept as varying ratios of double to single support durations have been reported in elite throwers (94, 100).

Table 4.4. Duration of phases in elite female (64.93 to 77.96 m) and male (78.31 to 82.05 m) throwers.

	Duration (s)	
Phase	Female	Male
1st single support	0.26 - 0.36	0.27 - 0.38
1st double support	0.22 - 0.41	0.21 - 0.57
2nd single support	0.26 - 0.30	0.24 - 0.34
2nd double support	0.16 - 0.29	0.18 - 0.26
3rd single support	0.22 - 0.30	0.20 - 0.32
3rd double support	0.14 - 0.28	0.14 - 0.24
4th single support	0.24 - 0.30	0.21 - 0.30
4th double support	0.18 - 0.27	0.20 - 0.28

Temporal data from Isele and Nixdorf (94) and Gutierrez-Davila et al. (100).

In summary, the progression of azimuth angle as a function of turn number is a component of elite performance, and azimuth angles differ between males and females (94). Given that technique differences in double and single support positions have been observed between male and female throwers, research into the mechanistic underpinnings of these sex differences is required and sex specific coaching models are likely warranted. Coaches should expect the orbit to incline turn to turn, reaching an ultimate inclination of 40° at release, although the optimal pattern of inclination per turn to maximise performance needs further investigation.

4.4.2 Double support

The purpose of double support is to accelerate the hammer (7, 100, 103). Linear acceleration of the hammer occurs when the tangential component of cable force (Tcf) is positive (Figure 4. 3, Tcf), i.e., the hammer's cable force is pulling in front of the radius of rotation and accelerates the hammer (97, 98). Propulsive forces are ultimately a function of GRF. The transference of GRF to the hammer can be increased by efficient usage of parametric oscillation (7), hip to shoulder and shoulder to hammer separation (94), and gravity (95).

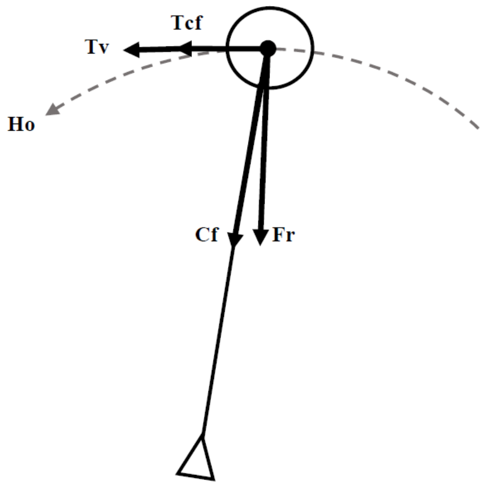


Figure 4. 3. Components involved in accelerating the hammer in propulsive force application. Ho = hammers orbital path, Tv = tangential velocity, Tcf = tangential component of cable force, Cf = cable force, Fr = Radial component of cable force.

The first instant of right foot contact marks the start of double support and occurs at azimuth angles between 286° and 221° in elite female throwers, and 288° and 170° in elite male throwers (94, 100). During double support, the hammer is primarily in the descending phase of its orbit (7) where gravity acts in a propulsive manner (95). Alongside the hammer's high to low movement during the initial stages of double support is the throwers low to high movement (7, 96). This phenomenon has been observed in elite populations, but not sub-elite. In the elite thrower, the athlete COM vertical height minima occurs 114 to 180° ahead of the hammer COM maxima (the hammer to thrower COM relationship is described as "approximately half phasic and asynchronous") (96, 98). Murofushi et al. (7) concluded that the asynchronous timing observed in elite hammer throwers aids acceleration in a similar fashion to the acceleration of a swing or hula-hoop (105). Swing and hula-hoop movements are best described by parametric oscillations whereby the moment of inertia is varied by manipulating the distance at which the COM is orientated from the axis of rotation through the oscillation (105, 109). Dapena (96) attributed the vertical changes in COM of the athlete to the vertical component of the GRF, though did not report GRF data. In agreement, Murofushi et al. (7) reported large vertical right foot GRFs (>1000 N of vertical GRF from right foot down to 360° azimuth angle) in an elite thrower that corresponded to the change in COM height (7).

Simultaneous with and likely part of three-dimensional parametric oscillation are methods of countering the cable forces that build as the turns progress (2, 7). Effective countering maintains balance and promotes hammer ball acceleration (97, 98). Two postures and countering methods (i.e., hip and shoulder) have been reported (98). Hip countering is characterised by the hip being in a backward position and the trunk being in a slight forward lean. Dapena and Feltner (97) described this countering strategy as a bent cylinder that rotates about an axis outside of its main longitudinal axis resulting in greater hammer radii. Theoretically, for the same hammer velocity, increasing radii decreases angular velocity, resulting in the ability to apply greater force due to the force-velocity properties of muscles (112). However, as elite throwers progress through the throw, a re-orientation towards a shoulder countering strategy has been observed (98). Shoulder countering is characterised by the hip being forward and shoulders backward. Dapena and Mcdonald (98) described this configuration as a rigid bent cylinder that rotates about its principle longitudinal axis and concluded that two likely explanations exist as to why hammer throwers re-orientate towards shoulder countering during the later turns. Firstly, to decrease shear forces acting on the spine, and secondly, weakness in the shoulder extensors that can be compensated for by shoulder countering. However, no data supporting these claims were provided.

In conjunction with the optimisation of GRF, hammer throwers use hip to shoulder and shoulder to hammer separation, generated in single support, as a method of increasing tangential propulsive forces. Isele and Nixdorf (94) reported hip to shoulder angles of 15 to 59° and 23 to 88° at right foot down in the top three male and female throwers at the 2009 IAAF World Championships, respectively. Additionally, such angles decreased to 5 to 32° and 6 to 26° at the end of double support. In a report on the characteristics of top female performers, Bartonietz et al. (111) suggested that generating large hip to shoulder separations was part of coaching models in the 1970s. Theoretically, hip to shoulder separation increases angular work in double support as the right foot can land earlier, leading to an earlier application of propulsive force. However, hip to shoulder separation magnitude at the end of double support [$r = -0.84$ to -0.97, $p < 0.05$ (106)] and angular displacement in the antepenultimate [$r = -0.503$, $p < 0.01$ (104)] and final action [r =

-0.386, $p < 0.05$ (104)] of the throw negatively correlate with hammer velocity. As hammer velocity increases within each turn, there is a tendency for turn duration to decrease, except for the penultimate turn (explained by the addition of the 0° to release azimuth angle to the penultimate turns total azimuth angle) (9, 94). Accordingly, less time is available to generate large magnitudes of axial separation in later turns. Therefore, the negative associations between hip to shoulder separation, angular displacement, and hammer velocity is likely a function of decreasing time. Furthermore, with an increasing plane of inclination, the need for vertical GRF may outweigh horizontal GRF requirements (7).

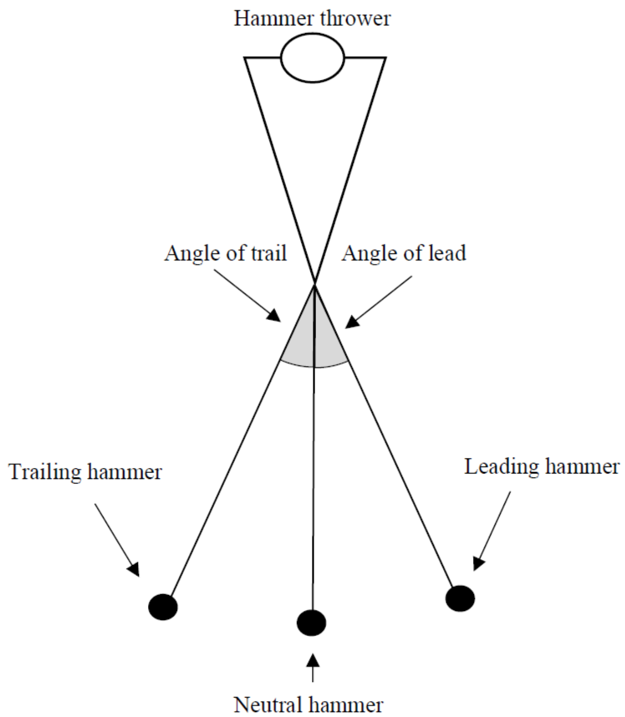


Figure 4. 4. Angle of hammer trail and lead from above in reference to a right-handed thrower.

A similar pattern of shoulder to hammer separation to that of hip to shoulder separation was reported by Isele and Nixdorf (94). The authors observed the hammer to be orientated between 90 and 123°, and 77 and 126° relative to the shoulder axis at the start of double support within elite female and male athletes, respectively. At the end of double support, 71 to 104° and 87 to 106° was reported for the same female and male athletes. A schematic representation given by Bartonietz et al. (111) suggests that the trailing angle (Figure 4. 4) is related to propulsive tangential force application; and thus, hammer acceleration. Although biomechanically valid, subsequent investigations have not explored this relationship.

In summary, linear acceleration of the hammer is observed in double support due to the application of propulsive tangential force. The asynchronous timing between hammer and thrower centre of masses has been suggested as a critical component of hammer acceleration in conjunction with shoulder to hip and shoulder to hammer separations (7, 96). To accelerate the hammer, large GRF should be applied during the early phases of double support. Concurrently, the athlete should maintain the largest radii while using the generated hip to shoulder and shoulder to hammer separation to apply propulsive tangential force (94, 111). Currently, little is known about the role of hip to shoulder and shoulder to hammer separation in accelerating the hammer.

4.4.3 Single support

Single support is characterised by a pivot about the left foot (right-handed throwers) while the right foot is repositioned in preparation for the next double support phase. During single support, translation across the circle occurs as the pivoting foot rolls over its lateral side. Elite throwers begin single support at an azimuth angle of 17 to 115° and end single support at azimuth angles between 170 to 288° (94, 100). Single support start and end azimuth angles tend to decrease and increase through each turn, respectively, within both male and female athletes (100). The hammer is predominantly in an ascending phase of its oblique plane, except for late single support when it descends (7).

The velocity of the hammer ball can be derived from the relationship between radial force (Fr), mass (m), and radius (r) by the equation $Fr = mv^2/r$. A decrease in cable force results in a decrease in hammer velocity (2, 7, 97). Through single support, decreases in hammer velocity that are a function of negative tangential force application have been observed in all throwers (2, 7, 95, 97). Brice et al. (2) reported significant correlations between the magnitude of negative tangential cable force normalised to hammer weight ($r = -0.89$, $p < 0.001$), the time spent applying negative tangential force ($r = 0.39$, $p < 0.001$), as well as the magnitude of the angle between the cable force vector and hammer velocity vector during early single support ($r = 0.87$, $p < 0.01$) and hammer deceleration. Isele and Nixdorf (94) reported a significant correlation between summed duration of single support phases and throwing performance ($r = -0.59$, p = not reported). It would seem that decreasing both the duration and magnitude of negative tangential cable force is an effective strategy to minimise hammer deceleration. Negative tangential force is likely an accumulation of several factors: gravity (95), the non-propulsive phase of parametric oscillation (97), decreased GRF (7), and the application of small negative torques to gain hip to shoulder and shoulder to hammer separation. Gravity would seem of minimal practical importance as it cannot be changed (95).

Dapena and Feltner (97) observed cable forces to be maintained when predicted relative to a reference frame that moved with the thrower. Such results indicate that hammer velocity would be maintained if translation across the circle did not occur. A likely explanation exists within the dynamics of parametric oscillatory systems. A loss of the parametric oscillation interaction occurs when the centre of rotation moves towards the hammer, which is apparent during single support (96). Murofushi et al. (7) observed continual vertical hammer to thrower height changes congruent with parametric oscillation, but deceleration was still apparent during single support. Noteworthy is that during the hammer throw, parametric oscillation occurs three-dimensionally as the hammer plane is oblique relative to the vertical (96). Thus, although the vertical component is maintained, decreasing the horizontal component leads to deceleration of the hammer via a loss in three-dimensional half phasic asynchrony. The decrease in GRF during single support that ultimately drives hammer acceleration is a function of the centre of mass dropping in a vertical plane (7). During the decrease in GRF, the left foot acts as the fulcrum (98) and no additional torque, until the right foot plants, is applied to the system. Although minimal, friction will work to decrease the angular velocity of the thrower – hammer system. As friction is related to GRF, a higher rate of vertical COM height change would minimise the impact of friction on the system by decreasing the magnitude of GRF.

Increases in hip to shoulder and shoulder to hammer separation during single support have been observed at an elite (94, 103) and sub-elite (106) level. Isele and Nixdorf (94) suggested large hip to shoulder separations are a negative trait that results in decreased radii. Gaining hip to shoulder separation applies negative torque to the thrower – hammer system and decreases the lead of the hammer over the shoulders (103).

In summary, a decrease in hammer velocity occurs during single support and is a product of negative tangential force magnitude and the time over which it is applied (2). Negative tangential force application is multifactorial, i.e., contribution of gravity, friction, parametric oscillation, and potential negative torque application as a result of gaining hip-shoulder separation. The majority of such factors are necessary to produce force during double support (i.e., increasing hip to shoulder separation) and release the implement at a release angle conducive to increasing distance (i.e., hammer plane). The variables likely to be impacted by technique are friction, parametric oscillation, and hip to shoulder separation, with the former two being interrelated. Coaches should try to attain a fast drop in the COM height during single support, as well as rapid and small amplitudes of hip to shoulder separation to attain double support earlier and decrease negative tangential force application. However, further research is required to understand the impact that hip to shoulder separation change rate and COM height drop velocity have on hammer deceleration, as currently limited evidence is available.

4.4.4 Hammer-throw release parameters

During the final stages of the third or fourth turn, depending on the number of turns used, the hammer is released into the sector. Projectile motion laws apply to the hammer as it follows a parabolic flight path. Release velocity, angle, and height predict distance. Release velocity is the main determinant of performance [$r = 0.98$, p = not reported (94)]. Brice et al. (2) reported a strong correlation ($r = 0.94$, $p < 0.001$) between distance thrown and cable force. Thus, devices that measure cable force, such as those used by Murofushi et al. (7), can be integrated into training as surrogate measure of release velocity. Elite males and female throwers release the hammer at

~27.1 m/s and 27.6 m/s respectively (94, 100). Isele and Nixdorf (94) suggested that females would need 26.5 m/s and 27.4 m/s of release velocity to throw over 70 and 75 m, respectively. To achieve distances of 77 m and 80 m, males require release velocities of 27.5 m/s and 28.1 m/s respectively.

From the laws of projectile motion, it would appear that an optimal launch angle is 45° when release and landing height are equal; and as release height increases, release angle decreases. Bartonietz et al. (111) reported that 44° was an optimal release angle for an elite female thrower, but did not indicate a corresponding release height. However, elite female and male throwers have been reported to release at angles of 37.6 to 41.8° and 39.9 to 44.5° at heights of 1.25 to 1.66 m and 1.43 to 1.91 m, respectively (94). Release height is a function of stature (94, 111), whereas release angle is a function of the hammer plane during the penultimate turn (110). Therefore, stature is a physical constraint and adjusting angle of release requires adjustments to the hammer plane during the preceding turns.

4.5 Conclusions

The primary predictor of hammer throw performance is release velocity, which is a product of the magnitude of tangential forces arising from large GRF, a large hammer radius, and the generation and proper use of hip to shoulder and shoulder to hammer separations during the turns preceding release. The pattern of hammer velocity will fluctuate (acceleration and deceleration) within each turn, but should increase throughout the throw. Moreover, deceleration through single support is an integral part of hammer throwing and should be minimised. Coached technical models should advocate kinematics that increase propulsive tangential force and decreases negative tangential force. The cues used to encourage propulsive kinematics may differ between sexes based on the observed differences in throwing mechanics at an elite level. Whether the later right foot down and off are a propulsive strategy of elite females or a result of the lighter implement used are undetermined. Future research should investigate the relationships between kinematic events such as hip to shoulder separation and angular displacement magnitude in double support. This data will provide valuable insight for coaches as to whether biomechanical phenomena are constrained by one another. Additionally, tracking mechanics over time to understand the influence that changing kinematics has on performance would provide valuable insight for coaches, biomechanists, and athletes.

Chapter 5

Resistance training in track and field rotational throws: A commentary on the current literature

5.0 Prelude

The prior three Chapters have addressed the biomechanics of discus, shot put, and hammer throw which are the three rotational throws within a track and field programme. All three reviews identified a paucity of literature documenting longitudinal change in kinematic and kinetic variables. Although certain biomechanical variables are important in improving throwing performance, neuromuscular qualities can also influence kinematic and kinetic variables. Coaches aim to develop neuromuscular qualities of athletes, alongside throwing abilities, via resistance training. Consequently, understanding which neuromuscular qualities better relate to performance could provide improved programming direction for strength coaches. Furthermore, understanding how throwing performance aligns with changes in these neuromuscular qualities provides an understanding of causation and additional resistance training direction. Therefore, the purpose of this Chapter was to provide a comprehensive synthesis of the resistance training literature pertaining to each rotational throw.

5.1 Introduction

Hammer, shot put, and discus throwing are three of the four throwing events within a full track and field programme, with the other one being javelin. Performance in these three former events results from rotational movements, with implements being released into the sector with the intention of achieving maximal distance. Performance in shot put and hammer throw can be determined by projectile motion (velocity, angle, and height of release) (28). In addition to projectile motion laws, discus performance involves maximizing the aerodynamic properties (lift/drag) of the discus at release (6, 28). However, the primary determinant of performance across all throws is the release velocity (2-4, 39) that results from the timing (7), direction (30), and magnitude (30, 74) of the force applied to the implement during the throwing action. Biomechanical and neuromuscular abilities can increase the magnitude of the force, which are a function of sports specific training (13, 14, 16) and resistance training methods (13). This review specifically focuses on the role that resistance training has on hammer throw, shot put, and discus performance.

Biomechanically, each throwing discipline involves a complex motion in which all segments move in a coordinated manner to enhance implement velocity. Biomechanical studies suggest that the lower limbs (7, 30, 74), trunk/core (5, 32, 106), and upper body (8, 94) play a significant role in enhancing implement velocity within each throw. Therefore, resistance training for throwers should include exercises that target all segments. Accordingly, coaches typically implement full body strength, power, and plyometric-based resistance training exercises to enhance performance, but have failed to provide evidence of transference to rotational throwing performance (10, 113-115).

Resistance training mode has a profound impact on neuromuscular adaptation (23, 116, 117). It is crucial in high performance sports to understand the relationship between neuromuscular and biomechanical variables and sports performance to inform resistance training programming. Indeed, understanding the impact enhancing given neuromuscular traits has on performance is invaluable to strength coaches to inform practice. Thus, an important step in providing direction to coaches involves synthesizing the literature relating to resistance training practices and relating variables for each throwing discipline to provide practical evidence-based recommendations.

5.2 Methods

This review was limited to articles where hammer throw, rotational shot put, and discus performance were of interest. The three throws are defined by rotational movement within a throwing circle, followed by implement release into a defined sector (i.e., landing area). Derivatives of these movements, such as standing, weighted, javelin, and linear shot put throws, were excluded. Linear shot put was not considered given the significant differences between the physical requirements of rotational and linear shot put (118).

SportDiscus^{TM}, PubMed^{TM}, and Google Scholar databases were searched for articles related to resistance training in rotational throws from June 2016 until December 2018. The following keywords were used "hammer throw" or "discus" or "shot put" combined with "strength and conditioning" or "muscular kinetics". Inclusion criteria were articles: (1) written in English; (2) relevant to one of the listed throwing events; (3) relevant to strength and conditioning; and (4) peer-reviewed original research. The reference lists of all retrieved articles were also searched to identify further literature of relevance. Although commonalities exist, the literature for each throwing event of interest is discussed separately as the movements differ in certain regards.

5.3 Results

5.3.1 Hammer throw

A summary of the resistance training literature pertaining to hammer throw is detailed in Table 5.1. Eight articles were sourced: five cross-sectional (119-123) and three longitudinal (14, 16, 22) studies.

The majority of cross-sectional investigations involved elite to sub-elite groups across sexes (119-122, 124), and suggest that strength and power are important to hammer throwing performance. More specifically, high magnitudes of lower body power [Wingate test kinetics: $r = 0.68 – 0.80$, $p < 0.05$ (119); overhead shot throw: $r = 0.95$, $p < 0.01$ (122)] more strongly relate to performance than that of absolute strength [back squat: $\beta = 0.33$, $p = 0.001$ (120)]. Lean mass [Total body lean mass: $r = 0.81$, $p < 0.01$; leg lean mass: $r = 0.84$, $p < 0.05$; trunk lean mass: $r = 0.85$, $p < 0.05$ (122)] and fibre type [vastus lateralis fibre type cross-sectional area type I: $r = 0.93$, $p < 0.01$; IIA: $r = 0.96$, $p < 0.01$; IIx: $r = 0.90$, $p < 0.01$ (122)] have also been related to performance.

With regards to the upper body, only two studies have investigated the association between upper body force and power measures, and hammer throwing performance. Strong correlations between bench press 1RM [$r = 0.83$, $p < 0.01$ (124)] and total revolutions during a modified Wingate test [$r = 0.58$, $p < 0.05$ (119)] were the only two upper body metrics identified to relate to throwing performance.

The three longitudinal investigations available are case studies with elite female participants and contained limited information regarding training methodology (14, 16, 22). Researchers have reported opposing findings in terms of strength and performance gains alongside performance (14, 16). For example, Judge et al. (22) reported increased strength [back squat 1RM: 155 to 175 kg, bench press 1RM: 68.5 to 80 kg] and power [power snatch 1RM: 65 kg to 70kg, back overhead throw distance: 16.04 to 16.80 m] in tandem with decreased throwing performance between years [distance: 65.32 to 64.35m]. In contrast, Pilianidis et al. (14) observed decreases in selected strength [back squat 1RM: ~165 to 150 kg] and power [snatch 1RM: ~88 to 80 kg, back overhead throw distance: ~13.45 to 13.2 m, standing jump: ~2.71 to 2.67 m] measures with increased performance [distance: 68.14 to 72.10m]. Of the assessed measures, only triple jump distance was reported to increase with throwing performance [triple jump: ~7.77 to 7.80 m]. Only one study by Judge et al. (16) reported concurrent increases in strength and power measures and performance; although acutely, Karampatsos et al. (121) observed performance increases following lower limb potentiation protocols. Collectively, these case studies suggest that strength and power improvements in a resistance-based setting may not mirror or translate to performance enhancements.

A common trend among all case studies reviewed is a large increase in throwing volume (hammer throws and auxiliary throws: 24 to 92% increase) alongside increased performance (14, 16, 22). Furthermore, Pilianidis et al. (14) observed fluctuations in performance that were associated with throwing volume between 2005 and 2007, more specifically, an increase in supplementary (e.g. medicine ball throws, throwing specific strength drills) throwing volume. Thus, throwing volume and throwing-specific training should be prioritized in the physical preparation of hammer throwers, followed by more conventional resistance-based training aimed at increasing strength and power (14, 16, 22, 120).

Table 5. 1. Summary of the resistance training literature pertaining to the hammer throw.

Authors	Participants (*n*)			Performance characteristics			Summary of results
	Male	Female	Total	Level	Release velocity	Distance	
				Cross-sectional studies			
Cook (119)	6	5	11	Sub-elite		M: 46.9 ± 7.3 m F: 48.0 ± 7.5 m	- Lower leg power (Wingate test metrics) was related to performance in male ($r = 0.68$ to 0.80, $p < 0.05$) and female ($r = 0.69$ to 0.70, $p < 0.05$) throwers. - Upper body power (modified Wingate test) was related to performance in male throwers ($r = 0.58$, $p < 0.05$).
Bourdin et al. (124)	8		8	Sub-elite	NS	63.7 ± 9.0% of the World Record (~ 54 m)	- Lower limb stiffness ($r = 0.73$, $p < 0.01$) and bench press maximal power ($r = 0.83$, $p < 0.01$) was related to performance. Maximal power during a squat tended to increase trend with performance.
Terzis et al. (122)	6		6	Elite	NS	72.17 ± 6.4 m	- Performance was related to backward overhead shot performance ($r = 0.95$, $p < 0.01$), lean body mass ($r = 0.81$, $p < 0.01$), lean leg mass ($r = 0.84$, $p < 0.05$), lean trunk mass ($r = 0.85$, $p < 0.05$) and muscle fibre type cross-sectional area ($r = 0.90$ to 0.93, $p < 0.01$).
Judge et al. (120)	37	37	74	Sub-elite – elite	NS	M: 59.7 ± 3.6 m F: 58.1 ± 4.9 m	- Throws per year ($r = 0.35$, $p < 0.002$), years throwing ($r = 0.22$, $p < 0.03$), back squat strength ($r = 0.33$, $p < 0.001$), and hammer technique ($r = 0.26$, $p < 0.01$) were related to performance. When combined with NCAA division, these variables accounted for 65% of the variance in performance.
				Acute (experimental) studies			
Karampatsos et al. (121)	6		6	Sub-elite – Elite	NS	61.1 to 74.9 m	- Performance increased following 3 countermovement jumps (Pre: 62.92±4.43m, Post: 64.42 ± 5.13 m, $p = 0.05$) or a 20 m sprint (Pre: 64.87 ± 3.90 m, Post: 65.30 ± 4.02 m, $p = 0.01$).
				Longitudinal studies			
Judge et al. (22)		1		Elite	25.9 to 27.2 (m/s)	64.8 to 73.9 m	- Performance increased across years (64.83 to 73.87 m) with increasing strength/power and throws per year (2003 to 2005).

Pilianidis et al. (14)	1	Elite	NS	68.08 to 72.10 m	- Performance increased (72.12 to 73.87 m) with increased strength/power metrics and decreased throws per year (2004 to 2005). - Performance level increased (68.08 to 72.10 m) across years with an increase in supplementary throws.
Judge et al. (16)	1	Sub-elite – Elite	NS	58.34 to 68.12 m	- Maximal power and strength decreased and jump performance increased with increased performance. - Performance increased (61.77 to 68.12 m) with strength/power metrics and throws per year across years (2010 to 2012). - When comparing within years, decreased performance (61.77 to 58.34m) was observed with increased strength/power and throws/year (2010 to 2011).

M = Male, F = Female, *Sex not reported, ** Estimated distance, not stated (NS) by authors.

5.3.2 Shot put

A summary of the six resistance training studies investigating rotational style shot put performance is presented in Table 5.2 (12, 15, 85, 118, 125), with one study including both rotational and linear shot putters (15). Half of these studies were cross-sectional in nature (84, 118, 124), two were longitudinal (12, 84), and one was experimental (125).

From the limited body of cross-sectional literature, it appears that greater levels of lower body strength and power as well as lean body mass are related to shot put performance (15, 84, 85, 118, 124). With regard to strength and power, Judge and Bellar (118) reported sub-elite male and female rotational shot putters to exhibit 14.86 ± 1.41 and 9.50 ± 1.95 kg of squat, 8.24 ± 0.93 and 5.88 ± 0.96 kg of power clean, and 9.98 ± 1.21 and 5.69 ± 0.87 kg of bench press strength per meter of shot put distance, respectively. In a group of similar level shot putters (personal best: 15.03 ± 1.71 m), Bourdin et al. (124) found significant positive correlations between squat jump power ($r = 0.68$, $p < 0.05$), bench press power ($r = 0.91$, $p < 0.05$), and lower limb stiffness ($r = 0.65$, $p < 0.05$) and shot put performance.

The two longitudinal investigations support the cross-sectional ones, showing that enhancing lower body strength and power, as well as upper limb strength, enhanced shot put performance (12, 84). Kyriazis et al. (12) reported squat 1RM (pre: 216 ± 19 kg, post: 230 ± 17 kg) and countermovement jump kinetics (CMJ power unloaded pre: 3042 ± 700 W, post: 3315 ± 550 W) and kinematics (CMJ unloaded jump height pre: 0.370 ± 0.04 m, post: 0.386 ± 0.06 m; velocity pre: 2.73 ± 0.1 m/s, post: 2.92 ± 0.3 m/s) to increase with performance (pre: 15.26 ± 1.67 m, post: 15.98 ± 2.11 m). The authors did not report individualized resistance programmes, but rather presented the broad principles of the linear periodisation plans of athletes. Terzis et al. (84) followed an elite shot putter over a nine-year period and reported strong correlations between 1RM squat ($r = 0.93$, $p < 0.01$), bench press ($r = 0.87$, $p < 0.01$), and snatch ($r = 0.92$, $p < 0.01$) with throwing performance. However, training programmes and periodisation models were not presented. When comparing the predicted data of Judge and Bellar (118) with longitudinal change, results disagree. Terzis et al. (84) observed an elite shot putter to throw 19.98 m with a bench press of 250 kg (equivalent of 12.5 kg/m), and Kyriazis et al. (12) reported squat repetition maximum to increase 14 kg (pre: 216 ± 19 kg, post: 230 ± 17 kg) with shot put performance increasing 0.72 m (pre: 15.26 ± 1.67 m, post: 15.98 ± 2.11 m), with equivalents of 14.2 and 14.4 kg/m pre and post. In summary, changes in performance with strength are not predictable across subjects and subject groups.

Table 5. 2. Summary of resistance training literature pertaining to the rotational shot put.

Author	Participants (*n*)			Performance characteristics				Summary of results
	Male	Female	Total	Level	Shot mass	Release velocity	Distance measured	
				Cross-sectional studies				
Bourdin et al. (124)	11		11	Sub-elite	7.26 kg	NS	15.03 ± 1.71 m	- Squat power (r = 0.68, p < 0.05), bench press (r = 0.91, p < 0.001) and lower limb stiffness (r = 0.65, p < 0.05) were related to performance.
Judge and Bellar (118)	24	29	53	Sub-elite	F: 4.0kg M: 7.26 kg		F: 15.24 ± 2.84 m M: 16.93 ± 2.45 m	- Bench press (M: 9.98 ± 1.21, F: 5.69 ± 0.87 kg), back squat (M: 14.86 ± 1.41, F: 9.50 ± 1.95 kg) and power clean (M: 8.24 ± 0.93, F: 5.88 ± 0.96 kg) kilograms per meter of shot put distance were reported, with less strength required for rotational shot.
Terzis et al. (84)	1		1	Elite	7.26 kg	NS	20.36 m	- 1RM snatch (r = 0.92, p < 0.01), bench press (r = 0.87, p < 0.01), and squat (r = 0.93, p < 0.01), as well as lean body mass (r = 0.92, p < 0.01) were related to performance.
				Acute (experimental) studies				
Terzis et al. (125)	10		10	Sub-elite	7.26 kg	NS	15.85 ± 2.41 m	- Performing 3 CMJ (throw distance pre: 15.45 ± 2.36 m, post: 15.85 ± 2.41 m, p = 0.00) or a 20 m (Pre: 15.34 ± 2.41 m, post: 15.90 ± 2.46 m, p = 0.00) sprint prior to shot putting acutely enhanced performance.
				Longitudinal studies				
Kyriazis et al. (12)	9		9	Sub-elite	7.26 kg	NS	Pre: 15.25 ± 1.67 m Post: 15.98 ± 2.11 m	- Shot put performance increased (pre: 15.26 ± 1.67 m, post: 15.98 ± 2.11 m, p < 0.05) after 12 weeks of strength and power type training. Concurrently, increases in CMJ kinetics and kinematics were observed that related to shot put performance.
Kyriazis et al. (85)	8		8	Sub-elite	7.26 kg	NS	Preseason: 13.97 ± 0.3 m Postseason: 14.34 ± 0.3 m	- Shot put performance preseason was related to fat-free mass (r = 0.70, p < 0.05), fat-free mass/height (r = 0.67, p < 0.05), and arm fat-free mass (r = 0.85, p < 0.05).

M = Male, F = Female, 1RM = One repetition maximum, CMJ = countermovement jump *Sex of participants not reported, ** Estimated distance, not stated (NS) by authors.

5.3.3 Discus throw

A summary of the three resistance training studies in discus throwers is presented in Table 5.3. There are few studies addressing neuromuscular variables and discus performance (13, 124, 126). Two of these studies were cross-sectional and showed significant correlations between incline bench press 1RM [$r = 0.97$, $p = 0.01$ (126)], maximal bench press power [$r = 0.65$, $p < 0.05$ (124)], lower limb stiffness [$r = 0.64$, $p < 0.05$ (124)], and distance thrown in sub-elite throwers. Additionally, both Bourdin et al. (124) and Karampatsos et al. (126) reported non-significant positive correlations between squat kinetics and performance, highlighting that lower limb strength and power are not as important as pressing kinetics as assessed through bench press performances. The one longitudinal investigation available observed increases in snatch 1RM (97.5 to 105 kg), overhead shot throw distance (19.60 to 20.60 m), and discus specific strength assessed on the 'discus strength training machine (STM)' that mimics the final acceleration of the discus (STM 8.5 kg velocity: 9.5 to 9.8 m/s) with an increase in discus performance (61.10 m to 72.00 m) (13). However, the authors did not report any training details across the one-year tracking period (13), making the interpretation of their protocol difficult.

Table 5. 3. Summary of resistance training literature pertaining to the discus throw.

Author	Participants (*n*)			Performance characteristics			Summary of results
	Male	Female	Total	Level	Release velocity	Distance measured	
				Cross-sectional studies			
Karampatsos et al. (126)	6		6	Sub-elite	NS	49.64 ± 4.3 m	- Throwing performance during a full throw (r = 0.96, p < 0.01) and from the power position (r = 0.97, p < 001) was related to incline bench press but not squat 1RM.
Bourdin et al. (124)	13		13	Sub-elite	NS	65 ± 5.8% of World Record (~48m)	- Lower limb stiffness (r = 0.64, p < 0.05) and maximal bench press power (r = 0.65, p < 0.05) were related to throwing performance.
				Longitudinal studies			
Losch and Bottcher (13)		1	1	Elite	NS	61.10 to 72.00 m	- Increased discus performance was reported concurrently with increases in discus strength training machine velocity, snatch 1RM, and backward shot throw distance.

M = Male, F = Female, *Sex of participants not reported, ** Estimated distance, not stated (NS) by authors.

5.4 Discussion

The hammer throw, shot put, and discus events share several commonalities with regard to movement mechanics, notably that they require the generation of high forces early in the execution of the movement to accelerate the implement in a rotational manner. Additionally, as performance level increases, so does the need to apply forces at higher movement velocities leading to the inclusion of resistance training to support performance via increasing early force – time and high velocity force application.

The four resistance training cross-sectional studies undertaken in hammer throwing indicate that lower and upper body pressing strength and power are important for performance (119, 120, 122, 124). However, much of the literature has focused on the relationship between traditional metrics (e.g., 1RM) and performance that – over longitudinal periods – do not relate to performance (14). Therefore, research directed at understanding the relationship between neuromuscular measures and hammer throwing performance should be undertaken. For shot put, it appears that lower limb strength and power are important to shot put performance (118, 124), and the magnitude of cross-over from strength to performance is individual (12, 15, 85, 118, 125). The majority of the literature in shot put has focused on traditional gym-based exercises (e.g., power clean, bench press, and squat), with the practical usefulness of other more rotational-specific exercises currently unknown. For discus, literature overall suggests that upper body pressing kinetics are more important than lower limb strength and power (124, 126). Across the three throws, the lack of resistance training literature renders practical recommendations difficult. More research, both longitudinal and cross-sectional, is required to better understand the impact of strength and conditioning on throwing performance. At the moment, the evidence indicates that practitioners should prioritise throwing and throwing-specific movements prior to strength and power gym-based training. It appears important that longitudinal investigations report training programmes and periodisation concurrently with neuromuscular and performance changes to better inform practice.

Resistance training is commonly regarded as a method to increase performance through enhanced muscular force production. Although a limited body of evidence exists, the majority of the literature supports increasing strength and power through traditional movements (power clean, bench press, and squat) (84, 118, 126). That said, considerable individual variation in the transference of enhanced strength and power to throwing performance has been reported (14, 84, 118). This lack of transference in certain athletes may be a result of adaptive responses to training that are related to force development at high velocity. Traditional strength and power training modes reduce the percentage of muscle comprised of type IIx muscle fibres (20, 21). Type II muscle fibre types are related to throwing performance and high velocity force application (5, 7, 83, 117, 122, 127). Therefore, traditional modes of strength training may not be the most efficient means to enhance throwing performance. As such, strength coaches should consider both physiological and biomechanical adaptations to training methods that maintain or enhance fibre type while enhancing peak force.

Another methodological factor to consider is exercise selection, which should adhere to the principle of specificity. The effect of including sports specific movements into resistance training programmes has been well documented to enhance performance (128, 129). Researchers studying longitudinal hammer throwing performance have shown that greater movement specificity (e.g., more hammers thrown) enhances performance (14, 120). Losch and Bottcher (13) reported similar trends in discus performance. Thus, when training for throwing, resistance training should be biomechanically specific in addition to prioritizing throwing-specific training.

Drawing practical conclusions from the literature should be undertaken with caution as the available longitudinal data show a sex bias and variance in performance level. Longitudinal hammer throwing data are from three female throwers (14, 16, 22). Conversely, shot put literature has only involved male throwers (12, 85). Shot and hammer mass vary between sexes, thus transferability of findings between sexes is problematic. Judge and Bellar (118) reported females required 28 to 42% less strength to throw similar distances to males at their respective competition implement masses. Based on implement weight male and female throwers likely have differing force – time and force – velocity needs. At present, between sex requisites are not well understood.

The biomechanical differences between sub-elite and elite throwers has been documented (7). Elite throwers exhibit time constrained force application from both low and high velocities during the throw (7, 29). Within similar time frames, elite throwers accelerate quickly from considerably faster movement velocities. Although sub-elite throwers show similar accelerations, their starting velocities are slower (7), resulting in overall slower movement velocities. It seems that the early force – time and high velocity force application differ between elites and sub-elites. The mechanistic underpinning of early force – time (0 to 250 ms) ability has been largely attributed to peak force (17), and high velocity force application to fast muscle fibre types and muscle architecture (130, 131). At present no longitudinal investigations have reported high velocity force variables or their determinants, which would add to the understanding of transference of resistance training across levels.

5.5 Conclusions

Overall, there is a paucity of resistance training literature in rotational throwers. The between-study discrepancy regarding the relationship between strength and power variables and throwing performance requires further research. It appears that part of the discrepancy between neuromuscular qualities and throwing performance maybe related to specificity of training and lack of reporting of training posology. Researchers and practitioners need to consider the effect of training mode and specificity of movement on neuromuscular adaptation, event biomechanics, and performance. Drawing strong recommendations from the current literature is challenging given the limited reporting of resistance training, throwing, and periodisation regimes. Consequently, there is little knowledge on how various training methodologies affect performance. Researchers are encouraged to report with greater detail training interventions to counter these limitations. Integrating testing methods that are more biomechanically similar to throwing performance might aid in improving our understanding of neuromuscular adaptation that lead to further enhancement in throwing performance. Finally, throws specific training should be prioritised ahead of other types of training, adhering to the principle of specificity.

Chapter 6

Periodisation to enhance early force – time and high velocity force application: A conceptual model for throwing events

6.0 Prelude

The literature review in the previous Chapter synthesised all available resistance training literature in hammer, rotational shot put, and discus throw. The results highlighted a severely limited and sex-biased body of evidence that suggested peak force and power of the lower and upper body as important for throwing performance to varying extents. However, the paucity of literature and its narrow scope constrain conclusions and practical applications as to best practice resistance training of throwers. The purpose of this Chapter therefore was to develop a theoretical resistance training model for rotational throws. To develop a theoretical model requires a degree of ecological validity, thus biomechanical phenomena from the former Chapters were used to determine the physical requirements of rotational throwing. It was theorised that resistance training directed at enhancing kinetics and kinematics observed in throwing would enhance performance. This theoretical model formed the basis for the single subject designs that were implemented later in the thesis.

6.1 Introduction

Periodisation refers to the organisation of training into components as a method of planning for peak performance (132). Several methods of resistance training periodisation exist, all of which describe the manipulation of programme variables within months or weeks (132). The foundations of such models are set in our perceived ability to predict an individual's adaptive response based on cross-sectional and longitudinal data (133). Such methods have been questioned on the basis that a multitude of unpredictable factors affect predicted adaptive responses (133). However, it should be recognised that periodisation is a dynamic model rather than a stringent framework, and the integration of multiyear learning, regular monitoring, and auto regulatory strategies can be used to shape training (133, 134). Also, it is questionable whether typical periodisation models are appropriate for sports that have one-off expressions of explosive strength and power such as shot put, discus, and hammer throwing. Throwing performance and associated biomechanical determinants should form the foundation of periodisation in individual technical sports that rely on one-off expressions of strength and power. From this foundation, the neuromuscular needs can be determined and ultimately lead to an informed periodisation plan (Figure 6. 1). This conceptual model of performance variables underpins this Chapter, which will focus on Level 3 (mechanical properties) and Level 4 (underpinning physiology) of this model.

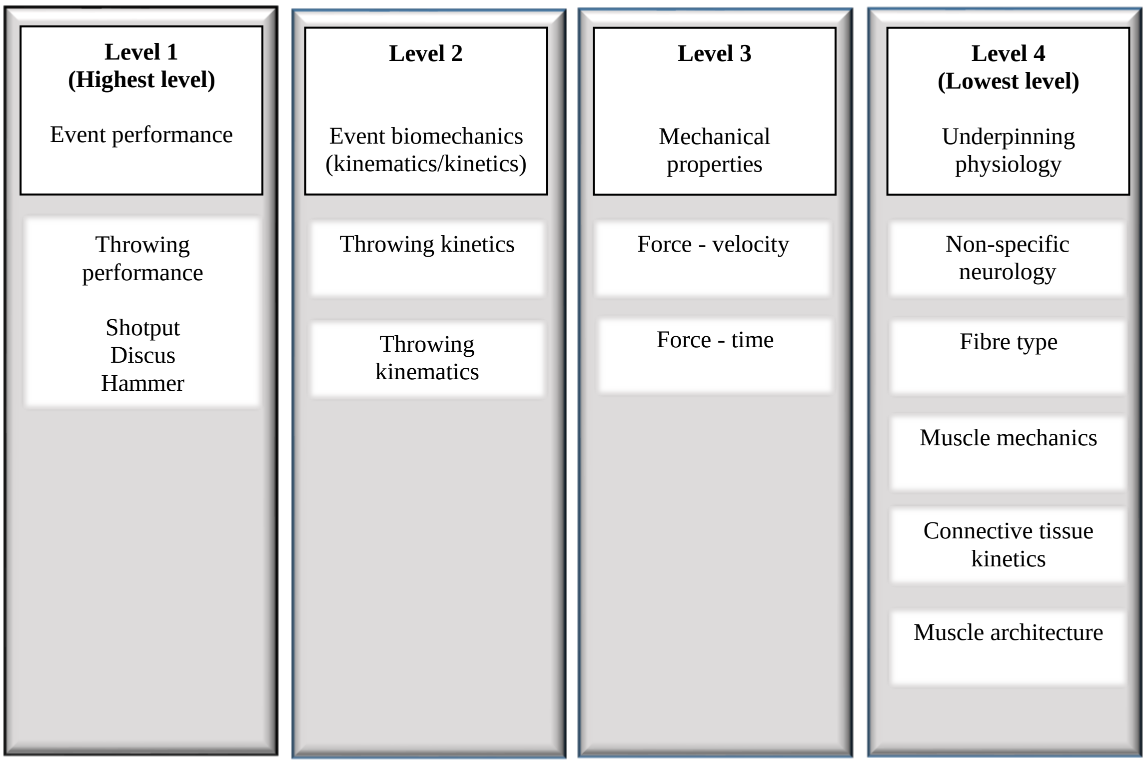


Figure 6. 1. Conceptual model of performance variables for track and field throwing events.

Performance within track and field throwing events requires the development of high implement velocities that are a result of force applied to the implement by the thrower. An understanding of the biomechanics of implement acceleration can be used to determine resistance training strategies that develop associated physiology (Figure 6. 1, Level 2). In track and field, throw phase durations (i.e., contractile windows) of 124 to 270 ms (47, 100) as well as high implement (7, 29) and segment (9, 25, 34) velocities have been reported. Generally, later phases of the throw involve shorter phase durations where superior acceleration characterises elite throwers (29, 100). Furthermore, track and field throwing is typified by concentric only (135) and stretch-shortening cycle type movements (5, 7) that occur cyclically during the event (7, 94). Thus, the ability to produce force rapidly (e.g., 200 ms) at high velocities repeatedly both during concentric-only and stretch-shortening contractions are important to accelerate the body and implement and enhance throwing performance (7, 135). Furthermore, to attain superior release velocities, the athlete must be able to accelerate their body and the implement from already high velocities within short time frames (7, 38, 39, 66). In summary, early force – time and high velocity force application are required in elite throwing. Resistance training strategies must target these qualities to raise the possible performance ceiling.

Historically, resistance training programmes in throwing events have revolved around enhancing strength and power measures (which relates to Level 3, Figure 6. 1) via gym-based exercises (e.g., bench press and power clean) thought to relate to performance based on cross-sectional data (15, 118, 120) and historical opinion (113). However, enhancing strength and power often comes at the expense of physiological adaptation that depresses force output at velocity, e.g., a shift in fibre type from Type IIx to Type IIa (20, 21, 117). The development of training methods that enhances all variables across Levels 1 to 4 of Figure 6.1 may enhance performance above that of traditional methods. Thus, the purpose of this Chapter was threefold: to understand 1) the mechanisms relating to early force – time and high velocity force application; 2) the responses of each mechanism to various training modes; and, 3) how to best periodise training to maximise adaptation to enhance early force – time and high velocity force application concurrently.

6.2 Methods

6.2.1 Literature reviewed

The search for relevant scientific literature was conducted using the SportDiscus^{TM} via EBSCO and Google Scholar with ‘rate of force development’, ‘impulse’, ‘contraction velocity’, ‘fibre type’, and ‘strength and conditioning’ as keyword search terms. Titles, abstracts, and full-texts of retrieved documents were sequentially reviewed to determine their relevance to the topic. In addition, the reference lists of all studies included for review were searched manually for additional studies of relevance. The inclusion criteria for articles were: 1) published in the English language; 2) addressed early force – time or high velocity force application; and, 3) addressed variables or mechanisms underpinning early force – time and/or high velocity force application.

6.3 Mechanical terminology

Early force – time application, rate of force development and impulse. Early force – time application refers to the magnitude of force that can be applied early in the muscular contraction (Figure 6. 2). For the purpose of this review, 200 ms was chosen as it is consistent with time frames associated with track and field throwing. RFD defines to the slope of the force – time trace. Impulse reflects the force – time integral of the force – time trace.

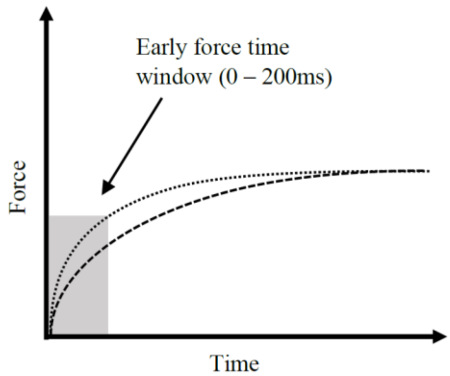


Figure 6. 2. Representative concentric force – time relationship (dashed line - - -). Grey box is the contractile window of interest. The dotted line (···) represents a relatively enhanced early force – time profile, which this article targets.

High velocity force application. High velocity force application refers to the ability to apply force at a high velocity or continue to apply force as the movement velocity increases (Figure 6. 3). A subjective interpretation of "high" velocity based on throwing sport biomechanics was taken for the purpose of this review.

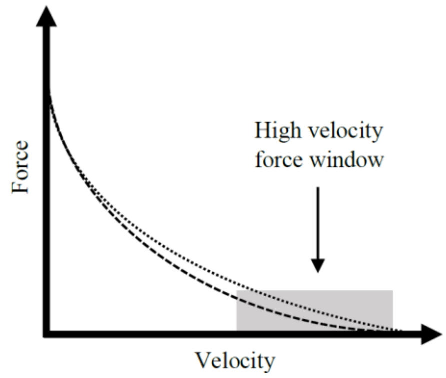


Figure 6. 3. Representative concentric force velocity curve (dashed line - - -). Grey box is the contractile window of interest. The dotted line (···) represents a relatively enhanced force – velocity profile, which this article targets.

Fibre type %. Fibre type % refers to the relative portion of fibres that are categorised as Type Ia, IIa, and IIx. Fibre type % area is independent of fibre cross sectional area (CSA) and therefore changes in fibre % can occur independently of CSA.

Fibre cross-sectional area (CSA). Fibre type CSA refers to the absolute size of each individual fibre. It is described as Type Ia, IIa or IIx CSA. CSA changes can be independent of changes in fibre type % as they describe separate adaptive responses.

Stiffness. Stiffness refers to a spectrum ranging from compliant to stiff (Figure 6. 4). The spectrum of compliant to stiff represents the mechanical properties of elastic structures that describe resistance to length change for a given force. A force – length relationship of tendinous tissue is non-linear.

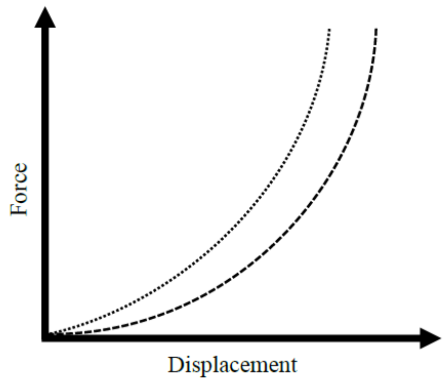


Figure 6. 4. Representative tendon stiffness profile (dashed line - - -). The dotted line (···) represents an increased stiffness profile.

Hysteresis. Hysteresis represents the relationship between energy storage and return. In stretch-shortening cycle movements, it is representative of the energy lost.

Peak force. Peak force refers to the absolute force generating capacity of a muscle or muscle groups with no time constraint. Resistance training literature often describes peak force as strength, maximal voluntary isometric contraction (MVIC), or maximal voluntary torque (MVT). Maximal bouts of concentric force are associated with the low velocity or isometric contractions generating high forces.

6.4 Early force – time and high velocity properties

6.4.1 Understanding early force – time properties

Muscular force production requires neural activation of motor neurons that innervate contractile elements which generate force that is transferred to the skeletal system through the tendon. Changes in the physiology of each component (neural, muscular, and tendinous) can markedly impact on the resulting force output.

Greater neural output has been observed to significantly relate to early force – time application (136, 137). Markers of neural activation, such as magnitude of electromyographic (EMG) activity at relevant time points (137-139), motor neuron activation (140), supraspinal drive, and recurrent inhibition (19), have explained a considerable portion of the variance in early force – time application. Nelson (141) and De Ruiter et al. (136) observed early force application to increase with increasing stimulation frequency. Corroborating these findings, Vecchio et al. (140) observed motor neuron discharge frequency of the tibialis anterior to explain a considerable portion of the variance ($r^2 = 0.56 – 0.85$, $p < 0.0001$) in early force – time variables during isometric dorsiflexion. Additionally, Tillin, Jimenez-reyes, Pain, and Folland (142) reported greater EMG signal synchronisation between muscles involved in knee extensions in athletes who exhibited greater RFD from 0 to 50 ms compared to controls. Thus, increasing the magnitude, synchronisation, and the frequency of electrical activation to muscles is of considerable interest when seeking to enhance early force application.

Muscle composition, fibre type, and architecture can also impact the magnitude of early force – time application (21, 139, 143). Faster fibre types have been observed to shorten more quickly than slower ones and develop tension at a greater rate (144). Farup et al. (21) reported significant correlations between Type IIx percentage area and RFD from 0 to 30 ms ($r = 0.61$, $p < 0.01$), 0 to 50 ms ($r = 0.56$, $p < 0.01$), and 0 to 100 ms ($r = 0.46$, $p < 0.05$). Furthermore, Anderson and Aagaard (17) reported significant correlations ($r = 0.45$ to 0.60, $p = 0.001$ to 0.05) between electrically evoked twitch RFD, a quasi-measure of fibre type, and voluntary RFD from 0 to 50 ms. The correlation decreased with increasing time epochs (e.g., epochs > 50 ms), which suggests fibre type becomes less important with longer contractile windows.

Architecture is another component of muscle that influences force generation, although only one investigation has reported a significant effect within early force – time application (143). Fascicle length (FL), pennation angle (PA), and CSA refer to the length of fascicle, angle of insertion into the aponeurosis, and size of individual muscle fibres, respectively. Earp et al. (143) observed gastrocnemius FL to explain a portion of the variance in RFD from 0 to 10 ms ($r^2 = 0.21$, $\beta = 0.46$, $p = 0.02$) and 10 to 30 ms ($r^2 = 0.22$, $\beta = 0.48$, $p = 0.019$) during a CMJ, suggesting fascicle length was weakly associated with greater CMJ jump heights. During a depth jump from a 30 cm drop height, gastrocnemius FL explained a similar portion of variance from 0 to 10 ms ($r^2 = 0.19$, $\beta = -0.43$, $p = 0.03$); however, the direction of association suggests shorter FL was associated with increased early RFD. Vastus lateralis ($r^2 = 0.19$, $\beta = 0.44$, $p = 0.03$) and gastrocnemius ($r^2 = 0.19$, $\beta = 0.43$, $p = 0.03$) PA also explained some of the variance in RFD from 0 to 10 ms during a drop jump, and gastrocnemius CSA ($r^2 = 0.19$, $\beta = 0.44$, $p = 0.028$) explained a portion of the variance in depth jump RFD from 30 to 50 ms. These results suggest that architectural variables relate to early force – time application in a task specific manner.

The final component of interest to early force – time application is tendon stiffness (18, 137). Theoretically, stiff tendons transmit muscular force in a more time efficient manner to the skeletal system. In support, Bojsen-Moller et al. (18) reported vastus lateralis tendon stiffness to significantly correlate to knee extension rate of torque development from 0 to 100 ms ($r = 0.54$, $0 < 0.05$) and 0 to 200 ms ($r = 0.56$, $p < 0.05$). Furthermore, Waugh et al. (137) reported Achilles tendon stiffness to explain a portion of the variance in plantar flexion RFD from 0 to 50 ms ($r^2 = 0.20$, $p < 0.05$) and 0 to 100 ms ($r^2 = 0.22$, $p < 0.05$). Thus, greater tendon stiffness increases the RFD during early force – time windows.

Although not a mechanistic variable, peak force needs to be mentioned in the context of early force – time application due to the strength of its relationship to RFD. Peak force has been shown to have a high association to early force development ($r = 0.43$ to 0.95, $p \leq 0.05$) (17, 138); however, both Anderson and Aagaard (17) and Folland et al. (138) observed an increase in the strength of association between peak force and RFD as time progressed from 0 to 200 ms and 0 to 150 ms, respectively. These data suggest that although peak force is important to RFD, the strength of its relationship to RFD is directly related to the contractile window duration.

6.4.2 Understanding high velocity force properties.

As the velocity of movement increases, the muscular-tendinous unit (MTU) must have the ability to shorten at velocities that exceed the load to continually apply propulsive forces (27, 145). Additionally, if the movement involves a high velocity and is cyclical, relaxation time becomes an important factor in repeated force production (146). Similar to that of early force – time application, neural factors (141), fibre type (26, 27), and tendon stiffness (27) relate to the ability of the MTU to shorten faster than the load.

During high velocity movements, shortening velocities of muscle fascicles increase linearly with joint angular velocities (27) and depend on muscle fibre type (130) and fascicle length (i.e., thought to reflect the number of sarcomeres in series) (131). Muscle fibre shortening velocity changes based on fibre type, where Type IIx fibres shorten faster than Type IIa, and Type IIa fibres shorten faster than Type Ia (17, 130). Strong correlations ($r = 0.61$ to 0.93, $p < 0.05$) between fibre type and the force applied at high angular velocities have been reported (26, 147). Aagaard and Andersen (147) reported the correlation between vastus lateralis Type II % and peak force during an isokinetic leg extension to increase as velocity increased from 120°/s to 240°/s ($r = 0.607$ to 0.857, $p < 0.05$), suggesting that fibre type becomes more important with increasing velocity. In cyclical movements where relaxation time limits repeated force expression, Hautier et al. (26) reported optimal pedalling velocity during an inertial load bicycle test to correlate to fibre type % of the vastus lateralis ($r = 0.88$, $p < 0.001$). Relaxation time is largely fibre type dependant as well, where faster fibre types have shorter relaxation times. Furthermore, Edman (145) suggested slow fibres apply resistive forces when subjected to supramaximal shortening velocities. Thus, high velocity force application, both cyclical and non-cyclical, requires the involved musculature to have more dominant % of fast fibres (27, 130, 147, 148).

Intuitively, neural activation is important to high velocity force application. However little literature has been directed at understanding the relationship between neural variables and high velocity force application. In one of the few existing investigations, Nelson (141) observed shortening velocity of isolated rat muscle fibres to increase (3.87 ± 1.24 to 4.32 ± 1.69 L/s, $p < 0.05$) with increasing stimulation frequency (52 ± 14 to 96 ± 36 Hz).

Tendinous tissue stores and returns energy. The contribution of the tendinous tissue during concentric movements is not constrained by a shortening velocity, but rather its properties that affect storage and energy return (i.e., stiffness and hysteresis), the contractile window, and the inertia of the system. Tendon input to high velocity movements is phasic: At high joint angular velocities, tendon shortening has greater input into MTU shortening when the muscular component is shortest (27, 149). Little research has investigated which properties have the largest impact on high velocity force application; however, during sprinting that exhibits high joint velocities, Kubo, Kanehisa, Kawakami, and Fukunaga (150) reported vastus lateralis tendon stiffness to be lower in sprinters than controls. In contrast Arampatzis, Karamanidis, Morey-Klapsing, Monte, and Stafilidis (151) observed Achilles tendon stiffness to be greater in sprinters than controls. These results suggest the potential need of segment specific stiffness in sports performance. The specificity of tendon stiffness that optimise performance is likely based on joint biomechanics (149) and biomechanical requirements of the movement (150, 151). Another important variable associated with tendinous function in all movement is hysteresis, which is the difference between energy storage and return that quantifies the efficiency of elastic energy return (152-154).

6.4.3 Understanding early force – time and high velocity force application in the context of throwing.

The importance of simultaneous early force – time and high velocity force application within throwing performance is not well understood from a resistance training perspective. Longitudinal data in throwing events traditionally target strength changes (12, 13, 16, 22). Although the importance of strength is not questioned, strength is only one feature of many that influences early force – time ability (147) and throwing biomechanics. Furthermore, the results of Judge et al. (15) suggest the relationship between strength and throwing performance is approximately quadratic, a finding that has been supported using longitudinal data (14, 16, 155).

During throwing movements, the thrower – implement system initially involves slower velocities with relatively long contractile epochs (5, 29, 94), thus high early force – time application aids in accelerating the implement. As the thrower moves through each phase of the throw, regardless of throw type, the thrower – implement system accelerates and the system's velocity upon entry into each phase increases (5, 94). Due to the increases in velocity and movement kinematics, contractile epochs remain constant or decrease (< 200 ms), but the velocity at which early force application starts increases (29). Thus, early force – time application from an already high velocity or at increasing velocities is required (7). During the final phase of shot put and discus, an increase from ~4 to over 14 m/s and from ~10 to over 24 m/s in implement velocity, respectively, occurs within a contractile window of ~200 ms (5, 29). Therefore, early force – time application on an implement that is already moving is required. Achieving high implement velocities in shot put requires the elbow joint to accelerate from rest to over 640 °/s, with greater elbow angular velocities observed with greater throwing distances (25, 66). Each throw exhibits a stretch-shortening type movement where a lengthening storage phase precedes the shortening release phase (7, 30). Stretch-shortening cycle movements promote greater dominance of tendinous tissue input into MTU shortening, but still require high fascicle shortening velocities (153, 154, 156, 157).

In summary, early – force time and high velocity force application have similar mechanistic underpinnings with the exception of peak force, which is further related to force development with increasing time epochs. During elite throwing performances, the expression of early force – time and high velocity force application is required. The presence of a high proportion of fast twitch muscle fibres, tendon stiffness, neural output, and peak force would in theory correspond to throwing kinetics and kinematics. The plasticity of such factors in response to periods of training modes of varying types has been reported (21, 23, 24, 151, 155, 158-164); therefore, the adaptive process of each mechanism individually as well as their interrelatedness need to be understood to optimise a throwing-specific neuromuscular profile and periodisation plan.

6.5 Resistance training to enhance related mechanistic variables.

6.5.1 Neural adaptations

Neural factors during early force – time windows such as the magnitude of EMG, rate of EMG rise, inhibitory mechanism input, and frequency of motor neuron discharge have been related to early force – time and high velocity force application (19, 138, 140, 158, 165). Furthermore, changes in EMG variables and motor unit firing frequency have been documented in response to resistance training (141, 166, 167), with no current literature addressing inhibitory mechanisms identified.

In response to resistance training, increases in the magnitude of EMG signals within early contractile epochs are well documented (159, 166-170). The ballistic nature of exercise appears to be an important consideration in resistance training to increase early EMG variables (166, 167). Balshaw et al. (166) and Barry et al. (170) reported increases in early contraction EMG variables in response to ballistic (as fast as possible) training in the knee extensors and elbow flexors.

Increased EMG root mean square (RMS) and mean rate of EMG rise (RER) were observed concurrently with increased early force – time variables collected from 0 to 200 ms. Interestingly, Balshaw et al. (166) observed the changes in early EMG variables to be greater when resistance training consisted of ballistic type contractions (4 x 10 contractions of ~ 1 s durations performed explosively) rather than sustained isometric contractions (4 x 10 contractions of ~4 s durations at 75% MVC). Although not consciously ballistic, increased mean EMG voltage and early force – time variables have been observed following sensorimotor training (balancing on unstable surface) (167, 169). To maintain balance, well-developed reflex activity is needed to rapidly respond to perturbations elicited by the unstable surface. Gruber et al. (167) compared sensorimotor training and ballistic strength training of the plantar flexors over a 4 week period. Following the training period, early force – time application increased in both groups; however, median power frequency of both gastrocnemius and soleus increased following sensorimotor training ($p < 0.05$), whereas median frequency of the gastrocnemius only and mean amplitude voltage (MAV) of both gastrocnemius and soleus ($p < 0.05$) increased following ballistic training. Previous literature has suggested that median power frequency is positively associated with muscle fibre conduction velocity (171, 172), where MAV maybe more associated with motor unit synchronisation (167). Thus the two training protocols likely promote two distinct neural adaptations.

In terms of firing frequency, Van Custem et al. (158) observed greater mean discharge frequency and double discharge incidences alongside an increased rate of tension development during dynamic ballistic contractions in response to 12 weeks of high velocity dorsiflexion training (10 sets x 10 repetitions at 30 – 40% 1RM, 5 times per week). Similarly, Gruber et al. (167) suggested that increased MAV indicated increased discharge frequency. Thus, high velocity contractions likely increase motor unit discharge frequency.

Collectively, literature suggests changes in neural factors associated with early force – time and high velocity force application occur in response to ballistic and high velocity contractions. It is not known if ballistic and high velocity contractions result in differential neural responses. The inclusion of sensory motor training may be beneficial to integrate as part of a warmup routine or to develop movement competencies.

6.5.2 Fibre type adaptation

Changes in fibre type percentage (up regulation of IIa to IIx) towards a faster fibre type have been reported following periods of maximal electrical stimulation (24), fast eccentric resistance training (23), and detraining (20, 117, 155, 173) (Table 6.1). These results are in contrast to what has been observed during traditional strength type resistance training.

Table 6. 1. Adaptations in response to methods of training associated with enhancing markers of early force or high velocity kinetics.

Training method	Early contraction kinetics	High velocity kinetics	Neural changes			IIx fibre %	Fibre type CSA	Tendon stiffness	Tendon hysteresis	Peak force	References
			0-50 ms	0-100 ms	0-200 ms						
Isometrics	↑				↑			↑		↑	(166, 174-176)
Ballistically intended isometricss	↑		↑	↑	↑					↑	(150, 159, 166, 168, 170, 177, 178)
Hypertrophy/strength	↑	↑	=	=	=	↓	↑	↑		↑	(20, 21, 116, 117, 174, 175, 179-183)
Maximal power		↑				=/↓	↑			↑	(183, 184)
Velocity decay threshold						=	↑			↑	(185-187)
High velocity	↑	↑	↑			=/↓			↓	↑	(158, 160, 183, 188, 189)
Plyometrics							↑	↑		↑	(190-193)
Fast eccentrics	↑	↑				↑	↑	↑		↑	(23, 161, 194, 195)
Slow eccentrics		↑				=			↑	↑	(23, 196)
Electrostimulation						↑	↓				(24)
Detraining		↑				↑	↓	↓		↓	(117, 155, 173, 176, 197-199)
Sensory motor training	↑		↑	↑		?				=	(167, 169)
Imagery						?				↑	(168)
Static type stretching						?		↓	↓	=	(152, 180, 200)

Notes. ↑, increase; ↓, decrease; =, no change; ?, unknown; CSA, cross sectional areas.

Only two resistance training studies have reported shifts in human muscle fibre types towards faster fibre types (23, 24). Delitto et al. (24) observed a shift towards more type IIx muscle fibres following four months of resistance training with periods of maximal electrical stimulation (10 x 11 s contractions at 2500 Hz and 200 mA 3 x per week) in an elite weightlifter. Large increases in 1RM were concurrently reported. In vitro, the dominance in fibre type proportion shifted from Ia to IIa following high frequency phasic stimulation (25 pulses at 150 Hz every 15 minutes) over 18 to 40 days in rat muscle (201, 202). Furthermore, in vitro experiments suggest initial fibre type, stimulation frequency relative to fibre type, and dosage affect fibre transformations following periods of electrical stimulation (202-204). In vivo, Delitto et al. (24) did not specify how duration and frequency were determined. Although "high" frequency is required, further research into exact frequencies and durations that shift human muscle fibre types towards faster ones is required. The other resistance based investigation, Paddon-Jones et al. (23), reported a shift towards more fast twitch muscle fibres (type I, IIa, IIx percentage pre: 53.82%, 40.39%, 5.79%, and post: 39.12%, 47.97%, 12.91%, respectively) following 10 weeks of high (3.14 rad/s), but not slow (0.52 rad/s), velocity eccentric training in untrained participants. Significant increases in isometric and dynamic torque were also reported following both high and slow velocity eccentric training. Both Delitto et al. (24) and Paddon-Jones et al. (23) advanced that the selective recruitment of fast fibre types underpinned their observed fibre type shift.

Detraining interventions lasting more than 3 weeks have resulted in fibre type adaptations towards a faster fibre type (20, 117, 155, 173, 205). An interaction between time and magnitude of fibre type shift appears evident as detraining for less than 2 weeks results in no fibre type change (206) and the amount of fibre type shift increases with time between 4 to 32 weeks (20, 117, 155, 173). Detraining adaptation is likely contraction volume (number of muscular contractions) rather than magnitude (load) dependant; therefore, similar adaptations can occur with high load, low volume training following high volume, high load training periods (184, 207-211). It should be noted that increased early force – time application post a detraining period is unlikely given the reported decreases in musculotendinous stiffness after two months of detraining (176), decreases in EMG signal amplitude with 2 to 12 weeks of detraining (117, 206), and decreases in peak force output (117, 155, 206).

Fibre type upregulation has been widely documented in response to periods of detraining (20, 117, 155, 173) and in response to a select few resistance training methods (23, 24). The latter resistance training methods require further research as a limited body of evidence is available that has investigated human musculature. However, to elicit a fibre type shift towards faster fibre types, high eccentric contraction velocities and electrical stimulation frequencies are required, with low contraction volumes during the detraining period. Finally, with regard to increasing early force – time application the deleterious adaptations that occur in response to detraining should be carefully planned.

6.5.3 Muscle architecture

Muscle architectural variables including FL, PA, and CSA, influence the contractile components ability to deliver force to the tendon (212). Furthermore, CSA has been observed to impact joint moment arm (213). The adaptive responses of muscle architectural variables have been extensively reported in literature (214-217).

Increases in FL of the hamstrings and quadriceps have been reported following supramaximal eccentric training [hamstrings: 2.0 to 2.4 cm increase, $p < 0.01$ (214, 216)], ballistic jump training with and without weights [quadriceps: 0.3 to 1.3 cm, $p < 0.01$ (217, 218)], and sprint and jump training [quadriceps: 4.2 to 5.2 cm, $p < 0.05$ (219)]. Conversely, decreases in FL have been observed during detraining (hamstring: 1.9 to 2.2 cm decrease, $p < 001$ (216)). The intensity and volume of load experienced during eccentric blocks appear to determine the time course of fascicle shortening during subsequent detraining (215, 216). When volume and intensity are not high enough, FL has been observed to decrease (hamstring: 0.93 to 1.77 cm decrease, $p < 0.005$) below pre training levels after four weeks of detraining (215, 216). That said, biceps femoris fascicle length has been observed to increase (2.4 cm increase, $p < 0.001$) with low volume (8 repetitions per week) supramaximal eccentric exercise (216).

Increases in PA have been observed following loaded explosive squat training [quadricep: 0.5 to 1.9°, $P < 0.05$ (218, 219)] and detraining [hamstrings: 1.2 to 2.3° increase, $p \leq 0.05$ (215, 216)]. Conversely, PA decreases during periods of supramaximal eccentric training [hamstrings: 1.5 to 2.7° decrease, $p < 0.001$ (215, 216)] and bodyweight sprint/jump training [quadriceps: 0.6 to 3.1° decrease, $p < 0.001$ (219)]. However, Coratella et al. (217) reported PA to increase (quadriceps: 3.2° increase, effect size = 1.03) following bodyweight squat jump training. The divergence between Coratella et al. (217) and Blazevich et al. (219) is likely the addition of sprint training. Similar to FL, Pollard et al. (215) observed variable PA changes during a 6 week eccentric, to 4 week detraining intervention. Their two eccentric groups, moderate and high load, showed similar changes from post intervention to post detraining (moderate vs high eccentric load groups: 1.2° vs 1.7° increase in hamstring PA, Cohen's d = 0.88 to 1.22). Due to the larger decrease in PA following high load eccentrics PA returned to pre intervention levels in the high eccentric load group. In contrast PA angle increased above pre intervention levels in the moderate load group following detraining. Presland et al. (216) observed PA to return towards baseline during detraining with no difference in the gradient of change between high volume and low volume eccentric groups. Thus, the magnitude of change during detraining is likely related to the mode of training and not the magnitude of training.

Muscle fibre CSA appears to be the most responsive muscle architecture quality to training, with increases in CSA being observed following supramaximal eccentric (215, 216), strength (183), power (184), and sprint/jump (219) training. Conversely, decreases in CSA are observed following periods of detraining (155). Thus changes in CSA are strain dependant.

Muscle architectural variables adapt in response to resistance training mode. CSA appears to have the most plasticity and increases in response to many resistance training stimuli. FL increases with high velocity and supramaximal eccentric training and decreases with detraining; whereas PA increases in response to jump type training and detraining, but decreases with supra-maximal eccentric training. Periodisation schemes should consider the time course of adaptation during detraining and preceding training methods as architectural responses could affect early force – time and high velocity force application.

6.5.4 Tendon stiffness and hysteresis adaptation

The mechanical properties of elastic tissue have been reported in numerous papers (151, 152, 163, 174, 176, 178, 180, 196, 199, 200, 220-227). Changes in stiffness are predominantly observed in the absence of changes to the tendon CSA which is thought to occur at a slower rate (163, 174, 180, 199, 228, 229). The avascular nature and sporadic fibroblasts associated with tendon morphology are likely a factor in the slow CSA adaptations (163). Changes in collagen fibre cross link pattern, proteoglycan content, structure, and packing of collagen can occur with tissue avascularity and have been suggested to underpin increases in tendon stiffness and decreased hysteresis following short term loading (174, 178, 180, 196, 199). Chronic tendinous tissue adaptation is reflected in loading dynamics (frequency and magnitude) (151, 178, 230). Increases in tendinous stiffness have been reported in response to long isometric (174, 175, 231), ballistically intended isometric (178, 190), plyometric (188, 190-192), strength/hypertrophy (180, 191, 196), and eccentric (196) type training (Table 6.1). Conversely, decreases in tendon stiffness have been reported following proprioceptive neuromuscular facilitation (PNF) stretching (200), static stretching (152), and detraining (176, 198, 199) (Table 6.1). Furthermore, differential tendinous adaptation between limbs within the same subjects have been reported in response to training and stretching, thus joint specific stiffness is an achievable quality (175, 178, 191).

The magnitude of loading is an important variable in enhancing tendinous stiffness where prolonged exposure to high (151, 174-176, 178, 188, 190, 191, 196) and low (19, 138, 152, 176, 178, 192, 200) stress magnitudes increases and decreases tendinous stiffness, respectively. In support, Arampatzis et al. (178) reported increases (17.1%, $p < 0.05$) in stiffness with high stress (5 sets of 1 s isometric contractions at 90% MVC, 4 x per week), and non-significant decreases (-5.2%, $p > 0.05$) with low stress (5 sets of 1 s isometric contractions at 55% MVC, 4 per week) resistance training over 14 weeks. Additionally, Malliaras et al. (196) observed greater increases in stiffness following a period of supramaximal eccentric training (84% increase) compared to concentric (70% increase) and low load eccentric (59% increase) training. In response to 20 days of bed rest, Kubo et al. (199) reported decreased (-20.2%, $p < 0.05$) patellar tendon stiffness that could be mitigated with daily exposure to resistance training (5 x 10 reps at 90% MVC). In a similar investigation, Reeves et al. (198) reported tendon stiffness to decrease following 90 days of bed rest. Such changes were partially attenuated with intermittent training [bed rest group: -58%, bed rest plus intermittent training: -38% (4 sets, 7 to 14 repetitions every third day on a flywheel trainer)]. An alternative to bed rest for attenuating stiffness is prolonged static (152, 200), but not ballistic, stretching (222). The magnitude of stress is likely to be high during ballistic stretching, thus providing sufficient stimulus for stiffness qualities to be maintained. Such results indicate the existence of a stress band width, whereby the tendon structure must be exposed to a level of stress in excess of normal ranges to promote increased tendon stiffness (178, 196). Conversely, decreasing exposure to stress below a lower threshold results in decreased stiffness (152, 178, 200).

With regards to hysteresis, decreases have been observed following stretching (5.6 to 7.1% decrease, $p < 0.05$) (232, 233), plyometric type training (35% decrease, $p < 0.05$) (188), and concurrent resistance training and stretching (17.0% decrease, $p = 0.09$) (180). In contrast, increases (11.7% increase, $p < 0.05$) in hysteresis have been reported following bed rest (199). Long duration static (3 to 10 minutes) stretching alone or with resistance training acutely and chronically decrease (5 to 17% decrease, $p < 0.09$) hysteresis (180, 232, 233). Following 15 weeks of plyometric training Foure et al. (188) observed a 35% decrease in hysteresis, whereas Wu et al. (192) and Kubo et al. (231) reported no change in hysteresis following 12 weeks of plyometric training. The differential changes in hysteresis may be related to training duration and total jumps performed. The former investigation included 6800 high intensity jumps (average: 485 per week) where the latter two included 720 to 3600 jumps (average: 90 to 300 per week).

Tendinous adaptation, stiffness, and hysteresis are important to kinetic return, thus the process of adapting tendon kinetics is of interest. Tendinous adaptation occurs in response to loading magnitude where high and low loads outside of a bandwidth of "normal" stimulate increases and decreases in stiffness. When seeking to enhance tendon stiffness higher volume plyometric type training may be most effective as decreases in hysteresis have also been reported. As performance in sporting movements often require segmentally specific stiffness, long duration stretching in appropriate poses to reduce stiffness in certain areas or mitigate unwanted increases in stiffness could be recommended, concurrently decreases in hysteresis likely occur.

6.5.5 Peak force development

Peak force is defined as the greatest magnitude of force a muscle is capable of producing and is a crude measure of strength. In dynamic activities, a common proxy for peak force is the maximal load lifted during a given movement pattern (1RM) (234). Peak force is reliant on both central (235-237) and peripheral adaptations where the innervation of motor units (236-238), amount and synchronicity of the innervated motor units (236-238), and CSA of the innervated musculature affect peak force (237, 239). Historically, resistance training (load, repetitions, sets) to increase peak force capabilities is based on the repetition – load strength continuum in which a decrease in number of repetitions is linked with an increase in load (240). It has been suggested and demonstrated that a load specificity adaptation occurs whereby training with high loads increases maximal force production capacity (164, 234, 241, 242).

Increases in peak force have been observed following strength (162, 164, 166, 243-246), hypertrophic (234, 242), isotonic (197), isometric (197), eccentric (23, 161), power (164, 186, 245, 246), ballistic (158-160, 166), complex/contrast (247), and mental imagery (168) based protocols (Table 6.1). All of the aforementioned interventions follow some form of progressive overloading type stimulus (21, 164, 168, 243-246, 248) with the exception of the imagery protocol (168).

Triweekly strength sessions are common in most research and practical settings, and have shown to benefit strength (164, 166, 234, 242, 243). Weightlifters often employ much greater frequencies that often encompass two sessions within one day (249, 250). Loads ranging between 30% and 90% of concentric repetition maximum (20, 179, 185, 186, 197, 234, 242, 245-248, 251) and greater than concentric repetition maximum have been reported to increase peak force (23, 161). Stimulating changes in peak force with submaximal loads relies on ballistic motions that increase neural drive to a level proportionate to that observed during maximal load efforts. More traditional paradigms would suggest loads that exceed 85% of 1RM are required to enhance strength (240), however the range of loads reported (30 – 90% 1RM) suggests high levels of neural drive to be equally as important as external load.

Repetition schemes generally correspond to load intensity (240). Increases in sets should occur in conjunction with increasing training age (252). Increases in peak force have been reported with 3 to 40 repetitions at loads corresponding to less than (20, 179, 197, 245-247) and equal to 1RM (197, 234, 251). Set ranges from 1 to 6 have been used to enhance strength (179, 197, 234, 242, 245-247, 251) in untrained (197, 234, 242, 248, 251), moderately trained (245, 247), and highly trained (179, 246) individuals.

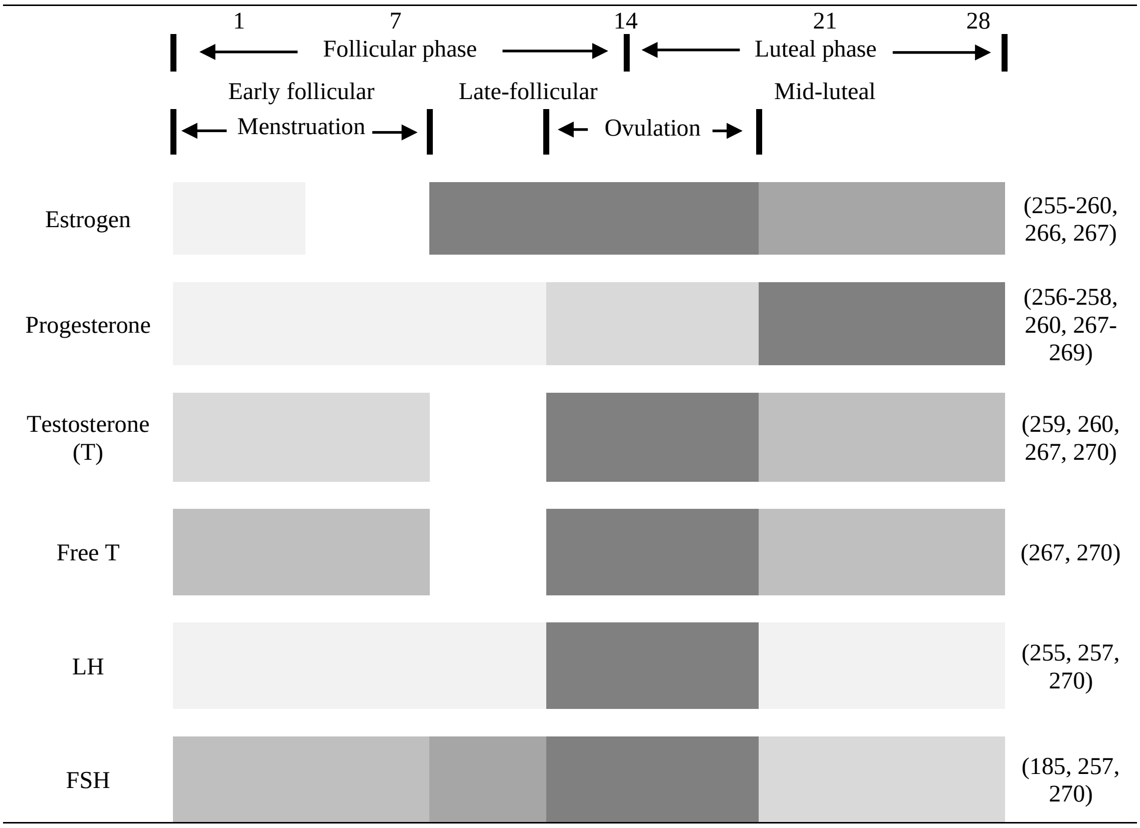
Increases in CSA have been reported in response to the aforementioned strength training methods and, for the most part, a reduction in IIx fibre types (20, 21, 164, 234). Only strength/power training with low velocity decay (percentage decrease in bar velocity across a set) thresholds and/or eccentric resistance training have increased peak force concurrently with the maintenance of fibre type characteristics (23, 185, 186, 194). Some evidence suggests higher movement velocities, that are controlled by load, maintain fibre type and velocity adaptation, while maintaining peak force adaptation (185-187)

In summary, peak force increases in response to a variety of loading schemes and contraction modes. Traditional paradigms lead to a decrease in IIx fibre type percentage; however, the inclusion of eccentric and velocity threshold type protocols likely negates such effects. Numerous methods exist to increase peak force, thus methods of resistance training can be varied to avoid monotony. Training methods focusing on increasing peak force should follow progressive overload training methods with high concentric intent. Coaches should also consider adaptive responses to the different methods of training that occur other than peak force.

6.5.6 Sex considerations

Fluctuations in hormone levels occur throughout the menstrual cycle (see Table 6.2) that affect variables related to performance and may impact adaptation and injury occurrence (253). Cook, Kilduff, and Crewther (254) reported significantly greater testosterone (42% increase, $p < 0.01$) on day 14 of the menstrual cycle when compared to day 7 and day 21. The increase in testosterone was associated with motivation and power response to a potentiation protocol. Increased testosterone has been associated with calcium availability and transport that aids in muscle contraction force and velocity (253). Concurrently with increasing testosterone, increasing levels of endogenous oestrogen (95.2 to 405%, $p < 0.05$) has been reported (255-260) and oestrogen (endogenous and exogenous) has been associated with decreased collagen synthesis in response to mechanical loading (261, 262). In contrast, endogenous oestrogen appears to have a protective role within muscle as muscle soreness, force decrements, and markers of muscle damage are attenuated in women following eccentric contractions (263-265). Such occurrences have implications for women taking oral contraceptives and suggest that adaptive responses during each phase of the menstrual cycle may vary.

Table 6. 2. Hormonal changes throughout the menstrual cycle.



Notes. LH, luteinizing hormone; FSH, follicular stimulating hormone; T, testosterone. Shading is based on reported changes in hormonal levels between phases. Dark shading indicates greater hormone levels, light shading indicates lower hormone levels.

Visco-elastic properties have been reported to vary through ovulation (257, 259, 271, 272). However, both decreases (257, 259, 271) and no change (260, 272) in stiffness have been reported during ovulation with no change in performance (255) (see Table 6.3). In addition to hormone levels, changes in stiffness may be related to increased body temperature that shows cyclical (256) and diurnal (273) variation that effects the visco-elastic properties of tendinous tissue (274). Diurnal variation may be the source of stiffness-related variations between investigations (257, 259, 260, 271, 272). Thus time of cycle and day should be factored in when assessing stiffness characteristics. Some conjecture in the literature exists as peak force has been reported to significantly decrease in magnitude during menstruation (258), ovulation (275), and mid luteal phases (276); while others have observed no change in peak force across phases (266-268, 277) (see Table 6.3). High velocity muscular kinetics and jump performance are maintained across the cycle (266, 268, 273, 277, 278). As such slow, but not high, velocity strength testing performed during menstruation may not be indicative of adaptive responses.

Table 6. 3. Changes in performance variables between menstrual cycle phases.

	1	7			14	21	28
		Follicular phase				Luteal phase	
	Early follicular			Late-follicular		Mid-luteal	
	Menstruation				Ovulation		
Lee and Petrofsky (271)					↓ plantar fascia thickness, ↑ postural sway and tremor		
Gordon et al. (258)	↓ PF at 60 - 120°/s						
Sunderland et al. (278)		= PP					
Fridén et al. (270)					↑ hop test		↓ kinesthesia
Lee et al. (259)	↓ passive muscle/tendon extensibility, ↑ hysteresis				↓ ligament stiffness and hysteresis		
Cook et al. (254)					↑ motivation		
Giacomoni and Falgairette (273)		= PP					
Eiling et al. (257)					↓ stiffness		
Bell et al. (272)					↑ ROM, = stiffness		
Abt et al. (255)	= motor control, postural sway, strength and biomechanics						
Montgomery and Shultz (268)	= PF						
Giacomoni et al. (277)	= PP, velocity, PF, multi jump and squat jump						
Shultz et al. (260)	= stiffness and laxity						
Tenan et al. (276)						↓ force	
De Jonge et al. (266)	= PF, = CP						
Sarwar et al. (275)					↓ PF, ↑ RT		
Elliott et al. (267)	= PF						

Notes. Analysed phases of the cycle highlighted in grey. PP, peak power; PF peak force; CP, contractile properties; RT, relaxation time; =, no change between phases; ↓, relative decrease in that phase; ↑, relative increase in that phase.

Longitudinally, few investigators have manipulated training variables (mode, frequency, intensity, volume) based on the menstrual cycle. Sakamaki-Sunaga, Yasuda, and Abe (279) reported greater strength and muscle volume adaptations when training was performed during the luteal phase compared to the follicular phase. In a later investigation, Sakamaki-Sunaga, Min, Kamemoto, and Okamoto (280) reported similar CSA and strength adaptations when one biceps brachii muscle was trained during the luteal phase and other during the follicular phase of the menstrual cycle. Given the general paucity of longitudinal data, further research is required to understand the changes in adaptive responses as a function of menstrual cycle timing.

Oral contraceptive (OC) users experience significantly less hormonal variability, but the OC can have a negative impact on biological processes underpinning mechanisms associated with performance variables (253, 281-283). Although non-significant differences in anaerobic power and strength have been reported when comparing OC users to naturally cycling women (258, 273, 278); OC users exhibit decreased collagen synthesis (283), increased muscle damage markers (264), and prolonged force recovery (263, 265) following exercise compared to natural cycling counterparts. In contrast, Kuhlmann and Wolf (284) observed positive effects of the OC on memory retrieval when exposed to cortisol, which may have practical application as elite female athletes have greater free cortisol levels (285). Given OC likely inhibit strength and power performance, women in explosive sports likely do not benefit from chronic use of OC pills. However, within highly technical explosive sports where skill dominates, the OC may aid in learning, although longitudinal evidence is required to support this premise.

Due to the lack of research and variability in findings, the most effective alignment of training structure to the menstrual cycle remains largely unknown. Within the current model, aligning eccentric loading to the luteal phase likely attenuates muscle soreness and enhances force recovery for subsequent sessions (263, 265). The adaptive response to training during the luteal phase may also be greater due to factors associated with peak force adaptation (254, 279). That said, the adaptive response of connective tissue is likely impaired around ovulation; as a result, the inclusion of high tendinous loading modes should be planned carefully and allow for appropriate recovery (259, 260). Athletes taking an OC will likely experience greater muscle soreness and prolonged recovery periods in response to eccentric type loading, indicating that lower volumes and longer recovery should be considered (263-265). The enhancement of skill acquisition while taking an OC may be considered as beneficial for those in technically demanding events (284).

6.6 Theoretical periodisation model to enhance early force – time and high velocity force application

Periodisation refers to the organisation of resistance training components into a sequence that likely results in peak performance (133). Resistance training components generally address contraction modes, sets, repetitions, and rest that are organised to promote certain neuromuscular adaptations. Resistance training mode is, however, the major factor affecting muscular adaptation for early force – time and high velocity force application (20, 23). The sequencing of training mode within a year is determined based on a realised or theoretical layering of adaptive responses that culminate in an enhanced neuromuscular state (20). Adaptive layering, the sequencing of training resulting in the enhancement of multiple neuromuscular variables at a certain time point, has been observed by Staron et al. (20) who showed similar peak force levels with enhanced fast fibre type expression following a resistance training, detraining, and retraining sequence. Thus, the longitudinal organisation of training based on the mechanisms of early force – time and high velocity force application is presented in Table 6.4. This is the first paper to present a periodised plan based on targeted neuromuscular adaptation for throwers. Readers need to be cognizant of its theoretical nature before implementation.

The model is eccentrically biased, moving from slow eccentrics to fast eccentrics. This sequence promotes a sequential increase in tissue stress (286). Overloaded eccentrics and electrical stimulation have been shown to maintain or encourage a shift towards fast fibre types with enhanced peak force (23, 24). That said, eccentric training has an increased residual fatigue response, exercise induced muscle damage, and likely changes the motor patterning due to acute changes in joint kinetics and kinematics (287). An increase in markers of fatigue that decrease muscular force remain elevated over days and weeks in response to increased eccentric intensity and movement velocity (288). Regular exposure to eccentric exercise somewhat attenuates changes in markers of soreness, force expression, and range of motion (288). Furthermore, fascicle lengths and pennation angles can be maintained through low volume eccentrics. The inclusion of electrical stimulation should be implemented with caution. Frequencies required to stimulate an up regulatory response can induce severe discomfort (24) resulting in a likely high emotional fatigue response. Due to the high physical and neural load experienced through overloaded eccentric exercise and electrical stimulation, the inclusion of intermittent periods of alternative training methods that result in lower acute fatigue are recommended (287-289). Decreased fatigue response has been observed immediately and 24 hours post resistance training with decreased loads (290, 291). Including velocity-based training (with decay thresholds) using submaximal loads is believed appropriate for both fatigue management and maintaining adaptive response (185, 292).

Table 6. 4. A theoretical model of periodisation for concurrent early force – time and high velocity force application.

	Block one *(slow eccentrics)*		Block two *(high velocity eccentrics)*		Block three *(overshoot)*	Block four *(retrain)*
Duration (weeks)	2 – 5	2 – 4	2 – 5	2 – 4	> 4	4 - 6
Primary training method	Slow eccentrics	Velocity decay	Fast eccentrics		Detraining	Velocity decay and epoch specific plyometric
Secondary training method	Ballistic and long SSC plyometric		Electrostimulation and short SSC plyometric	Velocity decay	Velocity decay threshold, epoch specific plyometric and low volume eccentrics	Ballistically intended isometrics
Maintained throughout	Sensory motor training and segment specific static stretching					
Specificity of movements*						
	Predicted adaptive response					
Neural adaptations (0-200ms)	↑	?	=/↑	?	↓	↑
Fibre type %	=	=	↑	=	↑	=
Fibre type CSA	↑	↑	↑	=/↑	↓	↑
Tendon stiffness	*↑/=	*=/↑	*=/↑	*=/↑	↓	*↑
Tendon hysteresis	↓	=/↓	=/↓	=/↓	=/↑	↓
Fascicle length	↑	↑	↑	↑	↓	↑
Pennation angle	↓	↓	↓	↓	↑	↓
Peak force	↑	↑	↑	↑	↓	↑

Notes. * May be mitigated by magnitude of exposure to long duration static stretching. All adaptive responses will depend on the athlete's proximity to their adaptive ceiling for each mechanism; ↑, increase; ↓, decrease; =, no change; ?, unknown; SSC, stretch shortening cycle; CSA, cross sectional area.

Detraining is included as a training method as it has been shown to be effective in eliciting fast fibre type shifts (20, 155) although the majority of factors associated with early force – time and high velocity force application decrease. There is a likely interaction between contraction volume and adaptation, as eliciting an overshoot response is related to a significant reduction in volume (20, 155, 173). Thus, fibre type adaptations in response to resistance training are dependent on an interaction between volume, frequency, and elicited fatigue (185, 293-295). Therefore, the inclusion of low frequency (once every 5 to 7 days (295)) and low fatigue (<10% velocity decay (185)) resistance training protocols may mitigate some of the decreases in peak force and tendon stiffness while maintaining fast fibre type adaptations. The inclusion of low volume eccentrics during training likely aids in the maintenance of fascicle length and pennation angle (216).

Short retraining periods (4 to 6 weeks) using similar resistance protocols to that employed during detraining with the addition of ballistically-intended isometrics increase peak force, tendon stiffness, and neural output, as well as maintain the majority of type IIx fibre type adaptations (20, 159, 178, 185, 190). Retraining periods beyond 6 weeks likely decrease muscle IIx fibre type adaptations to below pre-training levels (20). Therefore, the retraining period should be kept short before returning to full training. The addition of static stretching of targeted body segments, to mitigate increased tendon stiffness associated with retraining, can be included (152).

Prior to implementation of the proposed theoretical model, many factors must be considered. Sports specific training periodisation needs to be the primary consideration. The highly variable stimulus presented (i.e., supramaximal eccentrics to detraining) results in significant variation in neuromuscular status. Planning sports specific training needs to be implemented with consideration to changing physiology. Throwing based athletes historically perform skill and resistance training concurrently. Effective organisation of training (skill and resistance type trainings) resulting in enhanced sports performance is required as acute force – time, range of motion, and sensory feedback disruption exists following eccentric, strength, and explosive type resistance exercise (288, 290, 291). Skill performance sessions prior to resistance training sessions will be most effective when seeking to decrease the impact of acute musculoskeletal disruption on the skill performed. Furthermore, acute but prolonged responses in connective tissue and fatigue markers suggest that eccentric type training should be performed away from key technique sessions to avoid changes in skill execution (287, 288). Tendon and connective tissue adaptations may lead to prolonged skill changes that will be maintained through detraining periods, but needs to be forecasted within skill adaptation planning (180).

Throws training (i.e., skill sessions) is the most specific form of resistance training. Each throw is performed with a moderate external load (4 to 7.26 kg depending on sex) in a ballistic fashion that elicits high musuclo-tendinous loads on the athlete – implement system (7, 30). As such, throwing load should be factored into the periodised plan as it can add to fatigue and influence subsequent adaptive processes. The execution of the skill is important to adaptive tuning whereby generic adaptive processes (neural and physiological adaptations) are integrated to enhance performance (151, 296). The timeline of tuning likely varies as neural and physiological changes need to be performed in the context of the skill. As such, the specificity of training should move from non-specific to specific (Table 6.4). The rate and magnitude of adaptation and volume of skill execution during heavy training, detraining, and retraining periods all likely influence the degree to which adaptive changes are integrated into the skill. The timeline of such integration is unknown and can be referred to as a lag time (297).

6.7 Conclusion

Several physiological variables underpin early force – time and high velocity force application. It is apparent that a variety of resistance training methods concurrently increase and decrease determinants related to early force – time and high velocity force application. Furthermore, numerous modes of resistance training increase variables (e.g., peak force, fibre type, and stiffness) relating to both early force – time and high velocity force application, highlighting how the mode of training selected is important. The sequencing and duration of training mode to allow fatigue and recovery must be considered and factored in to the periodisation model. Aspects of the periodisation need to consider sex, e.g., consider that OC use dampens some adaptive processes. The level of thrower should also be a considered, this model promotes neuromuscular adaptations to enhance elite performance and thus may not be suitable for more novice throwers.

This review presents a conceptual model of periodisation appropriate for throwers. One limitation of the model is that skill practice was not included. Given the high magnitudes of force produced by throwers, practitioners using this model should carefully consider throwing timings and volumes. Additionally, acute changes in skill as a result of resistance training mode likely occur and should be taken into account. Finally, the conceptual model is a ‘best case scenario’. Future investigations should track adaptive responses and practitioners should seek to understand individual responses to training and the layering of adaptation within an individual that leads to peak performance.

Chapter 7

Multi-joint musculoarticular stiffness derived from a perturbation is highly variable

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7.0 Prelude

The two previous Chapters presented current resistance training knowledge (Chapter 5) and a conceptual model of resistance training (Chapter 6). These Chapters highlighted that elite throwers likely need high levels of musculotendinous stiffness to deliver time efficient force. Furthermore, Chapters 2, 3 and 4 suggested that the throwing motion is a complex system and involves stretch shortening cycle movements at multiple joints simultaneously. Therefore, an assessment of elastic capability spanning multiple joints in similar positions to that exhibited in throwing is of significant interest to throws testing and training. A perturbation protocol has been used to derive musculoarticular (multi-joint elastic properties) stiffness during a bench press; however, poor measures of reliability have been reported. Furthermore, pulling and squatting positions have not been investigated. Given this information, the aim of this Chapter was to determine the test-retest reliability of musuclo-articular stiffness measures assessed during a bench press, bench pull, and squat motion.

7.1 Introduction

Shot put, discus, and hammer throw can be categorized as stretch shortening cycle activities as eccentric actions are immediately proceeded by concentric actions, enhancing force output. These stretch-shortening cycle movements have been observed in the upper body (25, 63), trunk (25, 63), and lower limbs (66, 298). During stretch shortening cycle movements, musculotendinous units initially act eccentrically (i.e., stretch), where elastic energy is stored in the muscles and parallel and series elastic components and returned concentrically (i.e. shorten) at a rate and magnitude dependent on movement dynamics (e.g., system inertia and contractile epoch) and elastic properties (e.g., stiff versus compliant). Stiffness is an important performance variable which is the relationship between the deformation of a body segment, or multiple body segments, and a given force (299). Greater stiffness is associated with less energy leakage during the stretch shortening cycle, and therefore, enhanced force production (299).

During throwing movements, multiple segments interact at any one time, thus the stiffness of a singular tissue (e.g., Achilles tendon) does not tell us what is occurring with regards to the stiffness qualities at the multi-joint level, i.e., lower limb squat and upper body press (34, 66, 298). However, to date, much of the research has focused on single-joint elastic properties rather than multi-joint ones. Single-joint elastic properties have been shown to be reliable [intra-class correlation (ICC) = 0.88 to 0.98, coefficient of variation (CV) = 4.7 to 8.7%] (188, 192, 300), to distinguish between athlete groups (301, 302), and relate to athletic performance (124, 150, 301, 303); but less is known about multi-joint stiffness.

Multi-joint stiffness is otherwise known as musculoarticular stiffness as the assessment does not differentiate between individual structures. One method for quantifying musculoarticular stiffness is to use a perturbation protocol, during which a brief perturbation is applied to a load, generating a sinusoidal wave which is said to represent stiffness. One research group has reported excellent test-retest reliability of musculoarticular stiffness during a bench press movement (ICC = 0.89) (152) and observed stiffness to be positively related to 1 repetition maximum (RM) bench press performance ($r = -0.72$, $p < 0.01$) (226). The same research group observed a decrease in musculoarticular stiffness with an increased bench press 1RM (152). Based on these results, it seems that the natural frequency of tissue can be shifted, giving rise to the idea of regional elastic musculoarticular stiffness specificity (150, 152, 301). If elastic tissues exhibit stiffness that is "optimal" for a given movement, then the muscle can work closer to its optimal length and return elastic energy within the required time frames, ultimately increasing force outputs and performance (152, 304).

In track and field throwing events, performance is accomplished through a series of multi-joint interactions. Therefore, assessing musculoarticular stiffness may provide more practical insights into musculotendinous functioning during the actual performance tasks. However, to our knowledge, the reliability of musculoarticular stiffness has only been reported using ICC measures for a bench press movement (152). The inclusion of additional movements and measures of reliability would provide a more comprehensive understanding of the variability associated with multi-joint musculoarticular stiffness and its utility. Therefore, the purpose of this investigation was to quantify the test-retest reliability of musculoarticular stiffness derived from the perturbation technique across the bench pull, bench press, and squat movements. Given the previous literature on musculoarticular stiffness, we hypothesised that this physical characteristic would be reliable across loads and movements.

7.2 Methods

7.2.1 Experimental Approach to the Problem

This study used a within-subject repeated measures design to assess musculoarticular stiffness during a bench pull, bench press, and back squat in experienced resistance-trained males over three occasions. The subjects participated in a familiarization session where their 1RM strength was determined for each lift, and they were familiarized with the perturbation loads, an inertial load bike, and a seated medicine ball put. Testing took place over three weeks, with seven days separating each session. For each of the three test sessions upper and lower body force capabilities were quantified from the seated medicine ball put and inertial load bike, respectively. Thereafter, the subjects performed the bench pull, bench press, and back squat using perturbation loads between 15% and 70% of 1RM. During each of the perturbation trials, force plates and linear position transducer (LPT) were used to determine bar oscillations. Based on the resultant oscillations, musculoarticular system stiffness was derived for each movement and load.

7.3 Participants

Eight experienced resistance-trained males (six highly strength trained subjects and two elite track and field subjects) volunteered to participate in this investigation (Table 7.1). Experienced resistance-trained was determined as bench press and bench pull strength greater than body mass and greater than 1.5 times body mass for the back squat. Subjects were not included if they were, or had used, performance-enhancing substances (WADA 2016) and all protocols were approved by the host University’s Institutional Research Ethics Committee.

Table 7. 1. Participant characteristics.

		Mean	Standard deviation
Age	(y)	23.6	3.7
Height	(cm)	180.4	10.8
Mass	(kg)	90.1	19.6
Squat	(kg)	172.8	28.1
	(BM)	2.0	0.3
Bench press (kg)	(kg)	112.8	24.6
	(BM)	1.3	0.2
Bench pull (kg)	(kg)	95.6	15.5
	(BM)	1.1	0.1

Notes. BM, body mass.

7.4 Procedures

7.4.1 Equipment.

All testing was performed in a laboratory with ambient temperature set at 22°. Bar displacements were tracked by a PT5A [Fitness Technologies, SA, Australia] LPT connected to the bar, synchronized with two Accupower [Advanced Medical Technology Inc. (AMTI), Watertown, MA, USA] force plates to collect ground reaction force data. All devices were synchronised and collected at 1000 Hz via a custom LabView (LabView Professional 2016) programme.

7.4.2 Familiarisation and 1RM testing.

During the testing, subjects were asked to maintain regular dietary, hydration, and sleep behaviours, and refrain from intense resistance activity for 48 hours before testing. All subjects attended four testing sessions (1 x familiarisation and 3 x data collection) at the same time of day, with each testing occasion separated by 7 days. The initial familiarisation session included the collection of baseline data (height, mass, and age), determination of 1RM strength for each of the lifts, multiple perturbation trials at loads between 20 to 60 kg, and familiarisation with the inertial load bike and seated medicine ball put. All subjects were familiar with 1RM testing, during which multiple warm-up sets at increasing loads were performed and once ~90% repetition was reached 5 – 10 kg increments in load were used to establish the 1RM (305). 1RM was established in <5 repetitions following warm-up loads. The order of 1RM testing was bench pull, bench press, and back squat, respectively. Spotters and spotting bars were used across loads and lifts to ensure safety. A minimum recovery time of 120 s was implemented between attempts and exercises to limit the effect of fatigue.

7.4.3 Warm-up and pre-measures.

On arrival to all testing occasions, subjects performed 5 minutes of low intensity cycling, followed by 10 leg swings (both flexion/extension and abduction/adduction), lunges, push-ups, T-Y-W scapulae retraction movements, and open book torso rotations. Following the warm up, 3 maximal inertial load bike trials and 3 maximal seated medicine ball puts at 3 and 5 kg loads were performed to determine the force capabilities of the upper and lower body and to compare the subjects' contractile state between sessions. Briefly, the inertial load bike trials were performed on a custom made bike with a fixed weight (30kg) flywheel and crank length (165mm). Seat height was adjusted to a position where slight knee flexion was observed at the bottom of the pedal stroke and handle bar height to a position of comfort. Seat and handle bar heights were recorded and kept constant across days. The trial consisted of an 8-revolution maximal effort from which peak power, peak torque, revolutions per minute, and optimal cadence were derived. During the seated medicine ball put, subjects were strapped into a seat that limited hip movement. Holding the medicine ball in their dominant hand, each participant put the ball using a countermovement action as far as possible. Dominant hand was defined as the hand in which the subject preferred to put the medicine ball with. Three trials at each load starting with the 3kg ball were performed. Three electronically synchronised cameras (Camera; Vision Prosilica GX1050C, frame rate; 70 fps, shutter speed; 1/1000) recorded each put via custom written software (HPSNZ portable tracker™). Prior to data collection all cameras were calibrated following the manufactures procedure. Cameras were fixed behind (4.2m behind, 1.0m high.), to the right (3.7m right, 0.99m high) and above (5.0m above) the subject. The center of the medicine ball was manually digitised in each frame within the custom written software. Velocity and accelerations were calculated from position and time traces and filtered at 8 Hz using a low pass Butterworth filter. Cut-off frequency was determined using residual analysis.

7.4.4 Bench press.

A countermovement bench press was employed consistent with previously described methods (226, 240, 306). Briefly, lying supine on a bench press, the Olympic bar was lowered to the chest at a self-selected speed, followed immediately by a concentric press. Before the execution of the lift, grip width was determined as width needed to have the forearm perpendicular to the floor when the bar rested on the chest, and humerus abducted 70° (referenced from the anatomical position). Trials during which the head, shoulders, hips, or feet lost contact with their respective support surfaces (bench or force plate) or with excessive bouncing of the bar were disregarded and repeated. Additionally, light contact with the chest, roughly level with the lower chest was cued. To collect ground reaction force and bar data simultaneously, the bench press and participant were positioned spanning across two AMTI force plates synchronized to the LPT that was attached as centrally as possible to the bar.

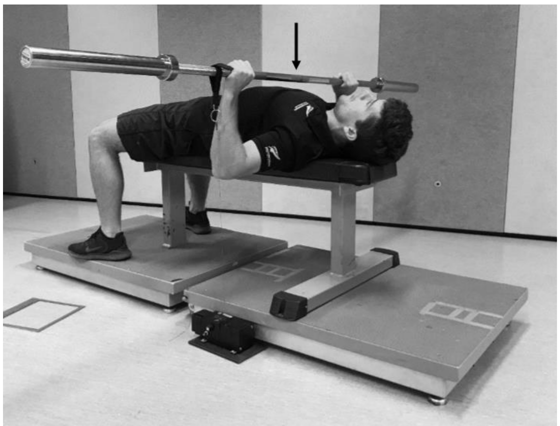

Figure 7. 1. Bench press perturbation set-up.

7.4.5 Bench pull.

A countermovement bench pull consistent with the methods detailed by Sanchez-Medina, Gonzalez-Badillo, Perez, and Pallares (307) was performed, although a Smith machine was not used. Briefly, lying prone on a high-pull bench, a grip position consistent with that of the bench press was attained via bar markings. Before the first repetition, the Olympic bar was held above an extended arm position with elbows flexed. Once released, the bar was lowered to the extended arm position. Subjects then rowed the bar into the bench making contact with a point coinciding with the xiphoid process. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xiphoid process due to the steel frame. Cues were given to contact the bench as forcefully as possible and only trials where contact was made were counted. Trials during which the chin, chest, or hips lifted off the bench were disregarded and repeated. To collect kinetic and kinematic data, the bench pull was placed on two synchronized AMTI force plates with the LPT attached as centrally as possible to the bar.

Figure 7. 2. Bench pull perturbation set-up.

7.4.6 Back Squat.

A countermovement back squat consistent with previous investigations (308, 309) was performed. Starting in an erect position with an Olympic bar securely resting on the upper back, subjects squatted down to a soft deformable hurdle placed at a height consistent with a 90° knee angle (310). Following a light touch, cues were given to drive up explosively. A 90° knee angle was employed as it corresponds to the knee angle observed in the power position during shot put and discus (81). Squatting belts were allowed if requested. Trials where a 90° knee flexion angle was not achieved were disregarded and repeated. To collect kinetic and kinematic data, all repetitions were performed standing on an AMTI force plate with a LPT attached as centrally as possible to the bar.

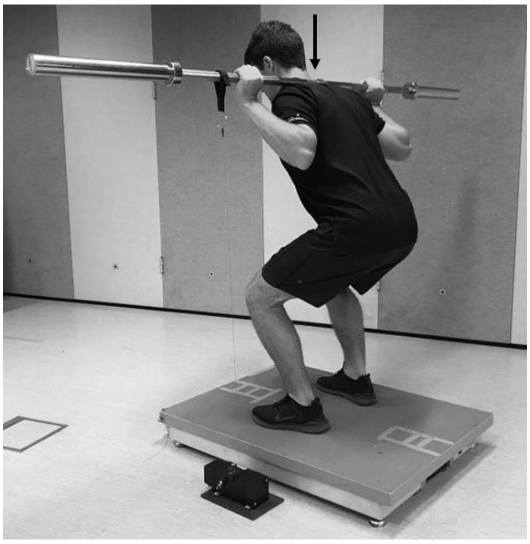

Figure 7. 3. Back squat perturbation set-up.

7.4.7 Perturbation method.

Loads concurrent with those used by Wilson, Murphy, and Pryor (311) were employed (perturbations at 15%, 30%, 45%, 60%, and 70% of 1RM) across movements. All loads were rounded to the nearest kilogram. For all three movements assessed, the perturbation was applied 3 cm above the maximal eccentric range of motion (see Figures 7.1, 7.2, and 7.3). As such, the bar was lowered and held isometrically for less than 2 s, 3 cm off the chest during the bench press, 3 cm above full elbow extension/shoulder adduction/protraction during the bench pull, and 3 cm above the deformable hurdle that marked the 90° knee angle during the squat. At this position, a perturbation of ~100 N was applied by a sharp press with the assessor's hand to the center of the bar. Manual application of force to the bar results in slight variation in perturbation magnitude between trials; however, stiffness is invariant as an elastic system oscillates at its resonant frequency (311). To standardize the protocol as much as possible, the same assessor applied the perturbation and practiced the perturbation method on the force plate.

Subjects were instructed to maintain an isometric position and "to not respond" to the perturbation to limit voluntary input (226, 311, 312). Furthermore, subjects were blinded to the perturbation by visually obstructing them from seeing the bar as per the recommendations of Ditroilo, Watsford, Murphy, and De Vito (313). Back squat perturbation data were not considered during analysis due to the inability to consistently determine the perturbations on the force plate and identify an oscillation pattern.

7.4.8 Musculoarticular stiffness calculation.

Musculoarticular system stiffness (Nm) of the system was determined using methods identical to those previously detailed by Wilson et al. (311) and Ditroilo et al. (313). Calculations were made from the initial damped oscillation cycle recorded. From the oscillation recordings and known constants, stiffness (k) was calculated as:

$k = 4mf^2\pi^2 + c^2/4m$

where m, f, and c represent the mass, damped natural frequency, and damping coefficient. The frequency of oscillation was quantified as the inverse of the period between successive force peaks. The damping ratio (s) was determined by plotting the natural log of force peaks against time, thereby obtaining the slope of the line. The damping coefficient (c) was then calculated as:

$c = 4\ \pi m(f')s$

where the natural frequency is given by:

$(f') = [f^2/(1-s^2)]\ ½$

7.4.9 Data analyses.

The data were analyzed using Matlab 2018a (Massachusetts, USA). First, the raw data were filtered using a low-pass Butterworth filter. The LPT and force plate data were filtered using a cut-off frequency of 8 and 15 Hz, respectively. Cut-off frequencies were determined by residual analysis. The perturbation was identified in the LPT data using a custom peak detection algorithm, which was time synchronized with the force plate data. The force plate data showed racking and un-racking artifacts which made it difficult to identify the perturbation signal correctly. The LPT was added to remove any ambiguity as it identified the 'un-rack,' 'perturbation,' and 're-rack' time points clearly. A second custom peak detection algorithm was used to identify the peaks in the oscillatory force signal (see Figure 7.4A). The first two peaks and their times were used to calculate the slope (Nm/s), period (s), and damped frequency (f_d) (see Figure 7.4B). The stiffness and natural frequency metrics were calculated, as described above.

$$Slope = \frac{Peak\ 2 - Peak\ 1}{Time\ 2 - Time\ 1} = \mathrm{Nm/s}$$

$$Damped\ frequency = \frac{1}{Period}$$

$$f_d = \frac{1}{Time\ 2 - Time\ 1}$$

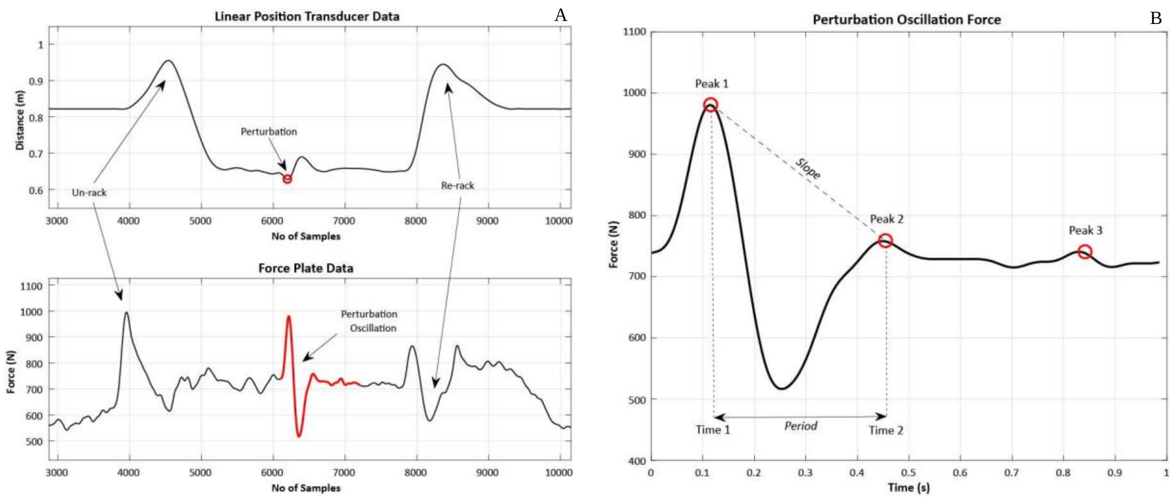

Figure 7. 4. A, linear position transducer signal used to determine perturbation onset. B, peak identification to calculate natural frequency and stiffness.

7.5 Statistical analysis

Reliability was quantified using the methods described by Hopkins (314) to calculate the change in mean (CM) as a percentage fluctuation in the overall mean, coefficient of variation (CV) to quantify the typical error as a percentage of each participant's mean, and, the intra class correlation coefficient (ICC) to indicate the consistency of measures of subjects in relation to their ranking in the group. Reliability thresholds of CV ≤ 10% (315), ICC ≥ 0.70 (316) were used as indicators of acceptable reliability. Two tailed paired t-tests were used to determine significant differences between testing days on the means of each performance variable, with the level of significance set a priori at $p < 0.05$.

7.6 Results

7.6.1 Inertial load bike and medicine ball put

All inertial load and seated medicine ball put variables were observed to be highly reliable (inertial load bike: ICC, 0.69 to 1.00; CV, 1.2 to 5.6%; CM, -2.6 to 2.1%; seated medicine ball put: ICC, 0.82 to 0.95; CV 2.7 to 6.8%, CM -3.7 to 0.7%). No significant difference between days was observed for any of the inertial load bike variables and 3 kg medicine ball put peak velocity and acceleration measures (Table 7.2). However, a significant decrease in 5 kg medicine ball put peak velocity, but not acceleration, was observed from Day 1 to Day 2.

Table 7. 2. Inertial load bike and seated medicine ball output variables mean data.

	Mean ± SD		
Variable	Day 1	Day 2	Day 3
Inertial load bike			
Peak power (W)	1489±347	1449±287	1439±280
Optimal cadence (Rpm)	132.6±6.6	129.3±9.0	131±8.0
Maximum torque (Nm)	201.9±56.6	205.7±53.8	201±50.4
Maximal cadence (Rpm)	264.9±24.6	265.2±25	271±27.1
Seated medicine ball put			
3 kg peak velocity (m/s)	8.0±0.95	7.8±0.8	7.7±0.8
3 kg peak acceleration (m/s^2)	47.4±6.7	45.7±6.1	46.0±6.4
5 kg peak velocity (m/s)	6.7±0.97	6.5±0.69*	6.3±0.71
5 kg peak acceleration (m/s^2)	35.5±5.3	33.0±5.0	32.3±4.3

Notes. SD, standard deviation; rpm, revolutions per minute; * significant differences days 1 – 2.

7.6.2 Bench press

Bench press stiffness data are presented in Table 7.3. The change in mean between days ranged from -35.1 to 15.8%, with a decrease observed from Day 2 to Day 3. No systematic change in CV (range: 16.1 to 111%) or ICC (range: -0.58 to 0.75) between days or across loads were observed.

Table 7. 3. Bench press and bench pull musculoarticular stiffness (Nm) data and reliability metrics across days.

% RM	Mean ± SD			Change in mean (%)		CV (%)		ICC	
	Day 1	Day 2	Day 3	Days 1 – 2	Days 2 – 3	Day s 1 – 2	Days 2 – 3	Day s 1 – 2	Days 2 – 3
Bench press									
15% RM	7858 ± 4254	5129 ± 1138	5295 ± 891	-29.3	4.22	31.4	16.1	0.50	0.53
30% RM	16589 ± 7636	11595 ± 7599	10491 ± 3641	-35.1	1.99	54.2	35.8	0.38	0.65
45% RM	14657 ± 5946	14147 ± 4741	15084 ± 5927	-3.7	7.16	60.1	47.7	-0.58	-0.04
60% RM	-11054 ± 100687	20942 ± 12386	20997 ± 12778	-9.33	-1.81	37.2	45.6	0.75	0.59
70% RM	21678 ± 7211	38314 ± 53393	35520 ± 37430	10.8	15.8	78.1	111	0.43	0.28
Bench pull									
15% RM	8896 ± 4219	7157 ± 2539	7492 ± 1613	-16.0	8.77	27.4	26.7	0.67	0.46
30% RM	17471 ± 6104	15499 ± 4712	13909 ± 2873	-10.2	-8.42	40.6	14.7	-0.15	0.79
45% RM	18871 ± 4996	18436 ± 3774	17960 ± 3313	-1.68	-2.19	19.9	10.3	0.29	0.79
60% RM	21279 ± 3711	21409 ± 2273	18097 ± 4082**	1.46	-16.9	7.07	14.3	0.84	0.50
70% RM	23135 ± 5441	22465 ± 4380	27066 ± 15844	-2.19	11.1	8.38	33.8	0.89	0.24

Notes. SD, standard deviation; CV, coefficient of variation; ICC, intra class correlation coefficient; %RM, percentage of one repetition maximum; ** significant differences days 2 – 3.

7.6.3 Bench pull

Bench pull stiffness data are detailed in Table 7.3. The change in means between days ranged from -16.9 to 11.1%, with no observable systematic change. No systematic change in CV (range: 7.07 to 40.6%) or ICC (range: -0.15 to 0.89) between days or across loads were observed. Only the musculoarticular stiffness measure from the bench pull at 60 and 70% of 1RM between Day 1 and Day 2 demonstrated an acceptable reliability based on the CV and ICC values.

7.7 Discussion

Musculoarticular stiffness is thought an important indicator of performance and tissue adaptation (124, 150, 226). The purpose of this investigation was to establish whether measures of stiffness via the perturbation technique were reproducible using the bench pull, bench press, and squat movements. The main findings were an inability to quantify any stiffness data for the squat movement; and that bench pull and bench press musculoarticular stiffness measures did not meet the pre-established thresholds of acceptable reliability (ICC > 0.70, CV < 10%) across the three experimental days. These findings do not support our hypothesis, yet provide important insights into the use of musculoarticular stiffness testing for upper and lower body movements.

Variability in data between testing sessions can be attributed to several sources, either technological error, biological change, or an inherent variability in the assessment. In the current investigation, force plates and LPT were powered before testing sessions to adjust to ambient conditions, calibrated, and zeroed to reduce technological error. Testing was undertaken 7 days apart at a similar time of day to avoid diurnal fluctuations in performance, with identical warm up performed prior to testing. In addition, to compare contractile state between sessions, maximal inertial load bike and seated medicine ball put measures were taken. A significant decrease in 5 kg medicine ball put peak velocity was noted on Day 2, with no change in any of the other maximal measures. These data would suggest similar muscular and biological status between days. The lack of correspondence between muscular output and musculoarticular stiffness measures between days leads us to conclude that the variability in musculoarticular stiffness can be attributed to the variability in the assessment itself.

This is the first study to our knowledge to attempt to quantify the musculoarticular stiffness associated with the squat movement using a perturbation technique. We were unable to measure stiffness from the squat movement due to an inability to identify an oscillatory pattern at the force plate. The LPT was used to determine the timing of the perturbation as movement in a sinewave on a force plate can be generated without visible change in bar displacement. It would appear that during the squat, the perturbation applied to the bar was dampened through the entire proximal-distal musculoskeletal system to the point that minimal or no sinewave was discernible at the force plate.

Wilson et al. (152) reported test-retest reliability of musculoarticular stiffness to be high for the bench press movement (ICC = 0.89), which contrasts to our bench press data (ICC < 0.70, CV >10%). Similar to Wilson et al. (152) experienced resistance trained subjects were involved in this study; however, we here report raw stiffness data versus predicted stiffness from an exponential curve. We observed greater maximal stiffness than that reported by Wilson et al. (226) (stiffness: 12,015 to 27,677 Nm) however, our stiffness values largely fall within the 10,000 Nm to 50,000 Nm reported in lower body musculature. Participant characteristics may explain our greater stiffness values. The subjects used in this study ranged from trained strength athletes to elite track and field throwers, which likely possess greater stiffness than untrained subjects (317). Alternatively, the large variation in stiffness values may relate to the poor reliability of the method and inability to control for neural input (conscious and reflex) on stiffness.

In our study, the reliability of musculoarticular stiffness values in an upper body pulling type movement (bench pull) was better than that of a pressing type movement (bench press), although both failed to reach the thresholds of acceptable reliability. Stiffness was higher than that previously reported in the literature (152, 226). The nature of the movement and involved tissue affect stiffness (150, 310), which is another likely source of between-study differences. Little data are available regarding pulling movements and musculoarticular stiffness, limiting the ability to make strong inferences. Further research is required to understand physiological elastic variability among tissues involved in pulling movements and throughout the body.

In the context of rotational throwing, elastic return of all involved tissues rather than the return of a particular structure is of importance to the outcome of the movement. Both elastic and contractile structures play an integral role in the storage and transfer of elastic energy during multi-joint movements (318-321). However, most assessments quantifying elastic resonant frequencies and stiffness describe the elastic properties of isolated elastic structures (150, 310). No reliable method to quantify multi-joint elastic properties across the body currently exists in vivo. Quantifying the mechanical properties of elastic structures in compound movements could be of benefit to sports performance; however, as demonstrated by the current study, the ability to repeatedly quantify natural frequency and musculoarticular stiffness in compound upper and lower body movements is poor. Further research should look to refine both bench press and bench pull perturbation protocols, or develop alternative methods to quantify elastic properties of movement patterns non-invasively that can be used to inform strength and conditioning practices. Alternative methods may include measuring natural frequency of individual limbs during compound movement perturbations via accelerometry or perturbing from different locations such as a belt squat during the squat protocol.

7.8 Practical recommendations

These data suggest that quantifying musculoarticular stiffness during a bench press, bench pull, or squat movements is un-reliable across multiple days and loads. Predicting stiffness from a regression curve may increase the reliability because it aids in reducing the impact of outliers on the data; however, the reproducibility of the raw data needs to be improved if practitioners wish to use this method. Familiarization with the protocol beyond 1 session seems to make little difference to reliability. Therefore, changes to the methodology or development of alternative methods are required. Future investigations should seek to refine perturbation protocols to increase the reliability of measures because musculoarticular stiffness has practical implications for strength and conditioning practitioners and sports performance.

Chapter 8

Kinematic and kinetic variability associated with the cable put and seated rotation assessments

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8.0 Prelude

The previous Chapter identified bench press, bench pull, and squat musculoarticular stiffness to be an unreliable assessment. Therefore, these protocols were not used in subsequent studies. Furthermore, it was outside the scope of this PhD to investigate further methods to assess musculoarticular stiffness. In Chapter 5, it was identified that the majority of cross sectional and longitudinal variables that were used to monitor neuromuscular status were non-specific to throwing, lacked ecological validity, and did not include rotational measures. Furthermore, it was established in Chapters 2, 3, and 4 that hip to shoulder separation was an important variable in all throws. During shot put (Chapter 3) specifically, most of the final velocity is gained in the final putting action. There were few practically implementable rotational testing methods sourced from the literature, especially for shot put. Establishing assessment methods to quantify axial rotation and putting ability has practical relevance to athletic training and testing. Therefore, the purpose of this Chapter was to develop and quantify the test-retest reliability of a seated rotation and novel cable put assessment method.

8.1 Introduction

Release velocity of implements is a key factor determining performances in track and field throwing events, such as shotput, hammer, and discus. Release velocity is related to the magnitude of force applied to the implement during the phases preceding release (322). To achieve high release velocities, technical proficiency and high muscular outputs are needed. Release velocity is dependent on the load of the implement, which may subsequently impact reliability of performance (323). Therefore, assessing muscular performance specific to throwing events is important to monitor and enhance performance.

Significant correlations between bench press [r = 0.63 to 0.96, $p \leq 0.05$ (124, 324-328)], back squat [r = 0.33 to 0.93, $p \leq 0.05$ (120, 324-327)], and power clean [r = 0.87, $p \leq 0.05$ (326)] and throwing performances have been reported in trained athletes. Although, Judge et al. (329) reported a quadratic relationship between power clean assessment and throwing performance, and Pilianidis, Mantzoyranis, and Berberidou (330) reported decreases in traditional measures (bench press, back squat, and power clean) as throwing performance increased. Traditional strength assessments may not capture the velocity-specific strength demands required for throwing performance (331). It may be that traditional strength measures have a threshold beyond which further gains do not necessarily enhance performance, whereas more throwing-specific strength measures, which include a rotational component, may be of greater relevance and demonstrate stronger relationships with throwing performance.

Shotput, discus, and hammer throwing all display relative hip to shoulder axial separation to increase the force applied to the implement (4, 332, 333). The final phase of shotput involves a sequential rotational put driven from the legs that accounts for 86% of release velocity (322, 327, 333, 334). Acceleration of the implement is required from low and high velocities; therefore, throwers need to produce forces across the force-velocity spectrum. Testing for shotput, discus, and hammer should involve axial trunk rotation, and testing for shotput specifically should involve a rotational put driven from the lower body. In addition, quantifying the force-velocity characteristics should be useful for characterising performance and developing targeted programs in throws athletes (332, 333).

Currently, testing axial rotation and putting ability off-field has mostly been performed using isokinetic or isometric dynamometry (335-339), and these tests have been found reliable based on ICC [ICC = 0.89 to 0.96 (335-337)]. High reliability of strength-machine based protocols (340) and medicine ball throw assessments has also been reported (ICC = 0.89 to 0.97) (341-343).

The dynamometer based protocols allow for an abundance of data to be collected in a controlled, laboratory-based setting; however, the ecological validity of these measures is limited in elite rotational athletes due to the constrained velocities, positions, and angles (338, 342). The medicine ball protocols are more ecologically valid and easy to administer in a range of settings, but are restricted in the kinematic and kinetic information they provide (340, 344). Furthermore, most studies on this topic have only reported ICCs, which is a measure of relative consistency only. However, retest correlations are sensitive to the spread of values between participants and the reliability of two measures cannot be compared on the basis of their retest correlations alone (345). Therefore, expressing test-retest reliability as a typical error has been recommended for practitioners and scientists because it is a measure of absolute consistency, simpler to grasp and the expected values are independent of sample size (315, 345). The typical error is expressed as raw units or percentages through the CV, with such measures of absolute consistency of considerable value when interpreting measures and changes in measures in practice.

Given the status of research in this area and the outlined limitations, it appears that the development of a rotational load velocity protocol that can assess force and velocity through a shotput specific movement would be valuable to athletes and coaches within rotational track and field throwing. Therefore, the purpose of this study was to determine the test-retest reliability of kinematic and kinetic measures acquired from rotational shotput specific and cable rotation protocols using a range of loads.

8.2 Methods

8.2.1 Participants

Nine rotationally resistance-trained males aged 23.8 ± 3.8 years (mean ± standard deviation); height 179.8 ± 10.2 cm; and mass 91.4 ± 21.0 kg, volunteered to be involved in this investigation. All subjects were free from acute and chronic injury and had not, or were not, using performance enhancing substances (WADA 2016). Resistance trained was defined as "being involved in resistance training for more than one year" and familiar with both rotational and pressing type movements. Prior to participating in this research, all subjects provided written informed consent and all procedures were approved by the Auckland University of Technology ethics committee.

8.2.2 Descriptive data and familiarisation

All subjects attended four testing sessions (1 x familiarisation, 3 x data collection) at the same time of day separated by 5 – 7 days. During the familiarisation session, anthropometric data (age, height, mass) were collected and subjects performed a standardized warm up and practiced both cable put and seated rotation movements (described below). A standardized warm-up was performed that included five minutes of low-level cycling followed by 10 lunges, 10 push-ups, 10 "T-Y-W" movement exercises, and 10 open-book exercises. Each subject was allowed two warm-up sets of five repetitions for both the cable put and seated rotation at perceived intensities of 40% and 60% of maximal exertion. All cable put loads were completed first, followed by all seated rotation loads. The repetitions at each load were performed consecutively. A minimum of

90 seconds of rest was given between loads, and three minutes between movements. During testing, subjects were asked to maintain their normal dietary, hydration, and sleep behaviours, and refrain from intense resistance activity for the 48 hours prior to testing.

8.2.3 Equipment

A multi-purpose cable stack (Fitness Works Inc., Auckland, NZ) was used to collect data. The cable was geared at a 1.8:1.0 gearing ratio; that is for every 1.8 m of cable displacement, there was 1 m of cable stack displacement. Recoil of the cable was controlled via two elastic stoppers set at a height consistent with the end range of motion of the specific movement assessed. A PT5A [Fitness Technologies, SA, Australia] LPT was attached to the top of the first weight plate on the cable stack, with data collection and sampling rates of 1000 Hz controlled via a custom written LabView (National Instruments, Austin, USA) program.

8.2.4 Cable put protocol

The cable height was adjusted to align with the height of each subject's anterior iliac crest when standing. Standing in a self-selected stance width, subjects rotated backwards (countermovement) into the power position. The power position is defined here as the position where the putting hand is tucked into the neck with the elbow flexed and the shoulders abducted. Slight forward rotation of the pelvis was recommended (i.e., slight relative hip to shoulder axial separation) with the trail knee flexed to approximately 100° and body weight located on the ball of foot. Eccentric velocity and range of motion within the countermovement was self-selected. Following the eccentric backwards movement into the power position, an explosive cable put was performed. Cues were given to "lead with the hips" and "put upwards" to mimic the sequence of the shotput movement and put through a 36 to 42° arm plane (Figure 8.1) with maximal effort. Upper loads were determined during pilot testing with potential subjects by an inability to complete the movement and/or visually observed compensatory strategies. Three right-handed (counter clockwise) trials at each of the six loads examined (6, 12, 18, 24, 30, and 36 kg) were recorded, with the average of the three trials used for analysis.

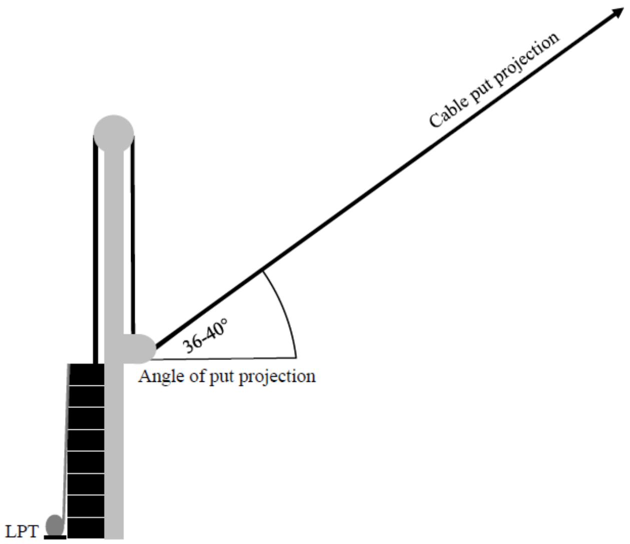

Figure 8. 1. Side view of the cable put setup showing the angle of put and LPT.

8.2.5 Seated rotation protocol

A box modified to fix the hip was secured in front of a line bisecting the two cables (Figure 8.2). This position allowed the sacrum to be on the bisecting line. To create the hip fixation, two adjustable rigid sides were added to the box, and width was adjusted to fit the pelvic width of each individual. The cable was set at a height corresponding to seated shoulder height. Facing forward in an upright position, subjects held the cable handle in two hands with elbows extended. Starting from neutral (i.e., relative rotation 0°), subjects rotated a minimum of 45° towards the cable and then reversed the movement rotating through 90° (i.e., 45° away from the cable) at maximal effort. Range of motion was set by positioning poles corresponding to 45° of rotation bilaterally. Countermovement speed was self-selected and only trials where extension in both arms was maintained were analysed. Trials with less than 45° of rotation or where visible elbow flexion was present were terminated and repeated. Three counter clockwise (dominant side) rotations were assessed at each load (6, 12, 18, 24, 30, 36 and 42 kg). An upper load of 42kg was determined in pilot testing with potential subjects as a load beyond which compensatory strategies were consistently observed.

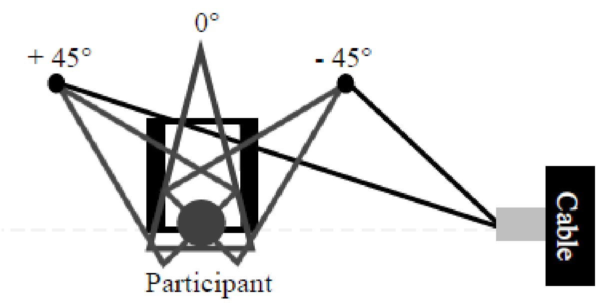

Figure 8. 2. Seated rotation set up.

8.2.6 Methods of repetition determination and kinetic outputs

A custom algorithm was written in MATLAB (v2018a, MA, USA) to analyse the displacement-time data from the LPT. All LPT displacement data were multiplied by 1.8 to account for the 1.8:1.0 gearing ratio.

A peak detection algorithm was used to identify each repetition. Peaks were required to reach 80% of the maximum rotation distance, and multiple peaks within 1 s were counted as a single repetition. The start of the seated rotation was identified by locating the minimum displacement. Displacement, velocity and, acceleration of the rotation was derived for each repetition. Force and impulse at 50, 100, and 200 milliseconds from the start of the rotation were also calculated by inputting cable stack mass. Acceleration was only derived to calculate force (f = ma) and was not reported, however, the reliability of force is reflective of the reliability of acceleration.

8.2.7 Statistical analysis

The data was explored using histogram plots, and normality of the distribution for all variables was tested using Shapiro-Wilk's test. Homogeneity of variance was tested using the Leven's test. Thereafter, descriptive statistics were calculated and reported as mean and standard deviations (SD). Reliability was established by calculating the following statistical measures: 1) absolute change was measured as a CM and expressed as a percentage (%); 2) absolute reliability was measured as a typical error and expressed as a CV ; and 3) relative reliability of subjects' performance in relation to the group was measured using test-retest correlation and expressed as an ICC (314, 346). Thresholds of CV ≤ 10% (315) and ICC ≥ 0.70 (347, 348) were used to denote acceptable reliability levels. Reliability was deemed "poor" when neither CV or ICC values reached their respective thresholds (CV > 10% and ICC < 0.70) and "excellent" when both thresholds were exceeded (CV < 10% and ICC > 0.70). Additionally, to determine whether velocities differed between loads within each movement, velocity data across days was pooled and a percentage change between means was calculated and compared using a paired t-test on the mean data. The level of significance was set a priori at $p < 0.05$ and 95% confidence intervals (CI) were used for all analyses.

8.3 Results

8.3.1 Cable put

Kinematic and kinetic data derived from the LPT are presented in Tables 8.1 and 8.2, respectively. Between session reliability was acceptable across all loads for peak displacement and velocity, as indicated by the ICC (range: 0.92 to 0.99) and CV (range: 3.1 to 8.6%) values. Across days, peak displacement tended to increase with minimal between session changes in peak velocity. No apparent load effect was observed. After pooling the means across days, peak velocity systematically decreased in a significant manner with increasing load intensity (6 to 12 kg, -14.37%; 12 to 18 kg, -17.40%; 18 to 24 kg, -13.00%, 24 to 30 kg, -12.56%; 30 to 36 kg, -23.04%; all $p < 0.01$).

With regard to kinetic variables (see Table 8.2), peak force was found to have acceptable reliability across the majority of loads. Alternatively, impulse tended to show relatively poor absolute reliability (CV = 4.70 to 38.5%) and moderate to excellent relative reliability (ICC = 0.71 to 0.99). No systematic changes between days in the kinetic variables were apparent.

Table 8. 1. Test retest reliability of kinematics derived from the linear position transducer across 6 loads during a maximum effort cable put.

	Mean ± SD			**Days 1 - 2**			**Days 2 - 3**		
Load	**Day 1**	**Day 2**	**Day 3**	**CM (%) (95% CI)**	**CV (%) (95% CI)**	**ICC (95% CI)**	**CM (%) (95% CI)**	**CV (%) (95% CI)**	**ICC (95% CI)**
					Peak displacement (m)				
6 kg	1.50 ± 0.29	1.56 ± 0.37	1.62 ± 0.35	6.02 (-1.18 – 13.8)	7.71 (5.38 – 14.3)	0.92 (0.71 – 0.98)	4.45 (-0.09 – 9.21)	4.81 (3.37 – 8.81)	0.97 (0.91 – 0.99)
12 kg	1.51 ± 0.29	1.67 ± 0.39	1.64 ± 0.39	9.71 (5.44 – 14.2)	4.63 (3.30 – 8.05)	0.97 (0.91 – 0.99)	1.09 (-1.88 – 4.16)	3.20 (2.25 – 5.83)	0.99 (0.96 – 1.00)
18 kg	1.54 ± 0.35	1.61 ± 0.44	1.59 ± 0.43	3.56 (-1.11 – 8.45)	5.40 (3.85 – 9.42)	0.97 (0.91 – 0.99)	2.54 (-1.76 – 7.02)	4.62 (3.24 – 8.46)	0.98 (0.91 – 0.99)
24 kg	1.50 ± 0.30	1.53 ± 0.43	1.55 ± 0.42	0.84 (-6.20 – 8.40)	8.60 (6.11 – 15.2)	0.93 (0.77 – 0.98)	5.65 (1.90 – 9.53)	3.89 (2.73 – 7.09)	0.99 (0.96 – 1.00)
30 kg	1.43 ± 0.32	1.49 ± 0.43	1.45 ± 0.39	3.42 (-1.55 – 8.65)	5.79 (4.12 – 10.1)	0.97 (0.91 – 0.99)	0.09 (-4.61 – 5.03)	5.21 (3.65 – 9.56)	0.98 (0.93 – 0.99)
36 kg	1.35 ± 0.31	1.41 ± 0.38	1.44 ± 0.42	2.04 (-3.16 – 7.52)	5.68 (3.97 – 10.4)	0.97 (0.89 – 0.99)	4.18 (0.97 – 7.50)	3.06 (2.10 – 5.95)	0.99 (0.97 – 1.00)
Mean				**4.27**	**6.30**	**0.95**	**3.00**	**4.13**	**0.98**
					Peak velocity (m/s)				
6 kg	7.65 ± 1.48	7.21 ± 1.39	7.79 ± 1.46	-2.42 (-6.86 – 2.25)	5.05 (3.54 – 9.26)	0.96 (0.84 – 0.99)	8.30 (1.71 – 15.3)	6.85 (4.78 – 12.7)	0.92 (0.73 – 0.98)
12 kg	6.55 ± 1.12	6.75 ± 1.31	6.85 ± 1.29	2.63 (-0.51 – 5.87)	3.61 (2.58 – 6.26)	0.97 (0.91 – 0.99)	3.88 (-1.06 – 9.06)	5.27 (3.69 – 9.67)	0.95 (0.82 – 0.99)
18 kg	5.94 ± 1.21	6.01 ± 1.44	5.99 ± 1.34	0.50 (-3.14 – 4.29)	4.31 (3.07 – 7.48)	0.98 (0.92 – 0.99)	3.50 (-0.27 – 7.42)	4.00 (2.80 – 7.30)	0.98 (0.93 – 0.99)
24 kg	5.33 ± 1.11	5.24 ± 1.41	5.31 ± 1.23	-2.68 (-8.68 – 3.71)	7.53 (5.35 – 13.2)	0.93 (0.79 – 0.98)	6.50 (1.11 – 12.2)	5.64 (3.94 – 10.4)	0.96 (0.87 – 0.99)
30 kg	4.67 ± 1.19	4.79 ± 1.28	4.64 ± 1.17	2.12 (-3.61 – 8.19)	6.81 (4.84 – 11.9)	0.96 (0.86 – 0.99)	0.34 (-3.51 – 4.35)	4.22 (2.96 – 7.71)	0.98 (0.94 – 1.00)
36 kg	4.07 ± 1.09	4.16 ± 1.05	4.21 ±1.20	-0.86 (-6.24 – 4.83)	6.07 (4.24 – 11.2)	0.97 (0.84 – 0.99)	4.13 (-3.85 – 12.8)	7.98 (5.44 – 15.8)	0.96 (0.75 – 0.99)
Mean				**-0.12**	**5.56**	**0.96**	**4.44**	**5.66**	**0.96**

Note. CM, change in mean, CV, coefficient of variation, ICC, intraclass correlation coefficient, SD, standard deviation.

Table 8. 2. Test retest reliability of kinetics derived from the linear position transducer across 6 loads during a maximal effort cable put.

Load	Mean			Days 1 - 2			Days 2 - 3		
	Day 1	Day 2	Day 3	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)
					Peak force (N)				
6 kg	411 ± 98.0	364 ± 62.7	389 ± 87.2	-5.95 (-13.1 – 1.80)	8.7 (6.07 – 16.2)	0.87 (0.58 – 0.96)	5.99 (-3.43 – 16.3)	10.3 (7.18 – 19.3)	0.82 (0.46 – 0.95)
12 kg	609 ± 118	658 ± 155	626 ± 109	7.09 (0.97 – 13.6)	6.93 (4.93 – 12.2)	0.93 (0.77 – 0.98)	0.12 (-10.4 – 11.8)	12.4 (8.58 – 23.3)	0.74 (0.27 – 0.92)
18 kg	825 ± 249	815 ± 256	773 ± 210	-1.68 (-8.71 – 5.90)	8.84 (6.27 – 15.6)	0.94 (0.80 – 0.98)	1.99 (-5.61 – 10.2)	8.51 (5.93 – 15.8)	0.94 (0.79 – 0.98)
24 kg	937 ± 274	900 ± 323	829 ± 211	-5.43 (-13.6 – 3.50)	10.8 (7.68 – 19.3)	0.91 (0.72 – 0.97)	1.66 (-5.04 – 8.83)	7.46 (5.21 – 13.8)	0.95 (0.72 – 0.97)
30 kg	973 ± 352	990 ± 306	864 ± 191	2.23 (-6.27 – 11.5)	10.4 (7.37 – 18.5)	0.92 (0.75 – 0.98)	-5.35 (-13.6 – 3.63)	10.0 (6.98 – 18.8)	0.90 (0.67 – 0.97)
36 kg	1016 ± 354	1000 ± 277	931 ± 176	-3.81 (-9.23 – 1.93)	6.3 (4.41 – 11.6)	0.97 (0.88 – 0.99)	1.26 (-6.13 – 9.23)	7.6 (5.16 – 15.0)	0.91 (0.74 – 0.98)
Mean				**-1.26**	**8.68**	**0.92**	**0.94**	**9.38**	**0.88**
					Impulse $_{0-50}$ (N·s)				
6 kg	7.88 ± 4.62	7.59 ± 3.69	7.49 ± 4.75	-5.67 (-31.0 – 28.4)	38.5 (25.8 – 79.5)	0.71 (0.21 – 0.92)	-6.76 (-24.4 – 15.0)	24.7 (16.9 – 48.8)	0.90 (0.66 – 0.97)
12 kg	12.3 ± 4.81	12.5 ± 6.68	13.6 ± 6.37	-1.96 (-14.6 – 12.5)	17.0 (11.9 – 30.8)	0.91 (0.73 – 0.97)	5.28 (-7.93 – 20.4)	15.2 (10.5 – 29.0)	0.94 (0.80 – 0.98)
18 kg	15.3 ± 6.33	16.0 ± 7.20	17.1 ± 7.31	3.34 (-10.2 – 18.9)	17.3 (12.2 – 31.4)	0.89 (0.66 – 0.97)	4.11 (-9.33 – 19.5)	15.7 (10.8 – 30.0)	0.92 (0.73 – 0.98)
24 kg	19.2 ± 5.82	19.7 ± 6.37	20.6 ± 7.15	2.26 (-4.38 – 9.36)	7.96 (5.66 – 14.0)	0.96 (0.87 – 0.99)	1.68 (-8.97 – 13.6)	12.4 (8.59 – 23.4)	0.91 (0.70 – 0.97)
30 kg	23.0 ± 6.23	23.8 ± 6.48	26.2 ± 7.82	3.65 (-4.84 – 12.9)	10.2 (7.26 – 18.2)	0.91 (0.72 – 0.97)	6.92 (-6.21 – 21.9)	14.8 (10.3 – 28.2)	0.83 (0.47 – 0.95)
36 kg	26.1 ± 3.94	27.4 ± 7.27	29.0 ± 6.03	1.53 (-6.88 – 10.7)	9.56 (6.65 – 17.8)	0.84 (0.51 – 0.96)	1.85 (-11.7 – 17.5)	14.7 (9.96 – 30.1)	0.77 (0.27 – 0.93)
Mean				**0.52**	**16.8**	**0.87**	**2.18**	**16.3**	**0.88**
					Impulse $_{0-100}$ (N·s)				
6 kg	16.7 ± 8.64	16.2 ± 7.25	16.0 ± 9.58	-7.07 (-26.5 – 17.6)	28.2 (19.1 – 56.2)	0.84 (0.50 – 0.96)	-6.38 (-26.2 – 18.7)	28.5 (19.3 – 56.9)	0.86 (0.55 – 0.96)
12 kg	27.4 ± 11.7	27.1 ± 13.6	30.0 ± 14.0	-3.85 (-17.2 – 11.6)	18.6 (13.0 – 33.9)	0.91 (0.72 – 0.97)	6.15 (-10.5 – 25.9)	19.7 (13.5 – 38.1)	0.91 (0.71 – 0.97)
18 kg	32.6 ± 14.5	33.5 ± 14.3	35.3 ± 14.7	2.27 (-11.1 – 17.6)	17.3 (12.2 – 31.4)	0.90 (0.68 – 0.97)	1.99 (-12.4 – 18.8)	17.5 (12.0 – 33.6)	0.90 (0.68 – 0.97)
24 kg	40.4 ± 13.6	41.9 ± 14.5	43.2 ± 15.2	3.67 (-0.46 – 7.96)	4.74 (3.38 – 8.24)	0.99 (0.96 – 1.00)	-0.14 (-11.9 – 13.2)	14.2 (9.79 – 26.9)	0.90 (0.66 – 0.97)
30 kg	47.2 ± 11.5	50.0 ± 14.9	54.2 ± 14.1	4.57 (-3.46 – 13.3)	9.54 (6.77 – 16.9)	0.93 (0.77 – 0.98)	6.29 (-5.47 – 19.5)	13.2 (9.13 – 24.9)	0.87 (0.59 – 0.96)
36 kg	53.4 ± 7.67	57.0 ± 14.1	58.8 ± 12.1	3.47 (-6.12 – 14.0)	10.8 (7.51 – 20.3)	0.79 (0.37 – 0.94)	-1.01 (13.6 – 13.5)	14.1 (9.50 – 28.6)	0.79 (0.31 – 0.94)
Mean				**0.51**	**14.86**	**0.89**	**1.15**	**17.84**	**0.87**

					Impulse $_{0-200}$ (N·s)				
6 kg	30.5 ± 9.73	31.5 ± 13.7	31.7 ± 10.3	-3.62 (-24.6 – 23.1)	29.5 (20.0 – 59.1)	0.72 (0.22 – 0.92)	4.40 (-13.7 – 26.3)	22.3 (15.2 – 43.5)	0.86 (0.55 – 0.96)
12 kg	54.7 ± 21.2	53.0 ± 23.4	60.4 ± 22.7	-5.04 (-16.2 – 7.55)	15.3 (10.7 – 27.5)	0.93 (0.78 – 0.98)	9.53 (-6.68 – 28.6)	18.4 (12.7 – 35.5)	0.91 (0.70 – 0.97)
18 kg	70.7 ± 25.8	70.7 ± 27.8	75.9 ± 27.9	-1.59 (-11.7 – 9.68)	13.2 (9.29 – 23.6)	0.93 (0.78 – 0.98)	3.85 (-10.4 – 20.3)	16.8 (11.6 – 32.3)	0.90 (0.67 – 0.97)
24 kg	92.1 ± 30.7	87.6 ± 30.2	87.8 ± 28.8	-5.24 (-8.98 – -1.34)	4.70 (3.36 – 8.18)	0.99 (0.96 – 1.00)	-3.14 (-16.7 – 12.7)	17.3 (11.9 – 33.2)	0.85 (0.54 – 0.96)
30 kg	100 ± 24.0	105 ± 35.5	109 ± 25.6	1.95 (-6.55 – 11.2)	10.4 (7.40 – 18.5)	0.92 (0.76 – 0.98)	2.11 (-11.5 – 17.8)	16.3 (11.3 – 31.2)	0.82 (0.45 – 0.94)
36 kg	116 ± 18.7	116 ± 24.1	118 ± 23.8	-2.90 (-9.62 – 4.33)	7.87 (5.49 – 14.6)	0.88 (0.61 – 0.97)	-1.34 (-13.1 – 12.1)	13.0 (8.83 – 26.5)	0.78 (0.29 – 0.94)
Mean				**-2.74**	**13.49**	**0.90**	**2.57**	**17.37**	**0.85**

Notes. CM, change in mean, CV, coefficient of variation, ICC, intraclass correlation coefficient, SD, standard deviation.

8.3.2 Cable rotation

For the cable rotation, between session reliability was acceptable for peak displacement and velocity across the majority of loads as indicated by the CV (range: -1.73 to 16.10%) and ICC (range: 0.76 to 0.99) values shown in Table 8.3. Peak displacement and velocity during the 6 kg condition had less than optimal reliability that improved across testing sessions (Table 8.3). Peak velocity systematically decreased in a significant manner with load intensity (6 to 12 kg: -10.09%, 12 to 18 kg: -11.83%, 18 to 24 kg: -13.71%, 24 to 30 kg: -12.99%, 30 to 36 kg: -14.91%, 36 to 42 kg -17.76%, all $p < 0.01$).

With regard to kinetics, peak force demonstrated acceptable reliability across half of the loads and days examined (Table 8.4). Reliability of peak force was less than optimal for a number of days and loads (Days 1 – 2: 6 kg, 24 kg, 30 kg; Days 2 – 3: 12 kg, 30 kg) as shown in Table 8.4. Reliability of impulse showed a mixture of results which tended towards sub-optimal absolute reliability (CV = 3.72 to 27.5%) and poor to excellent relative reliability (ICC = 0.31 to 0.99).

Table 8. 3. Test retest reliability of kinematics derived from the linear position transducer across 7 loads during a seated cable rotation.

Load	Mean			Days 1 - 2			Days 2 - 3		
	Day 1	Day 2	Day 3	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)
					Peak displacement (m)				
6 kg	1.22 ± 0.17	1.29 ± 0.33	1.47 ± 0.29	2.45 (-8.08 – 14.2)	13.2 (9.29 – 23.6)	0.76 (0.37 – 0.92)	16.3 (6.82 – 26.6)	10.2 (7.22 – 18.1)	0.89 (0.67 – 0.97)
12 kg	1.26 ± 0.22	1.29 ± 0.29	1.39 ± 0.28	2.17 (-1.93 – 6.45)	4.79 (3.42 – 8.33)	0.97 (0.89 – 0.99)	7.87 (1.97 – 14.1)	6.62 (4.71 – 11.6)	0.94 (0.82 – 0.98)
18 kg	1.19 ± 0.21	1.26 ± 0.27	1.33 ± 0.28	5.08 (0.40 – 9.98)	5.33 (3.80 – 9.29)	0.96 (0.85 – 0.99)	5.88 (1.21 – 10.76)	5.28 (3.76 – 9.20)	0.96 (0.87 – 0.99)
24 kg	1.15 ± 0.21	1.20 ± 0.26	1.24 ± 0.27	3.52 (0.06 – 7.10)	3.96 (2.83 – 6.87)	0.98 (0.92 – 0.99)	3.79 (-0.59 – 8.36)	5.04 (3.60 – 8.78)	0.97 (0.89 – 0.99)
30 kg	1.13 ± 0.19	1.18 ± 0.26	1.18 ± 0.24	3.03 (-1.21 – 7.46)	4.91 (3.50 – 8.55)	0.97 (0.89 – 0.99)	0.41 (-2.68 – 3.60)	3.64 (2.60 – 6.30)	0.98 (0.94 – 1.00)
36 kg	1.09 ± 0.21	1.12 ± 0.25	1.14 ± 0.23	1.82 (-1.41 – 5.15)	3.74 (2.67 – 6.49)	0.98 (0.94 – 0.99)	2.22 (-1.16 – 5.71)	3.90 (2.79 – 6.77)	0.98 (0.94 – 0.99)
42 kg	1.05 ± 0.19	1.07 ± 0.21	1.09 ± 0.20	1.79 (-0.43 – 4.07)	2.55 (1.83 – 4.41)	0.99 (0.97 – 1.00)	2.09 (0.18 – 4.02)	2.17 (1.55 – 3.74)	0.99 (0.98 – 1.00)
Mean				**2.84**	**5.49**	**0.94**	**5.51**	**5.26**	**0.96**
					Peak velocity (m/s)				
6 kg	4.88 ± 0.69	5.00 ± 1.30	5.53 ± 1.21	-0.07 (-10.6 – 11.7)	13.6 (9.58 – 24.3)	0.76 (0.37 – 0.92)	12.0 (2.51 – 22.4)	10.7 (7.55 – 18.9)	0.89 (0.66 – 0.97)
12 kg	4.63 ± 0.94	4.57 ± 1.05	4.80 ± 1.02	-1.73 (-4.48 – 1.11)	3.30 (2.36 – 5.71)	0.99 (0.95 – 1.00)	5.51 (-0.58 – 12.0)	7.02 (5.00 – 12.3)	0.93 (0.79 – 0.98)
18 kg	4.04 ± 0.82	4.11 ± 0.93	4.37 ± 1.00	1.21 (-1.83 – 4.33)	3.53 (2.52 – 6.12)	0.98 (0.94 – 0.99)	6.50 (1.67 – 11.56)	5.44 (3.88 – 9.48)	0.96 (0.87 – 0.99)
24 kg	3.51 ± 0.87	3.64 ± 0.93	3.86 ± 0.92	3.53 (-0.69 – 7.92)	4.85 (3.46 – 8.44)	0.97 (0.91 – 0.99)	6.34 (2.08 – 10.8)	4.78 (3.41 – 8.32)	0.97 (0.91 – 0.99)
30 kg	3.17 ± 0.85	3.29 ± 0.90	3.29 ± 0.97	3.79 (0.22 – 7.48)	4.07 (2.91 – 7.06)	0.98 (0.95 – 1.00)	-0.51 (-5.78 – 5.06)	6.41 (4.56 – 11.2)	0.96 (0.88 – 0.99)
36 kg	2.78 ± 0.91	2.82 ± 0.96	2.88 ± 0.94	0.87 (-4.48 – 6.52)	6.41 (4.57 – 11.2)	0.98 (0.92 – 0.99)	2.73 (-3.11 – 8.91)	6.90 (4.91 – 12.1)	0.97 (0.90 – 0.99)
42 kg	2.32 ± 0.93	2.40 ± 0.91	2.48 ± 0.83	4.69 (-5.72 – 16.3)	12.7 (8.97 – 22.7)	0.93 (0.77 – 0.98)	4.28 (-0.66 – 9.48)	5.70 (4.06 – 9.95)	0.98 (0.94 – 0.99)
Mean				**1.75**	**6.92**	**0.94**	**5.27**	**6.70**	**0.95**

Notes. CM, change in mean, CV, coefficient of variation, ICC, intraclass correlation coefficient, SD, standard deviation.

Table 8. 4. Test retest reliability of kinetics derived from the linear position transducer over 3 repeated measures across 7 loads during a seated cable rotation.

Load	Mean			Days 1 – 2			Days 2 - 3		
	Day 1	Day 2	Day 3	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)	CM (%) (95% CI)	CV (%) (95% CI)	ICC (95% CI)
					Peak force (N)				
6 kg	265 ± 51.6	260 ± 74.5	309 ± 102	-4.02 (-16.9 – 10.8)	17.8 (12.5 – 32.4)	0.65 (0.16 – 0.88)	18.6 (10.9 – 26.9)	8.00 (5.68 – 14.1)	0.95 (0.85 – 0.99)
12 kg	483 ± 144	455 ± 126	511 ± 174	-5.68 (-11.6 – 0.68)	7.73 (5.49 – 13.6)	0.95 (0.83 – 0.98)	10.9 (0.89 – 21.8)	11.4 (8.04 – 20.2)	0.91 (0.71 – 0.97)
18 kg	591 ± 145	575 ± 148	675 ± 204	-3.25 (-8.24 – 2.00)	6.22 (4.43 – 10.9)	0.95 (0.85 – 0.99)	16.1 (9.10 – 23.5)	7.31 (5.20 – 12.8)	0.95 (0.85 – 0.99)
24 kg	689 ± 261	693 ± 194	829 ± 248	2.28 (-6.54 – 11.9)	10.8 (7.67 – 19.2)	0.90 (0.70 – 0.97)	19.0 (15.7 – 22.5)	3.33 (2.38 – 5.76)	0.99 (0.97 – 1.00)
30 kg	773 ± 230	836 ± 211	880 ± 305	8.47 (-0.96 – 18.8)	10.9 (7.73 – 19.4)	0.88 (0.65 – 0.96)	3.81 (-7.45 – 16.4)	14.0 (9.87 – 25.1)	0.83 (0.65 – 0.96)
36 kg	851 ± 230	849 ± 228	937 ± 252	-0.22 (-5.09 – 4.89)	5.87 (4.18 – 10.3)	0.97 (0.89 – 0.99)	10.5 (5.45 – 15.7)	5.43 (3.87 – 9.47)	0.97 (0.90 – 0.99)
42 kg	907 ± 262	922 ± 251	978 ± 209	1.89 (-3.98 – 8.13)	7.01 (4.99 – 12.3)	0.95 (0.85 – 0.99)	7.24 (0.37 – 14.6)	7.85 (5.58 – 13.8)	0.93 (0.77 – 0.98)
Mean				**-0.08**	**9.49**	**0.89**	**12.3**	**8.18**	**0.93**
					Impulse $_{0-50}$ (N·s)				
6 kg	5.80 ± 1.65	6.49 ± 2.39	7.24 ± 2.14	9.27 (-9.64 – 32.1)	24.2 (16.8 – 44.9)	0.59 (0.06 – 0.86)	13.5 (2.62 – 25.6)	12.2 (8.64 – 21.8)	0.91 (0.72 – 0.97)
12 kg	11.2 ± 3.58	12.6 ± 3.92	12.8 ± 3.05	13.1 (4.50 – 22.5)	9.49 (6.73 – 16.8)	0.94 (0.81 – 0.98)	3.47 (-4.79 – 12.5)	9.96 (7.05 – 17.6)	0.91 (0.72 – 0.97)
18 kg	17.5 ± 6.26	18.8 ± 4.42	18.9 ± 4.14	10.7 (-2.75 – 26.0)	15.9 (11.2 – 28.7)	0.83 (0.51 – 0.95)	1.12 (-9.69 – 13.2)	13.8 (9.71 – 24.7)	0.77 (0.38 – 0.93)
24 kg	22.5 ± 6.26	24.4 ± 6.18	25.6 ± 6.95	9.29 (0.15 – 19.3)	10.5 (7.41 – 18.6)	0.91 (0.72 – 0.97)	4.26 (-4.71 – 14.1)	10.8 (7.65 – 19.2)	0.91 (0.71 – 0.97)
30 kg	25.9 ± 5.54	28.9 ± 8.99	29.5 ± 8.56	9.16 (-3.71 – 23.7)	15.4 (10.8 – 27.7)	0.78 (0.41 – 0.93)	2.04 (-7.04 – 12.0)	11.2 (7.93 – 19.9)	0.92 (0.74 – 0.98)
36 kg	28.6 ± 8.82	31.8 ± 9.37	32.4 ± 8.41	10.7 (1.33 – 20.9)	10.6 (7.49 – 18.8)	0.91 (0.71 – 0.97)	2.77 (-2.94 – 8.81)	6.74 (4.79 – 11.8)	0.96 (0.88 – 0.99)
42 kg	30.9 ± 8.68	35.9 ± 11.5	35.4 ± 10.1	14.9 (2.33 – 29.0)	14.1 (9.97 – 25.4)	0.84 (0.53 – 0.95)	-0.51 (-12.7 – 13.4)	16.1 (11.3 – 29.1)	0.80 (0.44 – 0.94)
Mean				**11.0**	**14.3**	**0.83**	**3.81**	**11.5**	**0.88**
					Impulse $_{0-100}$ (N·s)				
6 kg	13.8 ± 3.62	15.0 ± 5.26	17.3 ± 5.00	6.25 (-14.1 – 31.5)	27.5 (19.1 – 51.6)	0.48 (-0.09 – 0.81)	17.6 (5.50 – 31.1)	13.2 (9.32 – 23.6)	0.89 (0.66 – 0.97)
12 kg	25.5 ± 8.56	27.9 ± 8.75	29.0 ± 6.74	10.0 (2.23 – 18.5)	8.77 (6.22 – 15.5)	0.95 (0.85 – 0.99)	6.42 (-3.13 – 16.9)	11.3 (8.00 – 20.1)	0.88 (0.64 – 0.96)
18 kg	37.9 ± 13.3	41.2 ± 10.4	41.8 ± 9.77	11.4 (-1.69 – 26.3)	15.4 (10.8 – 27.7)	0.86 (0.58 – 0.96)	2.21 (-10.2 – 16.4)	16.0 (11.2 – 28.9)	0.74 (0.32 – 0.92)
24 kg	46.9 ± 12.9	52.7 ± 13.6	54.2 ± 14.9	12.3 (2.93 – 22.4)	10.4 (7.36 – 18.4)	0.92 (0.74 – 0.98)	2.57 (-5.84 – 11.7)	10.2 (7.26 – 18.2)	0.93 (0.77 – 0.98)
30 kg	55.6 ± 13.2	60.3 ± 18.3	60.2 ± 18.2	6.47 (-4.40 – 18.6)	13.1 (9.22 – 23.4)	0.87 (0.61 – 0.96)	0.05 (-8.49 – 9.39)	10.7 (7.58 – 19.0)	0.93 (0.78 – 0.98)
36 kg	60.1 ± 17.8	66.4 ± 19.0	67.8 ± 19.9	9.96 (2.02 – 18.5)	8.93 (6.33 – 15.8)	0.93 (0.79 – 0.98)	2.01 (-5.01 – 9.55)	8.47 (6.02 – 14.9)	0.95 (0.83 – 0.98)

42 kg	64.5 ± 19.4	76.8 ± 25.4	72.8 ± 21.7	17.6 (4.62 – 32.2)	14.3 (10.0 – 25.6)	0.86 (0.58 – 0.96)	-4.06 (-18.4 – 12.8)	20.3 (14.2 – 37.1)	0.70 (0.25 – 0.90)
Mean				**10.6**	**14.0**	**0.84**	**3.83**	**12.9**	**0.86**
					Impulse $_{0-200}$ (N·s)				
6 kg	33.4 ± 6.06	33.7 ± 7.71	40.4 ± 6.36	-0.02 (-15.3 – 18.0)	20.8 (14.5 – 38.1)	0.31 (-0.29 – 0.73)	21.5 (5.74 – 39.5)	17.1 (12.0 – 31.1)	0.47 (-0.11 – 0.81)
12 kg	60.0 ± 14.7	63.1 ± 12.1	69.8 ± 11.6	6.55 (0.10 – 13.4)	7.38 (5.25 – 13.0)	0.94 (0.81 – 0.98)	11.2 (1.94 – 21.4)	10.5 (7.40 – 18.5)	0.78 (0.40 – 0.93)
18 kg	81.1 ± 20.1	88.9 ± 20.2	93.2 ± 14.8	9.91 (-1.53 – 22.7)	13.3 (9.42 – 23.9)	0.84 (0.54 – 0.95)	6.57 (-1.64 – 15.5)	9.58 (6.79 – 16.9)	0.88 (0.64 – 0.96)
24 kg	99.7 ± 25.2	111 ± 30.7	116 ± 29.4	10.5 (1.69 – 20.1)	9.93 (7.04 – 17.6)	0.93 (0.78 – 0.98)	4.73 (-1.35 – 11.2)	7.06 (5.02 – 12.4)	0.97 (0.90 – 0.99)
30 kg	121 ± 28.9	127 ± 35.0	127 ± 33.3	3.61 (-5.55 – 13.7)	11.1 (7.89 – 19.8)	0.90 (0.70 – 0.97)	0.58 (-4.76 – 6.23)	6.43 (4.58 – 11.2)	0.97 (0.91 – 0.99)
36 kg	127 ± 29.2	136 ± 34.2	143 ± 37.1	6.43 (-1.63 – 15.1)	9.40 (6.67 – 16.6)	0.91 (0.72 – 0.97)	5.10 (1.79 – 8.53)	3.72 (2.66 – 6.46)	0.99 (0.96 – 1.00)
42 kg	137 ± 41.9	154 ± 48.3	148 ± 34.8	11.6 (1.14 – 23.2)	11.9 (8.43 – 21.3)	0.90 (0.68 – 0.97)	-1.85 (-15.1 – 13.5)	18.0 (12.6 – 32.7)	0.70 (0.25 – 0.90)
Mean				**6.94**	**12.0**	**0.82**	**6.83**	**10.3**	**0.82**

Note. CM, change in mean, CV, coefficient of variation, ICC, intraclass correlation coefficient, SD, standard deviation.

8.4 Discussion

This study aimed to determine the test-retest reliability of kinematics and kinetics during two rotational-specific strength and power assessments using a range of loads. The main findings for the cable put were: 1) peak displacement and velocity were reliable across loads and between days, and 2) kinetic measures were variable, with peak force being the most reliable kinetic measure across the majority of days and loads compared to impulse. The main findings for the seated rotation were: 1) peak displacement and velocity at loads above 6 kg were reliable across days; 2) reliability was acceptable for peak force across the majority of days and loads; and, 3) early epoch impulse measures were variable across days and loads. Overall, kinematic measures were more reliable between sessions than kinetic measures.

Inter-day reliability of the cable put kinematic variables was acceptable (CV = 3.06 to 8.60%; ICC = 0.92 to 0.99) across all loads and days based on ICC (≥ 0.70) and CV (≤ 10%) thresholds. However, kinetic variables showed much larger ranges in both absolute and relative reliability (CV = 4.70 to 38.5%; ICC = 0.71 to 0.99). Absolute reliability was particularly poor, as indicated by the high CV values, in contrast to the acceptable levels of relative reliability (as indicated by ICC values). Reliability is often based on ICC values that reflect relative relability but not absolute reliability (typical error) (349). Our data show that relative reliability can be acceptable while absolute reliability is not. Absolute reliability may result from learning effects, a change in biological state (e.g. fatigue) or normal biological fluctuation (349). No systematic trends in kinematics or kinetics were observed across testing sessions; therefore, the single familiarisation session was adequate to mitigate learning effects. To remove biological variation associated with diet (350), diurinal variation (351, 352), and fatigue (291), testing was performed at the same time of day and subjects were asked to avoid strenuous activity for 24 hours prior to testing and maintain their regular dietary intake avoiding caffeinated foods prior to testing. Thus, it is likely poor reliability of cable put kinetic measures is associated with random biological fluctuation and systematic error associated with calculating force values from displacement – time data. Further research should look to understand if this is a result of compounding error from integrating acceleration to derive force based measures.

Kinematic measures of the cable-rotation across the majority of loads (12 to 36kg) were mostly reliable between sessions (CV = -1.73 to 13.7; ICC = 0.76 to 0.99), with a few exceptions. More specifically, relative reliability was acceptable (ICC ≥ 0.70) across all loads, days, and kinematic measures. However, absolute reliability was less than adequate (CV > 10%) for peak displacement from 1 of 7 loads across days 1 to 2 and 2 to 3, and for peak velocity from 2 of 7 and 1 of 7 loads across days 1 to 2 and 2 to 3, respectively. The loads associated with less than adequate absolute reliability were the lighest (6 kg) and heaviest (42 kg) of the assessed loads, suggesting that different movement strategies are used at the extremes of the load spectrum to complete the rotational movements. Cable rotation peak velocity in this study was found to have similar ICC to that of rotational medicine ball throws (ICC to 0.89 to 0.97) (341-343) and cable rotations (peak power, ICC = 0.93 to 0.97) (353). However, these investigators did not report CVs or CMs, which give greater insight into the absolute reliability associated with an assessment.

High variability of the cable-rotation kinetic measures across loads and days was observed (CV = 3.33 to 27.5%, ICC = 0.31 to 0.99). In agreement with the kinematic variables, the load associated with poorer reliability was the lightest (6 kg). Similar to our peak force data with loads of 12 – 42kg, Sell, Tsai, Smoliga, Myers, and Lephart (354) demonstrated high relative reliability of peak torque at 60°/s (ICC = 0.89 to 0.91) with poorer absolute reliability (SEM = 12.4 to 13.5% BW) during an isokinetic torso rotation. It is likely kinetic measures, both measured and derived, exhibit less than optimal absolute reliability. Thus, we suggest the use of kinematic, but not kinetic, variables in athlete profiling through the cable rotation assessments and the use of intermediate loads (12 to 36 kg) that exhibit greater between day reliability.

Reliability was acceptable for kinematic, but not kinetic, variables during both cable put and cable rotation assessments. The disparity between the reliability of kinematic and kinetic measures is likely a function of 1) error associated with calculations of force using second derivatives (acceleration) of the measured variables (positon and time), and 2) early force time measures being unreliable. Peak velocity derived from LPT data has been shown reliable across loads during barbell based movements (355, 356); however, few have reported kinetics. Garnacho-Castaño, López-Lastra, and Maté-Muñoz (357) and Andre et al. (353) reported acceptable relative reliability of LPT derived peak power [ICC: 0.92 to 0.97 (353, 357)] and mean power [ICC: 0.97 to 0.98 (357)] similar to our peak force findings (ICC: 0.82 to 0.99). However, Garnacho-Castaño et al. (357) reported similar absolute reliability of peak (CV: 13.0 to 13.2%) and mean (CV: 10.7 to 10.9%) power to that of peak force in the current investigation (CV: 3.3 to 17.8%), altogether suggesting caution in the interpretation of kinetic measures derived from displacement time data.

With regard to early force time measures, our data indicate poor absolute reliability of impulse at early epochs across the majority of days and loads. Similarly, Palmer, Pineda, and Durham (358) reported poor absolute reliability (CV: 12.3 to 55.9%) of measured, rarther than derived, early rate of force development (RFD 0 – 30, 0 – 50, 0 – 100, 0 – 200 ms) during a squat. Collectively, these data also suggest early force time measures within constrained epochs are not repeatable across days. As such, practitioners should use caution when interpreting early force time measures to guide athlete assessment and monitoring. However, readers should be cognizant that the recommendations provided are based on a relatively small sample size in resistance trained males, and further research using the cable rotational assessment protocols described in this study is required to either clarify these findings or extrapolate these results to other populations. Additionally, these are novel assessment protocols and future research should aim to compare these movements with actual throwing performance to better understand the utility of cable rotational assessments for throws athletes.

8.5 Conclusions

Based on preset thresholds, the relative and absolute reliability of kinematics during our novel cable put and cable rotation assessment protocols are acceptable across multiple loads and days, although load selection should be considered during cable rotations as very light or very heavy loads have the potential to negatively influence reliability. Relative reliabilty of kinetic measures was overall acceptable across loads and days; however, absolute reliability was often poor. As such, although kinematic variables are repeatable and can be appropriate in athletic throws testing and training, kinetic variables are not. Our findings suggest that strength and conditioners, physiotherapists, and coaches can use kinematic variables with confidence to assess cable shot and/or rotation abilites across days in resistance trained males. The apparent ecological validity of the cable put and seated rotation movements to shotput and rotational throws does not infer a causal relationship to performance. Future researchers should determine if changes in these measures correlate to changes in throwing performance.

Chapter 9

Reliability of manual digitisation of seated shot put kinematics with reduced camera numbers

9.0 Prelude

The previous Chapter investigated the reliability of cable rotation and cable put assessments. As a result of peak velocity displaying acceptable reliability, these assessments can be included in testing batteries that assess rotational and putting ability in athletes and will be used going forward in this thesis. Like neuromuscular testing methods, the reliability of biomechanical testing needs to be established prior to its inclusion in testing batteries. Specifically, biomechanical data are often derived from manually digitised video. The reliability of the movement itself and of the digitiser needs to be quantified. As demonstrated in in Chapters 2, 3, and 4, the video data capture methodologies within the literature were varied. As such, the reliability of the capture methods used in this thesis needed to be established to understand the comparability of data and generalisation of research findings. Thus, the purpose of this Chapter was three-fold: 1) to understand the reliability of the kinematics of a seated medicine ball put assessment; 2) to quantify the intra-digitiser error; and, 3) to quantify the effect of reducing camera numbers on seated medicine ball put kinematics. This information was to be used for refining the biomechanical analyses in Chapters 10, and Chapters 11 and 12 that involved case studies.

9.1 Introduction

Throwing event performances are determined by the ability to generate high implement velocities through the release phase. In research and high-performance sport settings, biomechanists use three dimensional analyses to quantify kinematics through the entire throwing motion or to extract data from specific time points (e.g., release). To generate such data from field environments and at competitions, biomechanists typically film each event and digitise cinematographic films (34, 65, 66, 95, 96). Several iterations of cinematographic capture set-ups have been employed in track and field throwing. Commonly two cameras sampling at frame rates of 25 to 60 Hz (5, 25, 38, 66, 94, 100, 102, 104) are used. However, when analysing athletic movements, using frame rates of less than 50 Hz likely lead to errors in data, for instance, missed events (93). In addition to frame rate, the use of appropriate shutter speeds and aperture is needed to generate clear images, which are set relative to lighting conditions and selected frame rates (93).

To generate three dimension coordinates from cinematographic analyses, the object of interest must be visible within the field of view of two cameras at all times, with the use of more cameras suggested to increase accuracy (359). Track and field researchers commonly record shot put, discus, and hammer using two (5, 8, 36, 38, 45, 63, 66, 74, 95, 97, 104) to three (7, 30, 44, 66) cameras placed orthogonally from each other to retrospectively manually digitise objects and points of interest for biomechanical analyses.

Cinematographic film digitisation in the absence of markers relies on the subjective and manual localisation of points (93). Points of interest in throwing are generally the implement or human joint centres; therefore, the movement and size of the object can influence results. The digitisation of visually observable points like markers are subject to small errors due to fluctuations in localising the centroid (93). For example, Badura (45) reported a 0.4 to 1.05% change between manually digitised and spirit level angles from a two camera set-up, suggesting there is minimal error in quantifying kinematic outputs. In practise, the localisation of points of interest are more subjective in nature, as joint centres are underneath the skin and the centroid of larger objects are located within a larger silhouette. Additionally, the effect of camera numbers on manually digitised measures from cinematographic film needs to be considered and quantified. As such, the purpose of this investigation was to determine: 1) test-retest reliability of manually digitised measures from a medicine ball thrown maximally during a seated shot put, 2) intra-rater reliability of these measures, and 3) effect of camera numbers on kinematic measures.

9.2 Methods

9.2.1 Participants

Nine resistance-trained males (mean ± standard deviation, age: 23.8 ± 3.7 years; height: 180.4 ± 10.8 cm; and mass 90.1 ± 19.6 kg) free from acute and chronic injury were recruited for the purposes of this investigation. Resistance trained was defined as "being involved in resistance training twice per week for more than one year", and familiar with both rotational and pressing type movements. Participants commonly performed medicine ball throws as part of their resistance training programs for their respective sports. All participants had not or were not using performance enhancing substances (WADA 2016). All procedures were approved by the Auckland University of Technology ethics committee (16/438).

9.2.2 Procedures

All participants were required to attend four testing sessions (1 x familiarisation, 3 x data collection) at the same time of day separated by 5 to 7 days. During the course of testing, participants were asked to maintain their normal dietary, hydration, and sleep behaviours, and refrain from intense resistance activities for the 48 hours prior to testing. Figure 9.1 depicts the timing of testing and re-digitisation occasions. The test-retest reliability of measures was determined from comparing the 3 data collection sessions completed by each athlete. To test intra-rater reliability, an experienced researcher digitised all films from one load again 6 months after the first digitisation session. To determine the effect of camera numbers on kinematic measures, the same films were digitised again using two instead of three camera views 4 months following the second digitisation occasion (Figure 9.1).

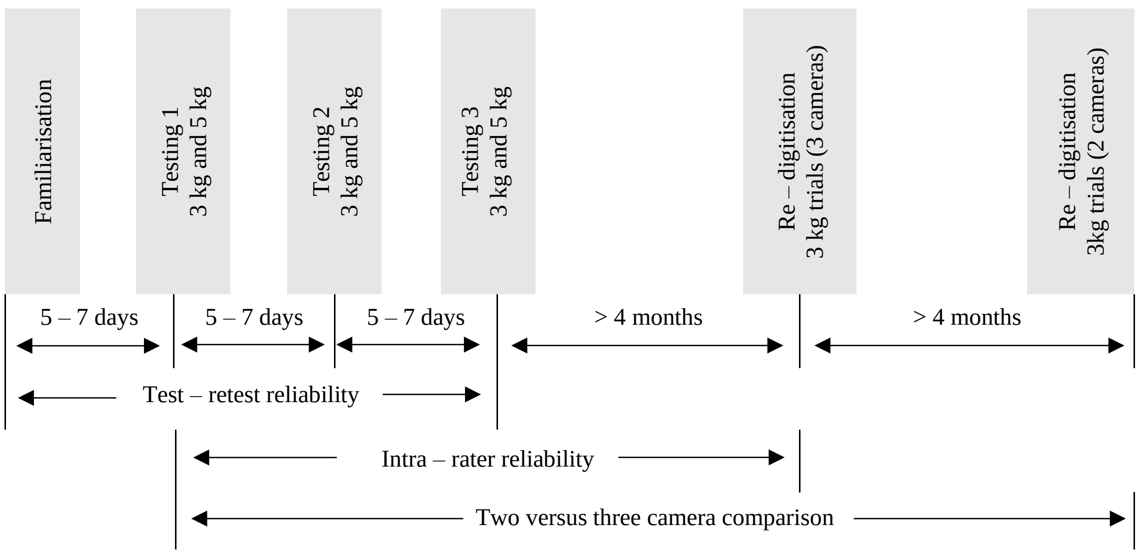

Figure 9. 1. Flow diagram of experimental procedure depicting the relative timing of testing and digitisation occasions.

9.2.3 Equipment

All testing was performed indoors in the HPSNZ – Athletics New Zealand throws room with ambient atmospheric conditions controlled at 22 °C. Athletes were recorded using three (posterior, laterally, and superior) Vision Prosilica GX1050C cameras sampling at 70 frames per second (Hz) with shutter speeds of 1/1000 (Figure 9.2, cameras 1 to 3). Table 9.1 shows the positions of the cameras in an X - Y - Z coordinate system and the throwing circle, where the X-axis is orientated in the anterior-posterior plane, Y-axis in the medial-lateral plane, and Z-axis in the superior-inferior plane. Positive signs represent anterior (towards the throwing direction), laterally to the right, and superior orientations.

Table 9. 1. Camera positions relative to the center of the throwing circle.

	X (mm)	Y (mm)	Z (mm)
Camera 1 (Superior)	-24	-58	5042
Camera 2 (Posterior)	4173	-56	998
Camera 3 (Lateral)	16	-3747	992

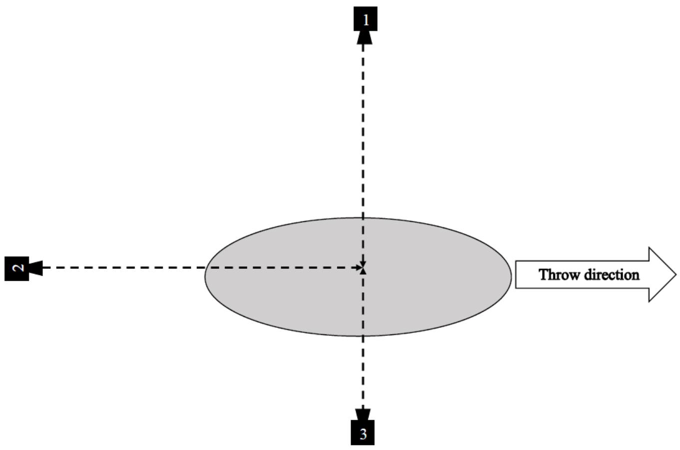

Figure 9. 2. High Performance Sport New Zealand – Athletics New Zealand throws room. Cameras 1 (superior), 2 (posterior), and 3 (lateral) are positioned roughly perpendicular to one another.

9.2.4 Warm-up

On arrival to the laboratory, a standardised warm-up was completed that included 5 minutes of low level cycling followed by 10 lunges, 10 push-ups, 10 “T-Y-W” movement exercises, and 10 open-book exercises. Two warm-up 3 kg seated puts were completed prior to the first 3 kg medicine ball load experimental trial during which maximal efforts were encouraged.

9.2.5 Seated medicine ball put

Participants were strapped into a seat that restricted hip rotation with non-extensible Velcro straps. Hip rotation was restricted by two rigid sides extending 160 mm vertically and 510 mm posteriorly, which extended above and beyond the length of the femur of all participants. To restrict anterior-posterior sliding of the hip, participants were strapped to the box using a Velcro strap around the lower limb. Participants used both hands to secure the medicine ball into the dominant side of their neck during the preparation phases of the put. Starting in a forward facing direction, participants rotated away, moving eccentrically prior to a maximal concentric rotation to put the ball into a hanging target positioned 5 m away. Three trials following two warm-up throws with the 3 kg load were collected at both a 3 and 5 kg medicine ball loads. Loads of 3 and 5 kg were chosen as they are concurrent with previous literature (360, 361).

9.2.6 Digitisation

Manual digitisation was performed using custom written software (HPSNZ portable tracker™, Auckland, NZ). Cameras were electronically synchronised from the start of filming. The centre of the medicine ball was manually digitised in all frames from the start of the concentric movement (two frames after the presence of obvious forward movement of the medicine ball) until the first frame in which the participant visibly lost contact with the ball in all camera views (finish time). A least squares calculation generated each point within the calibrated space from which velocity was outputted into a comma separated file. To compare two and three camera set-ups, the superior view camera (camera 1, Figure 9.2) was removed from the third digitisation occasion. The superior view was removed as track and field research commonly uses two cameras, one posterior and one lateral view (8, 65). Velocity data were filtered at 8 Hz using a Butterworth bi-directional low pass filter, cut off frequency was determined by residual analysis (362).

Acceleration (peak and mean), acceleration$_{50\text{-}100}$, concentric duration (Concentric duration = finish time – start time), and start time values were extracted from each put. Acceleration$_{50\text{-}100}$ was calculated as the mean acceleration from the time when 50% of the peak velocity was reached until the time the medicine ball reached peak velocity (i.e., acceleration from 50 to 100% of peak velocity). All throws were manually digitised by the same researcher. On average, two of the three experimental trials per athlete were digitised, using the best two trials or the two that had no more than two missing frames. Best trials were determined by either greatest velocity attained when all frames were present or by the trials with the least missing frames. The start of the concentric movement was set at two frames following the frame at which an obvious forward movement of the medicine ball was observed. This frame was chosen as it was observed that consistent forward movement from this frame onwards was observed in all videos. Finish time set as the first frame in which the participant visibly lost contact with the medicine ball.

9.2.7 Statistical analysis

Means and standard deviations (SD) were used as measures of centrality and spread of data. Reliability was established by calculating the following statistical measures: 1) CM was absolute change expressed as a percentage, 2) CV expressed as a percentage of each participant's mean as a typical error measure, and 3) ICC as a relative reliability measure (346). Thresholds of CV ≤ 10% (315) and ICCs ≥ 0.70 (316) were used to denote acceptable reliability.

To compare two and three camera configurations percentage change between means was calculated and a paired t-test was performed to identify significant differences in mean data. The level of significance was set *a priori* at $p < 0.05$. All analysis was performed in Microsoft excel (2016).

9.3 Results

9.3.1 Test-retest reliability

Seated shot put mean ± SD data and reliability statistics across loads are presented in Table 9.2. Peak velocity, peak acceleration, and acceleration$_{50\text{-}100}$ exhibited excellent reliability between all testing occasions at both 3 kg (CV = 2.7 to 8.2%, ICC = 0.82 to 0.90) and 5 kg (CV = 4.0 to 8.4%, ICC = 0.82 to 0.90) loads. On the other hand, the reliability of mean velocity measures across loads was less than acceptable (ICC > 0.70), with peak velocity and acceleration$_{50\text{-}100}$ at both loads decreasing across days (Table 9.2).

Table 9. 2. The test-retest reliability for seated shot put kinematics.

	Mean ± SD			CM (%)		CV (%)		ICC	
	Day 1	Day 2	Day 3	Day 1-2	Day 2-3	Day 1-2	Day 2-3	Day 1-2	Day 2-3
				3 kg medicine ball					
Peak velocity (m/s)	8.01 ± 0.95	7.82 ± 0.78	7.69 ± 0.77	-2.26	-1.70	4.48	2.75	0.87	0.95
Peak acceleration (m/s^2)	47.4 ± 6.70	45.6 ± 6.06	46.0 ± 6.42	-3.75	0.69	5.13	6.75	0.90	0.82
Mean acceleration (m/s^2)	22.2 ± 2.53	22.4 ± 3.89	20.9 ± 2.56	0.08	-6.19	10.3	10.2	0.60	0.65
Acceleration$_{50\text{-}100}$ (m/s^2)	33.9 ± 4.49	27.9 ± 4.93	26.9 ± 4.60	-18.2	-3.25	7.67	8.15	0.82	0.84
				5 kg medicine ball					
Peak velocity (m/s)	6.66 ± 0.87	6.53 ± 0.69	6.34 ± 0.71	-1.74	-3.01	5.69	4.02	0.82	0.90
Peak acceleration (m/s^2)	35.5 ± 5.25	33.0 ± 4.98	32.3 ± 4.25	-6.81	-2.08	5.57	6.05	0.90	0.86
Mean acceleration (m/s^2)	15.7 ± 2.62	15.8 ± 2.56	15.0 ± 1.38	0.43	-3.81	13.5	8.51	0.51	0.71
Acceleration$_{50\text{-}100}$ (m/s^2)	23.6 ± 4.03	19.1 ± 4.20	17.9 ± 3.96	-19.5	-6.25	8.38	7.96	0.87	0.91

Notes. Acceleration$_{50\text{-}100}$ = acceleration from 50 to 100% of peak medicine ball velocity, CM = change in mean, CV = coefficient of variation, ICC = intra-class correlation coefficient, SD = standard deviation.

9.3.2 Intra-rater reliability

Results from the intra-rater manual digitisation assessment are presented in Table 9.3. Regarding intra-rater reliability, all variables of interest were reliable (CV < 10%, ICC > 0.70).

Table 9. 3. Intra assessor digitisation reliability.

	Mean ± SD		CM (%)	CV (%)	ICC
	Day 1	Day 2	Day 1 - 2	Day 1 - 2	Day 1 - 2
Peak velocity (m/s)	8.01 ± 0.95	7.85 ± 1.05	-2.10	2.87	0.96
Peak acceleration (m/s^2)	47.4 ± 6.70	46.2 ± 7.05	-2.76	2.51	0.98
Mean acceleration (m/s^2)	22.2 ± 2.53	24.3 ± 3.34	9.49	5.15	0.87
Acceleration$_{50-100}$ (m/s^2)	33.9 ± 4.49	32.5 ± 5.51	-4.54	4.98	0.92
Start time (s)	2.35 ± 0.50	2.40 ± 0.50	2.12	0.76	1.00
Finish time (s)	2.69 ± 0.50	2.69 ± 0.50	0.08	0.12	1.00
Duration (s)	0.34 ± 0.05	0.30 ± 0.06	-13.7	4.40	0.95

Notes. ICC = intra-class correlation coefficient, SD = standard deviation, CM = change in mean, CV = coefficient of variation, Acceleration$_{50-100}$ = acceleration from 50% of peak medicine ball velocity to peak velocity.

9.3.3 Effect of camera numbers

Changes in kinematics between two and three camera views are reported in Table 9.4. Peak velocity and acceleration were similar between the two and three camera digitisations, however significant differences ($p < 0.05$) were observed between all other variables.

Table 9. 4. Change in mean between digitisation and camera number.

	(Mean ± SD)			
	3 cameras	2 cameras	CM (%)	p value
Peak velocity (m/s)	8.01 ± 0.95	7.89 ± 0.90	-1.5%	0.177
Peak acceleration (m/s^2)	47.4 ± 6.70	47.3 ±6.41	-0.3%	0.803
Mean acceleration (m/s^2)	22.2 ± 2.53	24.5 ± 3.43	10.6%	0.002
Acceleration$_{50-100}$ (m/s^2)	33.9 ± 4.49	30.6 ± 4.89	-9.6%	0.001
Start time (s)	2.35 ± 0.50	2.41 ± 0.50	2.6%	0.000
Finish time (s)	2.69 ± 0.50	2.69 ± 0.50	0.2%	0.049
Duration (s)	0.34 ± 0.05	0.27 ± 0.08	-20.1%	0.001

Notes. ICC = intra-class correlation coefficient, SD = standard deviation, CM = change in mean, CV = coefficient of variation, Acceleration$_{50-100}$ = acceleration from 50 to 100% of peak medicine ball velocity.

9.4 Discussion

The purpose of this study was to investigate the reliability of seated shot put kinematics acquired using manual digitisation methods over repeated testing occasions using 3 and 5 kg medicine ball loads, and the effects of camera numbers on measures. The main findings were: 1) seated shot put kinematics are reliable between days (CV = 2.7 to 8.4%, ICC = 0.82 to 0.90); 2) intra-rater reliability is acceptable for kinematics and temporal parameters (CM = -4.74 to 9.49%, CV = 0.12 to 4.98%, ICC = 0.87 to 1.0); and, 3) peak kinematic measures are similar when digitised with two versus three cameras (-1.5 to -0.3%, $p > 0.05$), whereas mean kinematic and temporal parameters significantly differ (-20.1 to 10.6%, $p < 0.05$).

Peak velocity, peak acceleration, and acceleration$_{50–100}$ (i.e., mean acceleration from 50 to 100% of peak velocity) measures were reliable in this study when digitised from a three-camera set-up between days. Previous literature has demonstrated similar test-retest reliability of distance [ICC: 0.88 to 0.996 (363, 364)] and peak velocity [ICC: 0.83 to 0.93, CV: 3.2 – 3.3% (365, 366)] measures during medicine ball throws. Sayers and Bishop (366) demonstrated similar reliability of peak acceleration (ICC: 0.91 to 0.95, CV: 4.8 to 5.3%) to that of the current investigation, and reliability of time to peak velocity (ICC: 0.87 to 0.93, CV: 2.6 to 4.0%) when medicine ball throws were measured using optical-electric systems.

We chose to investigate the reliability of acceleration from 50 to 100% of peak velocity given that this metric reflects the ability to produce force at velocity, which is of interest in throwing events. The present results have practical implications as a more complete set of kinematic data extending beyond distance and peak velocity measures are reliable from readily available, practical equipment. Intra-rater digitisation reliability reached acceptable thresholds within the current investigation, except for the duration of the concentric movement. Ugbolue, Papi, Kerr, Earl, and Pomeroy (367) reported similar intra-rater reliability of limb velocity (ICC: 0.97 to 1.00) in healthy individuals and stroke survivor patients during gait; however, in contrast to the current investigation, temporal variables (step time) were shown as reliable. Step times are based on foot-ground contacts and are more easily detectable than perceived forward movements during a seated shot put throw. Furthermore, throwing compared to walking movements are performed much quicker, which can also explain the lower reliability of time-point determination. Recent biomechanical reports from the IAAF athletics world championships suggested low intra-rater errors (60); however, no objective data or statistical results were presented, limiting the ability to compare findings with our findings or prior investigations (60, 367, 368).

The lower reliability determined for the duration of the concentric put movement was moreover due to errors arising from onset determination (start time) than release (finish time), as can be seen in Table 9.3. The determination of concentric onset in the current investigation was set at two frames following that where a visible forward movement of the medicine ball was seen. The rater found it difficult to determine concentric onset at low velocities as there was minimal visual differentiation in movement between frames; thus, it is likely that concentric onset at higher movement velocities would be more accurate.

Two camera configurations are commonly used in track and field events (5, 63, 66, 95, 97), making it important to understand the comparability between kinematics derived from two and three camera views. No changes in peak variables were observed between camera numbers, but significant differences in all remaining variables were detected. That said, although a significant difference in finish time was observed (Table 9.4), the magnitude of the difference did not affect the overall mean at two decimal places. Such results suggest that peak kinematic data derived from either two and three cinematographic cameras are comparable, as are release times.

9.5 Conclusion

Kinematic measures from the manual digitisation of seated shot put movements are reliable for assessing upper body putting ability, especially when considering peak velocity and acceleration values. However, the subjective nature of cinematographic film digitisation lends itself to errors in detecting the onset of movement that disrupts selected kinematic parameters. Lastly, peak kinematic data derived from two and three camera configurations are comparable. Practitioners can therefore use two and three camera set-ups, as in the current investigation, relatively interchangeably to generate comparable peak kinematic parameters when digitising implements.

Chapter 10

Brief report: Seated medicine ball put kinematics are related to both bench press and bench pull bar velocities across multiple loads

10.0 Prelude

From the previous Chapter we concluded that the seated shot put was a reliable assessment and that there was very little change in kinematic outputs when digitised on multiple occasions. Furthermore, kinematics digitised in two versus three camera set-ups were comparable suggesting kinematics derived from varying camera setups as detailed in Chapters 2, 3 and 4 are comparable. A primary conclusion of Chapter 5 was that limited information was available in reference to resistance training in rotational throwing. With regards to the upper body and throwing performance, the bench press was advocated to enhance putting ability (Chapter 5). No measure of upper body pulling performance and its relationship to throwing performance had been documented across throws. Furthermore the lack of ecological validity of the bench pull to throwing (primarily a pushing movement) makes justification into a testing battery difficult. Thus, the primary purpose of this investigation was to understand the relationship between bench pull and putting performance. Given the high reliability of seated medicine ball put kinematics documented in Chapter 9 in resistance trained non throwers it seemed an appropriate test to assess putting ability. The results of this investigation would provide justification to the coach as to its inclusion into the subsequent case studies Chapters.

10.1 Introduction

Throwing events are determined by the ability to generate high implement velocities during the release phase. To generate high release velocities during the putting motion, strength and conditioning coaches and researchers have focused on increasing bench press maximal strength (1RM), as generally a consensus exists that increases in bench pressing kinematics and kinetics result in an increase in putting velocity (83, 84, 118, 124, 164, 324, 369). Terzis et al. (83) investigated the relationship between front on seated shot put and bench press velocity and reported strong correlations ($r = 0.78$ to 0.94, $p < 0.01$) between light load bench press throw height and throwing distance. However, the relationship between bench press velocity across a spectrum of loads and putting kinematics, specifically velocity and acceleration, have yet to be investigated.

The similarities between pressing and putting are apparent, thus one would expect a positive association between motions according to the principle of specificity. However, the rotational aspect of the putting motion in practise likely requires the development of large pulling, not only pressing, forces. McGill (370) demonstrated the latissimus dorsi to be most active during standing axial rotation, the findings of which have since been corroborated by others (371, 372). Additionally, Harasin et al. (63) and Dapena et al. (53) suggested that during the put or throw, the lead arm pulls into the release position, stretching the throwing side and resulting in greater force application to the implement. However, strength coaches and researchers have yet to report measures of absolute pulling strength or bar velocity during a pulling motion and their relationship to putting performance. Both horizontal shoulder extension and latissimus dorsi activation can be assessed through a bench pull. Indeed, Wattanaprakornkul, Halaki, Cathers, and Ginn (373) reported high activation of the latissimus dorsi through a bench pull type movement. Of interest to strength coaches and athletes, therefore, is whether there is any association between the bench pull and putting performance. The presence of such an association would affirm the importance of pulling strength in shot putters and the incorporation of resistance training practises targeting relevant muscles.

A better understanding of the relationship between shot putting kinematics and bench press and bench pull would inform resistance training practices of throwing athletes. The purpose of this study was to understand the relationship between seated medicine ball put kinematics, specifically velocity and acceleration metrics, and bench pull and bench press bar velocities across multiple loads.

10.2 Methods

10.2.1 Participants

Nine resistance-trained males (mean ± standard deviation, age 23.8 ± 3.7 years, height 180.4±10.8 cm, and mass 90.1 ± 19.6 kg) free from acute and chronic injury were recruited for the purpose of this investigation. Resistance trained was defined as being able to bench press and bench pull greater than their body mass and familiar with medicine ball throwing activities. All participants regularly performed medicine ball throws as part of their individual sports training. All participants had not or were not using performance enhancing substances (WADA 2016), and all procedures were approved by the Auckland University of Technology ethics committee.

10.2.2 Descriptive data and familiarisation

All participants were required to attend two testing sessions (1 x bench press and bench pull data collection, 1 x seated medicine ball put data collection) at the same time of day separated by 5 to 7 days. The first testing session involved the collection of anthropometric data (age, height, and mass), completion of a standardised warm up, collection of bench pull and bench press data, and familiarisation to seated medicine ball put. The second testing session involved the completion of a standardised warm up and collection of the seated medicine ball put data. All participants were highly trained and regularly performed bench throws, bench press, and bench pull movements as part of their athletic training programmes. During the course of the testing, participants were asked to maintain their normal dietary, hydration and sleep behaviours and refrain from intense resistance activities for the 48 hours prior to testing.

10.2.3 Warm-up

On arrival to the laboratory, a standardised warm-up was completed that included 5 minutes of low-level cycling followed by 10 lunges, 10 push-ups, 10 “T-Y-W” movement exercises, and 10 open-book exercises. Prior to the medicine ball trials two warm-up 3 kg seated puts were completed prior to the first 3 kg medicine ball load experimental trial during which maximal efforts were encouraged.

10.2.4 Bench pull

A countermovement bench pull consistent with the methods described by Sanchez-Medina et al. (307) was performed with the exception of the use of the Smith machine. Lying prone on a high-pull bench, a grip position consistent with that of the bench press was replicated via bar markings. The first repetition started in elbow flexion in order for each repetition to be a countermovement. Therefore, the bar was lowered to an extended arm position followed immediately by a row into the bench making contact with a point coinciding with the xyphoid process. The bar was then lowered for the ensuing repetition that was immediately performed. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xyphoid process due to the steel frame. Cues were given to contact the bench as forcefully as possible and only trials where contact was made were counted. Trials during which the chin, chest, or hips lifted off the bench were terminated and repeated. Each participant performed 3 repetitions at each of the set loads (20, 30, 40, 50, and 60 kg) following which additional loads were added to establish 1RM. The 1RM load was established within 3 to 5 load increments and full recoveries (more than 2 minutes) between all attempts and sets were given. Absolute rather than relative loads were used during both bench pull and bench press movements as we believe them to be more concurrent with track and field throwing.

10.2.5 Bench press

A countermovement bench press was employed to record bench press efforts consistent with previous methods (226, 240, 306). Lying supine on a bench press apparatus, the bar was lowered to the chest at a self-selected speed, followed immediately by a concentric press (1RM test) or throw (during loads at 20, 30, 40, 50, and 60 kg).

Prior to the execution of the bench press and bench pull, grip width was set lying supine on the bench with the elbows at 90° of flexion and shoulders at 70° of humeral abduction (referenced from the anatomical position). Grip width was recorded and marked with tape. Trials during which the head, shoulders, hips, or feet lost contact with their respective surfaces were disregarded and repeated. Additionally, light contact with the chest, roughly level with the nipples, was cued. Bouncing of the bar resulted in disregarding and repeating trials. Each participant performed 3 repetitions at each of the set loads (20, 30, 40, 50, and 60 kg) following which additional load was added to establish 1RM. The 1RM load was established within 3 to 5 load increments and full recoveries (more than 2 minutes) between all attempts and sets were given.

10.2.6 Seated medicine ball put

Participants were strapped into a seat that restricted hip rotation with non-extensible Velcro straps. Hip rotation was restricted by two rigid sides extending 160 mm vertically and 510 mm posteriorly, which extended above and beyond the length of the femur of all participants. To restrict anterior-posterior sliding of the hip, participants were strapped to the box using a Velcro strap around the lower limb. Participants used both hands to secure the medicine ball into the dominant side of their neck during the preparation phases of the put. Starting in a forward facing direction, participants rotated away, moving eccentrically prior to a maximal concentric rotation to put the ball into a hanging target positioned 5 m away. Three trials following two warm-up throws with the 3 kg load were collected at both a 3 and 5 kg medicine ball loads. Loads of 3 and 5 kg were chosen as they are concurrent with previous literature (360, 361).

10.2.7 Equipment and data extraction

All testing was performed indoors with ambient atmospheric conditions controlled at ~22°. Bar velocities were collected during bench press and bench pull trials using a rotary encoder (GymAware, Canberra, Australia) and its associated software. This method has been previously shown to be a reliable method of collecting bar displacement data (374). A Velcro strap fixed the GymAware to the bar which was situated directly under the bar at full extension. Bar displacement data were captured at every 0.0006 m of bar displacement from which automated velocity outputs were generated. For the bench pull and bench throw an average of three repetition was taken for further analysis.

During the seated medicine ball put, athlete and put motion was recorded in the HPSNZ/Athletics New Zealand throws room using three (rear, laterally to the right, and above) Vision Prosilica GX1050C cameras sampling at 70 frames per second (fps) with shutter speeds of 1/1000. Prior to testing all cameras were calibrated to known positions within the frame of view according to manufactures specifications.

Manual digitisation of videos was performed in custom written software from which instantaneous velocity of the medicine ball put was calculated from displacement-time data. From instantaneous velocity, acceleration was calculated as the rate of change in velocity. Peak acceleration was then identified and acceleration from 50% of peak velocity to peak velocity was averaged ($accel_{50\text{-}100\%PV}$). On average, two of the three experimental trials per athlete were digitised, using the best two trials or the two that had no more than two missing frames were digitised. Best trials were determined by either greatest velocity attained when all frames were present or by the trials with the least missing frames. All participants returned on three separate occasions separated by seven days to determine the reliability of seated medicine ball put peak velocity and acceleration. Excellent between day reliability was observed (see Chapter 9, CV: -6.81 to 0.69%, ICC: 0.82 to 0.90).

10.2.8 Statistical analysis

Means SD were used to describe each variable. A Pearson's product moment correlation was used to quantify the strength of the association between seated medicine ball put and bench press and bench pull kinematics. Correlations were classed as *negligible* (r = 0.00 to 0.19), *weak* (r = 0.20 to 0.29), *moderate* (r = 0.30 to 0.39), *strong* (r = 0.40 to 0.69), *very strong* (*r* = 0.70 to 0.99), and *perfect* (r = 1.00) based on the magnitudes of the Pearson's product moment correlation (375). Additionally, a paired t-test was used to examine differences between bench pull and bench press velocities at the same loads. Significance was set at $p < 0.05$ for all statistical analyses.

10.3 Results

10.3.1 Bar velocities and seated medicine ball put kinematics

Bench press and bench pull bar velocities are reported in Table 10.1. When comparing between bench pull and bench press, bench pull bar velocity was significantly greater at 60 kg (6.41%, $p < 0.05$) and during the 1RM conditions (54.6%, $p < 0.05$), but not at loads from 20 to 50 kg.

Table 10. 1. Bench press and bench pull peak velocity (PV) and percentage of repetition maximum (1RM).

Bench press			Bench pull		
Load (kg)	1RM (%)	PV (m/s)	Load (kg)	1RM (%)	PV (m/s)
20	17.7	2.84 ± 0.38	20	20.9	2.79 ± 0.46
30	26.6	2.35 ± 0.41	30	31.4	2.31 ± 0.41
40	35.5	1.93 ± 0.41	40	41.9	1.98 ± 0.31
50	44.3	1.65 ± 0.42	50	52.3	1.70 ± 0.32
60	53.2	1.36 ± 0.40	60	62.8	1.45 ± 0.30*
112.8 ± 24.6	100	0.40 ± 0.12	95.6 ± 15.5	100	0.89 ± 0.07*

Notes. * Significant difference between bench press and bench pull peak velocities ($p < 0.05$).

Peak velocities with the 3 and 5 kg medicine balls were 8.01 ± 0.95 and 6.66 ± 0.87 m/s, respectively. The difference in velocity between loads was significant (16.8%, $p < 0.01$). Peak accelerations of 47.4 ± 6.7 and 35.5 ± 5.3 m/s^2 and Accel$_{50\text{-}100\%PV}$ of 33.9 ± 4.5 and 23.6 ± 4.0 m/s^2 were recorded at the 3 and 5 kg loads, respectively. The difference between loads for peak acceleration (25.3%) and Accel$_{50\text{-}100\%PV}$ (30.4%) were significant ($p < 0.05$).

10.3.2 The relationship between seated medicine ball kinematics and bench press and bench pull bar velocities

All correlations between seated medicine ball put kinematics and bench press and bench pull bar velocities are reported in Table 10.2. Bench pull and bench press bar velocity from 20 to 60 kg was very strongly correlated to 3 and 5 kg medicine ball put performance. Peak acceleration of the 3 kg medicine ball was strong to very strongly correlated with bench pull velocity at lighter loads (20 to 50 kg) and the 1RM bar velocity during the bench press. No significant correlations were observed between bench press bar velocity and peak acceleration of the 5 kg medicine ball. Bench pull velocity at lighter loads (20 and 30 kg) was moderately to very strongly correlated to accel$_{50\text{-}100\%PV}$ of 3 and 5 kg medicine ball. Accel$_{50\text{-}100\%PV}$ of the 3 kg medicine ball was also strongly related to the 1RM bench press velocity.

Table 10. 2. Correlations between seated medicine ball put at 3kg and 5kg loads and bench pull and bench press.

	Bench pull						Bench press					
	20 kg	30 kg	40 kg	50 kg	60 kg	1RM	20 kg	30 kg	40 kg	50 kg	60 kg	1RM
3 kg peak velocity	0.80**	0.89**	0.81**	0.83**	0.77*	0.62	0.73*	0.73*	0.77*	0.71*	0.76*	0.82**
3 kg peak acceleration	0.82**	0.77*	0.68*	0.69*	0.63	0.50	0.57	0.59	0.64	0.56	0.64	0.76*
3 kg $accel_{50\text{-}100\%PV}$	0.83**	0.73*	0.64	0.66	0.63	0.49	0.57	0.59	0.66	0.57	0.65	0.76*
5 kg peak velocity	0.77*	0.83**	0.76*	0.79*	0.75*	0.64	0.76*	0.74*	0.76*	0.70*	0.76*	0.80**
5 kg peak acceleration	0.61	0.45	0.33	0.38	0.32	0.31	0.31	0.35	0.35	0.31	0.41	0.50
5 kg $accel_{50\text{-}100\%PV}$	0.81**	0.67*	0.56	0.62	0.56	0.40	0.49	0.50	0.52	0.43	0.53	0.60

Notes. * Significant correlation at the 0.05 level. ** Significant correlation at the 0.01 level. $accel_{50\text{-}100\%PV}$, acceleration from 50% of peak velocity to peak velocity. 1RM, one repetition maximum.

10.4 Discussion

The purpose of this study was to understand the relationship between seated 3 and 5 kg medicine ball put kinematics and bench pull and bench press bar velocities across multiple loads. The main findings of the this investigation were: 1) peak medicine ball velocity at both 3 and 5 kg loads significantly correlated ($r = 0.71$ to 0.89, $p < 0.05$) to bench pull and bench press peak bar velocities across loads, except at the 1RM bench pull load; 2) peak acceleration and $accel_{50\text{-}100\%PV}$ of the 3 and 5 kg medicine ball puts significantly correlated ($r = 0.67$ to 0.83, $p < 0.05$) with bench pull bar velocities at lighter loads, 3) 1RM bench press bar velocity correlated with peak velocity, peak acceleration, and $accel_{50\text{-}100\%PV}$ in the 3 kg put condition, but to peak velocity only in the 5 kg put condition; and 4) significant differences in bench pull and bench press bar velocities were observed at the two heaviest loads examined.

Putting performance in shot put, and derivatives of shot put, are determined by factors affecting projectile motion, namely height, angle, and release velocity. Of these parameters, release velocity appears the most important in differentiating between performance levels (3, 86), which is the reason for selecting this variable from the medicine ball seated shot put assessment. Medicine ball put peak (i.e., release) velocity was strongly to very strongly related to bench press across loads indicating that pressing strength is important for putting performance. In agreement with our results, Terzis et al. (83) observed strong correlations ($r = 0.74$ to 0.94, $p < 0.01$) between bench throw bar displacement with loads of 10 to 30 kg and seated medicine ball put distance with loads between 1 and 5 kg. Correlation coefficients in this study were relatively strong and comparable between medicine ball loads and bench throw loads ($r = 0.71$ to 0.76), which is similar to findings from Terzis et al. (83). Altogether, these findings suggest that seated shot putting ability requires both high velocity (i.e., lighter loads) and maximum force (i.e., heavier loads) capabilities as assessed using the bench press movement. The strength of association between the bench pull and medicine ball put peak velocity was very similar to that of the bench press, except at 1RM where the relationship was strong but not significant. Most of the literature has reported relationships between pressing and shot put release velocities (83, 118). To our knowledge, this is the first investigation to report correlations for pulling type movements. It seems that pulling type strength abilities are also important for putting performance; however, the effect of increasing bench pull strength on putting performance is currently unknown.

Generating high release velocities is dependent on the initial acceleration and the athlete's ability to apply additional force as velocity increases. Therefore, understanding the effects of initial acceleration, and acceleration from 50% to 100% of peak velocity, is important in enhancing putting performance. Peak acceleration with the 3 kg, but not 5 kg, load strongly correlated to bench press bar velocity at 1RM loads (Table 10.2). Bar velocity during maximal bench press attempts was 0.40 m/s, which was the lowest recorded and largely differed from the other loads.

Explaining the association detected between peak acceleration with the 3 kg medicine ball and bench press peak velocity at 1RM is challenging in the absence of an association between light load bench press and peak acceleration. Furthermore, acceleration from an already accelerating position ($accel_{50\text{-}100\%PV}$) only correlated to bar velocity at the heaviest load. In contrast, both peak acceleration and $accel_{50\text{-}100\%PV}$ were strong to very strongly related to light load bench pull bar velocities. Thus, our results suggest that fast pulling velocities facilitate steeper acceleration profiles across the entire putting motion. There are two theories that could explain this finding. First, the rotational component to the seated medicine ball put enhances the need for rotational torque production. The latissimus dorsi generates rotational motion and substantially contributes to the bench pull motion (371). Second, the ability to pull fast allows the athlete to pull the free arm around the axis of rotation. Through fascial connections (376), this motion stretches the putting musculature and contributes to enhancing the stretch shortening cycle (63). Given that this investigation is the first to concurrently look at bench press, bench pull, and putting kinematics in a subset of throwing athletes, further research with a greater number of participants would assist in substantiating the relationship between measures. The similarities in bench press and bench pull velocities at the lighter loads (20 to 50 kg) yet differing levels of associations to seated medicine ball put kinematics suggests that their functional roles within throwing differ. Interventional research tracking bench pull, bench press, and putting performance is required to further understand the functional contribution and importance of these movements in shot putters.

Our results show a systematic decrease in velocity with increasing load, which has been documented previously (179, 307, 377, 378). However, the majority of literature has prescribed loads as a percentage of repetition maximum (307, 377, 379) versus absolute loads reported in the present investigation. Similar to our results, Pearson et al. (377) reported significant differences in bar velocity between bench press and bench pull at 1RM and 60 kg (53.2% and 62.8% of 1RM) loads in a group of elite sailors. When comparing the current data to that of Cronin et al. (379), higher peak bench throw velocities were observed. The difference in peak velocity can likely be attributed to differences in participants as the current investigation involved experienced power-based athletes in contrast to club-based athletes. The results of the present investigation therefore might not apply to athletes who are not experienced, power-based athletes.

10.5 Limitations

This investigation is not without limitations. This investigation included a small sample size. However, it needs to be noted that similar sample sizes have been used in throwing literature, with strong associations reported between various neuromuscular variables and throwing performance (12, 125, 369). The strong correlations reported in this investigation would likely be strengthened with a larger and more heterogeneous cohort.

Medicine balls were used instead of shots, meaning the results might only apply to medicine ball putting. Terzis et al. (83) reported significant correlations between linear shot put and seated medicine ball putting at various loads ($r = 0.60$ to 079, $p < 0.05$). It is therefore justifiable to assume seated medicine ball put performance explains a certain level of the variance in rotational shot put performance. It may be that our results have greater application to para Olympic seated shot put due to the seated nature of the event that is ecologically similar to the current investigation.

10.6 Conclusion

Previous researchers and practitioners have focussed on the association between bench press and the putting motion. The importance of antagonist musculature is frequently overlooked and under-reported in research. Our findings show that within a group of experienced power based athletes, higher medicine ball velocities are associated with higher bar velocities from light-load bench pulls and across loads during bench presses. However, acceleration is predominantly related to bench pull bar kinematics across loads. Thus, it is likely that pushing and pulling musculature have differing functional roles within the putting motion, warranting the inclusion of both in a thrower's assessment battery. Future interventional research should include both bench pull and bench throw kinematics at multiple loads in longitudinal assessments of athletes to further understand the functional contribution and importance of these movements to shot put performance.

Chapter 11

The integration of biomechanics and resistance training in male hammer throwing: A case study

11.0 Prelude

In previous Chapters, literature on the biomechanics (Chapters 2, 3, and 4) and resistance training methods pertaining to each throw (Chapter 5) were reviewed, and a conceptual model of resistance training for throws was advanced (Chapter 6). It was apparent in the hammer throwing biomechanics review (Chapter 4) that biomechanical changes had not been documented longitudinally despite several biomechanical variables shown to strongly correlate to performance. Similarly, resistance training literature pertaining to hammer throwing over longitudinal periods was limited and included mostly strength measures. To provide a more comprehensive understanding of which biomechanical and neuromuscular variables are of most importance to performance, longitudinal monitoring of several variables is required. Given that this thesis targeted high performance athletes, case studies were undertaken bearing in mind the individual-dependent biomechanical traits linked with performance and neuromuscular responses to training interventions. The purpose of this Chapter was to longitudinally track changes in hammer throwing kinematics alongside neuromuscular changes in a high-level athlete. The theoretical periodisation model presented in Chapter 6 was used to inform the resistance training programme. The seated rotation and bench pull assessment methods presented in Chapters 8 and 9 were included as part of the physical testing battery. Throwing performance was assessed using the manual digitisation method presented in Chapter 9 given that release velocity is the primary predictor of performance (Chapter 4). This variable was the surrogate performance measure used outside of actual competition events.

11.1 Introduction

The hammer throw is one of the four throwing events within the Olympic track and field programme. Competitive athletes perform three to four rotations holding the hammer with the objective of generating the greatest hammer ball velocities in each turn to throw the hammer as far as possible. The four rotations must be performed within a 2.135 m circle and the hammer ball must land within the throwing sector to be an official result (1). The hammer itself weighs between 3.00 and 7.26 kg and is 1195 to 1215 mm in length, depending on the age and sex of the thrower. Increasing the distance thrown is predominantly a function of increasing release velocity, with elite male and female throwers releasing the hammer at 27.3 m/s and reaching a distance exceeding 74 m (94). As such, technical throws coaches and strength coaches train athletes with the goal of improving biomechanical and neuromuscular capabilities related to increased hammer ball velocity.

To develop high magnitudes of ball velocity, the athlete must apply large net propulsive tangential forces to the hammer handle (2). Propulsive tangential forces are developed in double support and are associated with increased hammer ball velocity (97). In contrast, during single support, forces are applied to the hammer handle in a manner that results in hammer ball deceleration (2). Thus, increasing the magnitude of propulsive tangential forces applied in double support (azimuth angles) and increasing the duration over which it is applied are sought to enhance release velocity (2, 7). Furthermore, decreasing the duration of single support is recommended also to reduce hammer deceleration during each turn. To further understand the underlying mechanisms of ball velocity, the azimuth angle (i.e., angle of the hammer wire relative to the throwing circle) can be tracked as it describes the angular displacement of the hammer in double and single support (100, 111). Although acutely and theoretically related to performance, research has not reported how these biomechanical throwing variables fluctuate over a longitudinal period in competitive athletes. This information would aid practitioners understanding their relationship with, or impact on, release velocity.

Another avenue to enhance hammer throwing performance is through resistance training. Research has suggested that high magnitudes of lower body strength and power are important predictors of throwing performance (119, 122). However, other research in the area has found less conclusive evidence relating to the influence of strength and power training on hammer throwing performance (14, 16, 22). The reason for the disagreement in the scientific literature is likely the result of differences in sampled population. At the highest level of performance, athletes have likely attained the required levels of maximal strength beyond which further improvement does not necessarily enhance performance. Furthermore, strength is normally assessed using static (i.e., isometric) or gym-based measures, and it would be more appropriate to use more dynamic and throwing-specific strength assessments. In fact, longitudinal data do show a trend towards increased performance with increased throwing volume (14), as throwing is considered a "specific form" of resistance training to the hammer athlete. The planning of gym-based training needs account for acute resistance training effects (i.e., resulting fatigue, delayed onset muscle soreness, etc.) in order to not disrupt throws based training (14, 22). What is obvious from the literature reviewed is that no studies have reported the influence of resistance training and technique training over extended periods. The purpose of this investigation was therefore to monitor the influence of a resistance training and throwing programme on hammer performance longitudinally using biomechanical and neuromuscular measures. We hypothesised that performance would change with event-specific biomechanical variables (azimuth angle and hammer velocity), as well as specific neuromuscular variables.

11.2 Participant description and performance history

One sub-elite junior male (18 years old at the start of this investigation) hammer thrower was recruited. Junior competition-level throwing performance using a standard competition implement (mass: 6.00 kg, length: 1212 mm, and ball diameter: 105 to 125 mm) was prospectively tracked for a year as part of this longitudinal case study. Alongside throwing performance, the High Performance Team granted access to throwing and resistance training workouts for the duration of this study. The athlete had not, and was not, taking performance-enhancing substances (WADA 2018). Average distance thrown during the 11-month period prior to the investigation was 60.98 ± 2.23 m with an improving performance trend. This performance trend was verified by a linear regression conducted on the performances from the 11 months prior to the investigation predicting that the athlete would throw 64.34 m in 12-months time.

11.3 Biomechanical testing

11.3.1 Warm-up and testing

An individual competition warm-up was performed prior to the throw's biomechanics test. The warm-up consisted of 5 minutes of stationary ergometer cycling at a self-selected pace, dynamic stretching, any prescribed pre-habilitation exercises, and two throws at a self-selected intensity. Six throws were performed at a competition intensity within a competition circle. Strong verbal encouragement was provided, and more than 120 s of rest was given between attempts to ensure adequate recovery. The three 'best' throws based on coach and athlete feedback were kept for further analysis, from which the average was presented. To avoid diurnal effects on performance, all testing was performed at the same time of day [1:00 to 4:00 pm] throughout the duration of this investigation. To avoid the impact of environmental conditions on performance, all testing was performed indoor with ambient temperatures controlled at ~22°.

11.3.2 Three dimensional analysis

All throwing analysis was performed indoors in the HPSNZ/Athletics New Zealand throws room. The athlete and hammer were recorded using three electronically synchronised Vision Prosilica GX1050C cameras sampling at 70 frames per second (fps) with shutter speeds of 1/1000. The cameras were positioned above (Figure 11.1, camera 1), to the rear (Figure 11.1, camera 2), and laterally to the right (Figure 11.1, camera 3) of the athlete. Prior to testing all cameras were calibrated to known positions within the frame of view according to manufactures specifications.

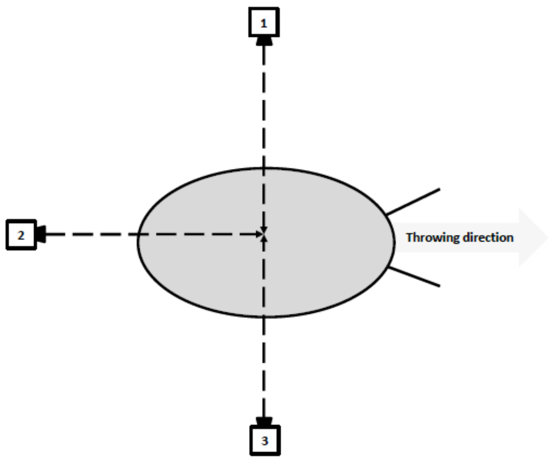

Figure 11. 1. Throws room. Cameras 1 (above), 2 (rear), and 3 (laterally to the right) are positioned perpendicular to one another to collect athlete and hammer movement.

The centre of the hammer, handle, and known points defining the centre and rear of the circle were manually digitised in custom written software that used a least squares approach to generate coordinates in three-dimensional space. Our laboratory has previously shown manual digitisation of throwing kinematics to have high degrees of test-retest (CV: 2.75 to 8.38%, ICC: 0.82 to 0.95) and intra-rater (CV: 0.12 to 4.98%, ICC: 0.92 to 1.00) digitisation reliability (refer to Chapter 9). All velocity data were filtered using an Butterworth filter with an 8 Hz cut-off frequency that was determined by residual analysis (362).

11.3.3 Parameters

The two main throwing parameters of interest were hammer velocity (m/s) and azimuth angle (°). To generate hammer velocity profiles, the centre of the hammer was manually digitised in all frames prior to the first right foot off and throughout the duration of the throw until it left the field of view of two cameras. Azimuth angles were calculated from the intersection of the sector (a line joining the back to the front of the circle centre corresponding with the throwing direction) and hammer (a line joining the hammer ball and handle centres) lines. Hammer velocities and azimuth angles were recorded at right foot contact, as determined from the rear and side view cameras, as the first and last point of contact of the right foot with the ground through each turn.

11.4 Neuromuscular testing

11.4.1 Warm-up and testing

Neuromuscular testing was performed in a separate session to the throws testing at the same time of day [1:00 to 4:00 pm] within 3 days. The participant was familiarised with all tests prior to the initial testing occasion and had prior experience with all tested movements. Jumping, rotational, and explosive upper body pushing and pulling movements formed an essential part of weekly training programmes; hence, a certain level of familiarisation to testing procedures was maintained throughout the longitudinal tracking period. On arrival to the laboratory, a warm-up was performed that consisted of 5 minutes on a stationary bike and dynamic stretching. The order of testing was kept consistent for the duration of this investigation: vertical jump, inertial load bike, cable rotation, bench pull, bench throw, and countermovement jump. A submaximal warm-up set was performed before each assessment, after which verbal encouragement to perform each exercise with maximal intent was given. To control for the influence of environmental factors all testing was performed with ambient temperatures controlled at ~22°.

11.4.2 Vertical jump

Six maximal effort vertical jump trials were completed with more than 120 seconds rest between trials. Data from the best trial were used for analysis as the coach wanted data to compare with historical data. Vertical jump testing was performed using a Vertec (Swift Performance, QLD, Australia) following previously reported protocols (380). Standing reach was measured initially as the highest point reached on the dominant side with the heels in contact with the ground. The athlete then performed a countermovement jump for maximal vertical height, squatting to a self-selected depth from an erect stance, immediately concentrically jumping explosively to tap the vanes on the Vertec. This assessment method has previous been shown to be reliable for quantifying vertical jump height (CV: 4.6 to 7.6%, ICC: 0.87 to 0.94) (381).

11.4.3 Inertial load bike

Three maximal effort inertial load bike trials were completed with more than 120 seconds rest between trials. The average from the three trials was used for analysis. The inertial load bike trial involved 8 maximal effort revolutions seated on a fixed-weight flywheel cycling ergometer. Flywheel weight was fixed at 30 kg with a moment of inertia of 1.08 $kg \cdot m^2$ and 165 mm crank length. Based on the results of Hautier et al. (26), optimal cadence was used as a quasi-measure of muscle fibre type. This assessment method has previously been shown to be reliable for assessing optimal cadence in power trained athletes following multiple familiarisations within our laboratory (Days 1 vs 2, CV: 3.8%, ICC: 0.69; Days 2 vs 3, CV: 2.2%, ICC: 0.92).

11.4.4 Load velocity profiling

Three continuous maximal effort trials at each load were completed across movements (i.e. cable rotation, bench pull, bench throw and countermovement jump) with more than 120 seconds of rest between each load. The average of the three trials was used for analysis. The cable rotation involved 12, 24, and 36 kg loads, and the bench pull, bench throw, and countermovement jump involved 20, 40, and 60 kg loads. An additional 80 kg load was used during the countermovement jump. More than 120 s of rest was given between each attempt to ensure recovery. All tested loads followed a lightest to heaviest progression. Absolute loads were chosen as they are more ecologically valid to throwing as implement weight is fixed regardless of strength level. Furthermore the cable rotation loads are consistent with those observed to be reliable (see Chapter 8). Bench press and bench pull loads are consistent with the loads used in Chapter 10 whereby bar velocity was related to seated putting performance.

11.4.5 Cable rotation

A box modified to fixate the hip was secured in front of a line bisecting two cables (Figure 11.2), allowing the sacrum to be positioned on the bisecting line. To fixate the hip, two adjustable rigid sides adjusted to pelvis width were added to the box. The cable was set at a height corresponding to seated shoulder height. Facing forward in an upright posture, the athlete held the cable handle in two hands with both elbows extended. Starting from neutral (Figure 11.2), the athlete rotated towards the cable pulley machine and immediately rotated concentrically in the opposite direction. Poles corresponding to 45° of rotation bilaterally were set to define the range of motion. Countermovement speed was self-selected and only trials where extension in both arms was maintained were analysed. Trials where 45° of rotation was not achieved or where visible elbow flexion was present were terminated and repeated. Only counter clockwise (dominant side) rotations were assessed. This assessment method has previously been shown to be reliable for assessing peak velocity (m/s, CV: 3.30 to 6.90%, ICC: 0.93 to 0.99) (382).

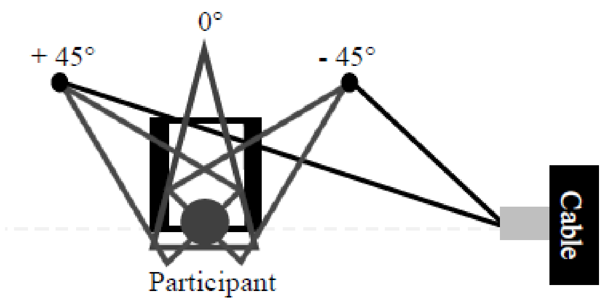

Figure 11. 2. Seated cable rotation set up.

11.4.6 Prone bench pull

A countermovement bench pull consistent with the methods of Sanchez-Medina et al. (307) was performed without the use of a Smith machine. Lying prone on a high-pull bench with a self-selected hand width, the athlete lowered the bar to an extended arm position and pulled the bar into the bench contacting a point coinciding with the xyphoid process. The bar was then lowered for the ensuing repetition that was immediately performed from full extension. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xyphoid process due to the steel frame. Instructions and verbal encouragement to contact the bench as forcefully as possible were given and only trials where contact was made were counted. Trials during which the chest or hips lifted off the bench were disregarded and repeated. The reliability of load velocity profiling in the bench pull has previously been documented (ICC: 0.81 to 0.90, CV: 5.19 to 6.89%) (383).

11.4.7 Bench throw

A countermovement bench throw was employed consistent with previous methods (226, 306, 384). Lying supine on a bench press, the bar was lowered to the chest at a self-selected speed, which was followed immediately by a concentric throw. The athlete was instructed that the bar should make light contact with the lower portion of the chest. Trials during which the head, shoulders, hips, or feet lost contact with their respective surfaces or bouncing of the bar off the chest was observed were disregarded and repeated. Instructions and verbal encouragement to throw the bar as high as possible were given. The reliability of peak bar velocity at similar loads during a bench throw has been previously documented (ICC: 0.86 to 0.96, CV: 1.80 to 3.55%) (384).

11.4.8 Countermovement jump

A CMJ consistent with previous investigations (308, 309) was used to quantify lower body neuromuscular performance. Starting in an erect position with an Olympic bar resting on the upper back, the athlete squatted down to a self-selected depth (310) and completed a concentric jump as explosively as possible. Instructions and verbal encouraged to jump as high as possible were given. The reliability of countermovement jump peak bar velocity has previously been demonstrated (ICC: 0.84 to 0.93, CV: 3.4%) (385).

11.4.9 Equipment and data analysis

All movements were analysed using a PT5A (Fitness Technologies, SA, Australia) LPT connected to the cable stack or bar. Displacement – time data was captured via a custom written LabVIEW programme at 1000 Hz. Manufactures recommendations for calibration were followed.

Displacement – time data from the LPT were analysed using a custom script written in MatLab (v2018a, MA, USA). Cable rotation LPT displacement data were multiplied by 1.8 to account for the 1.8:1 cable pulley gearing ratio and all data were filtered at 100 Hz using a 4th order Butterworth low-pass filter.

A peak detection algorithm was implemented to identify each repetition. Peaks were required to reach 80% of the maximum distance, and multiple peaks within one second were counted as a single repetition. The start of each repetition (concentric onset) was identified by finding the minimum displacement with an additional 1% added to exclude minor movements between repetitions. For each repetition across all movements peak velocity was calculated. For each repetition during the bench pull, bench throw, and countermovement jump peak velocity 100 ms pre (ECC100) and post (CON100) concentric onset was also calculated. One hundred millisecond windows pre and post concentric onset were chosen as they are consistent with contractile windows observed in elite throwing (9, 100, 386).

11.5 Resistance training and throwing periodisation

Resistance training and throwing training followed a periodised plan (Figures 11.3 and 11.4), with peaking planned to occur in February, March, and December 2018. Prior to April 2018, throwing programmes were unavailable as the throws coach did not plan or document training. Following April 2018, the participant changed coaches and both resistance training and throwing periodisation programmes were available, along with technical coaching directives. Throwing periodisation was planned in conjunction with the resistance training that had a throws-driven focus. Throws-driven meant that throwing was prioritised over resistance training. Therefore, the resistance training programmes were designed to maximise adaptation with minimal residual fatigue to allow the completion of throwing trainings with maximal efforts. A throws-driven resistance training method was chosen based on the association between hammers thrown and years throwing reported by Judge et al. (120), and the connection between throwing volume and performance observed in prior case studies (14, 22). During periods of heavy throwing (i.e., more volume and heavy hammer weights), more fatiguing modes of resistance training were integrated. In contrast, during lighter throwing periods, a detraining phase (mid-October to mid-December 2018) was integrated.

The resistance training periodisation was based on a theoretical model of periodisation (see Chapter 6). Briefly, the periodisation model aimed to increase early force – time and high velocity force application by cycling resistance training modes to conserve or increase fibre type qualities, enhance tendinous qualities, and increase peak force. From December 2017 to mid-March 2018, power type resistance training was included. From March 2018 to mid-July 2018, base strength and power modes of training were used to enhance general force qualities. Resistance training programmes generally consisted of 3 to 5 sets of 2 to 6 repetitions of compound type movements (e.g., power clean, back squat, and medicine ball throws). Thereafter, two power based weeks were followed by two to three eccentric based weeks. Eccentric training was performed with supra-maximal loads with eccentric phase durations of ~3 s (slow, S ECC), ~2 s (moderate, M ECC) or less than 1 s (fast, F ECC) (Figures 11.3 and 11.4). Throughout the programme, loads were adjusted to modulate the eccentric duration. Similarly, modes were modulated to ensure movements were ballistic in nature during ballistic periods.

	Month	December				January					February				March				April					May				June			
General	Week starts	*4/12/2017*	*11/12/2017*	*18/12/2017*	*25/12/2017*	*1/01/2018*	*8/01/2018*	*15/01/2018*	*22/01/2018*	*29/01/2018*	*5/02/2018*	*12/02/2018*	*19/02/2018*	*26/02/2018*	*5/03/2018*	*12/03/2018*	*19/03/2018*	*26/03/2018*	*2/04/2018*	*9/04/2018*	*16/04/2018*	*23/04/2018*	*30/04/2018*	*7/05/2018*	*14/05/2018*	*21/05/2018*	*28/05/2018*	*4/06/2018*	*11/06/2018*	*18/06/2018*	*25/06/2018*
	Weekly intensity (H-M-L)	L	L	M	H	H	L	L	H	H	L	L	L-M	L-M	L		M	H	L	M	H	H	L	L	M	H	L	M	H	H	L
Throwing	Phase	Unknown														Off	Unknown							Technical change							
	Sessions/week	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3	2-3		2-3	2-3	2-3	2-3	2-3	2-3	2-3	3	4	4	2	4	5	6	3
	Total weekly throws	30 - 80															30 - 80						Coach Change	60-80	80-100	80-100	80-100	100-120		50-80	80-100
	Percentage of volume spent with implement: 5.5kg	Unknown															Unknown														
	6kg																														
	6.7kg																														
	7kg																														
	7.26kg																														
	8kg																														
Gym	Phase	Specific															Non - specific							Semi specific							
	Sessions/week	3	3	4	4	4	2	2	3	3	2	2	3	3	2		3	3	2	3	3	3	3	3	3	3	2	3	4	4	2
	Primary mode	Pwr									Ballistic					Off	Strength														
	Secondary mode																Pwr														

Figure 11. 3. Throwing and resistance training periodisation from December 2017 to June 2018. Pwr, power; H – M – L, high – moderate – low. In the shaded areas, the darker colours indicate a greater percentage contribution.

	Month	July					August				September				October					November				December				January				
General	Week starts	*2/07/2018*	*9/07/2018*	*16/07/2018*	*23/07/2018*	*30/07/2018*	*6/08/2018*	*13/08/2018*	*20/08/2018*	*27/08/2018*	*3/09/2018*	*10/09/2018*	*17/09/2018*	*24/09/2018*	*1/10/2018*	*8/10/2018*	*15/10/2018*	*22/10/2018*	*29/10/2018*	*5/11/2018*	*12/11/2018*	*19/11/2018*	*26/11/2018*	*3/12/2018*	*10/12/2018*	*17/12/2018*	*24/12/2018*	*31/12/2018*	*7/01/2019*	*14/01/2019*	*21/01/2019*	*28/01/2019*
	Weekly intensity (H-M-L)	M	H	H	L	M	H	H	L	L	M	H	L	M	H	H	L	L	L	L	L	L	L	L	L	M	H	H	L	H	H	L-M
Throwing	Phase	Technical change															Competition throwing									Retrain - Semi-Specific						
	Sessions/week	5	6	6	3	5	6	6	3	5	6	6	3	5	6	6	7	7	7	7	7	7	7	7	7	7	7	7	5	7	7	5
	Total weekly throws	100-120		50-80	100-120	>140	>140	50-80	50-80	100-120	>140	50-80	100-120	>140	>140	50-80	50-80	50-80	50-80	50-80	50-80	50-80	50-80	50-80	100-120	>140	>140	50-80	100-120	>140	100-120	50-80
	Percentage of volume spent with implement: 5.5kg																															
	6kg																															
	6.7kg																															
	7kg																															
	7.26kg																															
	8kg																															
Gym	Phase	Semi - specific															Overshoot - Specific									Retrain. Semi-Specific						
	Sessions/week	3	4	4	3	4	4	4	2	2	3	3	2	3	3	3	1/10 days									3	3	3	2	3	3	2
	Primary mode	Strength				S ECC			Ballistic		S ECC		Ballistic		F ECC		Pwr									M ECC			Pwr	F ECC		VBT
	Secondary mode	Pwr															Plyo									Ballistic				Pwr		

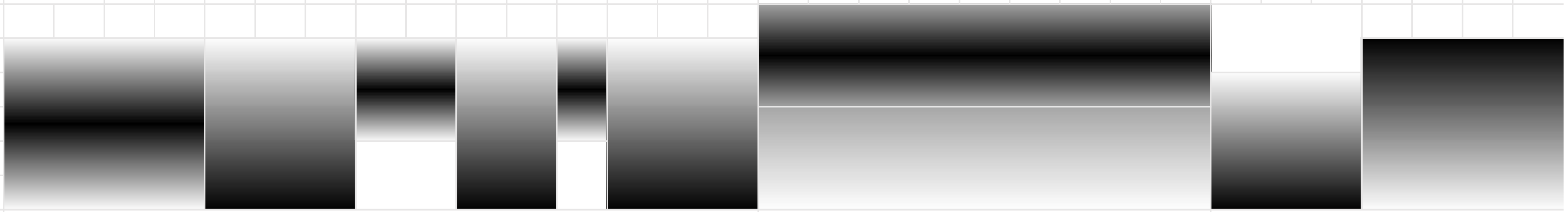

Figure 11. 4. Throwing and resistance training periodisation from July 2018 to January 2019. H – M – L, high – moderate – low; Pwr, power; S ECC, slow velocity eccentric training; M ECC, moderate velocity eccentric training; F ECC, fast velocity eccentric training; Plyo, plyometric training; VBT, velocity based training. In the shaded areas, the darker colours indicate a greater percentage contribution.

11.6 Coaching directives

There were two main periods where the main coaching directives differed. From May to October 2018, the coaching directives were:

- Earlier first catch – The first catch needed to occur earlier as to increase the time before right foot off the athlete has to increase ball velocity.
- Flatter first turn – The first swing needed to be less oblique when viewed from the side, which would allow for a more gradual increase in hammer orbit.
- Gain body mass.

From October to December 2018, the coaching directives were:

- Starting faster – The ball needs to be moving faster at first right foot off.
- Work towards an ascending rhythm – An increase in velocity from turn-to-turn needs to be seen alongside the faster starting velocity.
- Gain body mass.

11.7 Statistical analysis

Longitudinal change was quantified using a mixed statistical and visual analysis method (387) to allow for the quantification of large changes in the analysed variables (388). The two band SD method was used for the purpose of this investigation due to its agreement with the C statistic and split method of trend estimation (388). Within this method, numerical changes were tracked via graphs with significant change quantified by a clear set of rules. The graphs have two bands that indicate two SD above (upper band) and two SD below (lower band) the pre-test mean. Post-test data points on the graph that fall outside either bands define a significant change. Changes are considered more meaningful when consecutive or numerous data points fall outside the SD lines (Figure 11.5) (388). Visual analysis was used to identify trends in the data and was defined as two or more data points trending in the same direction (Figure 11.5). Furthermore, neuromuscular and biomechanical variables were mapped against the criterion performance variable to identify concurrent changes over prolonged periods. Additionally, to provide comparison between distinct data points where performance or release velocity showed large changes, raw (and percentage) change in variables was quantified and presented as mean ± standard deviation. This gave the ability to compare biomechanical and neuromuscular status between data points.

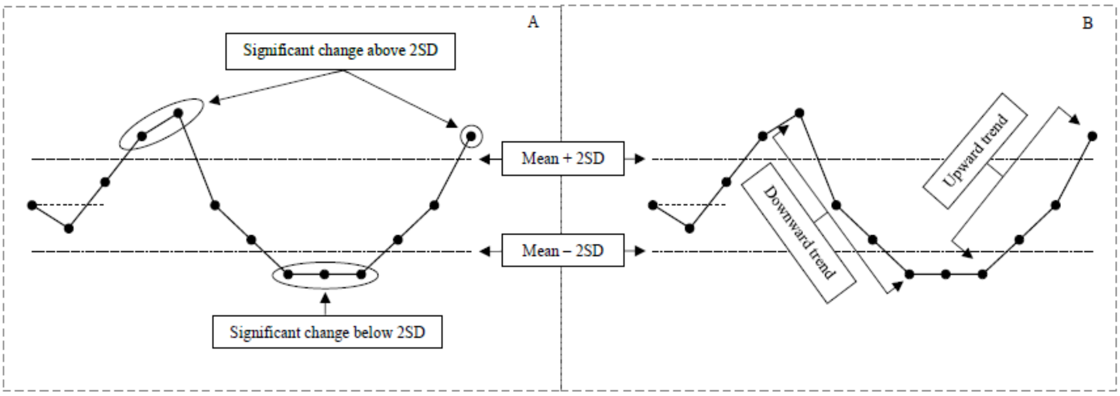

Figure 11. 5. (A) Statistical, and (B) visual analysis methods used.

11.8 Results

11.8.1 Throwing performance

Competition performance change can be observed in Figure 11.6. Fluctuating performances that trended upwards were observed prior to and during the early portion of the investigation period. The last three performances recorded were statistically greater than at baseline. A linear trend line fitted to competition performances prior to the first month predicted a throw of 64.34 m in the next 12 months. However, competition performances exceeded this prediction during December 2018 by 7.3% with the athlete throwing a distance of 69.14m. Within the intervention period, throwing performance visually trended upwards from April/May 2018 to December 2018, with an increase in competition performance of 7.7%. This period was designated as the period of interest and was selected for further analysis given the improved performance.

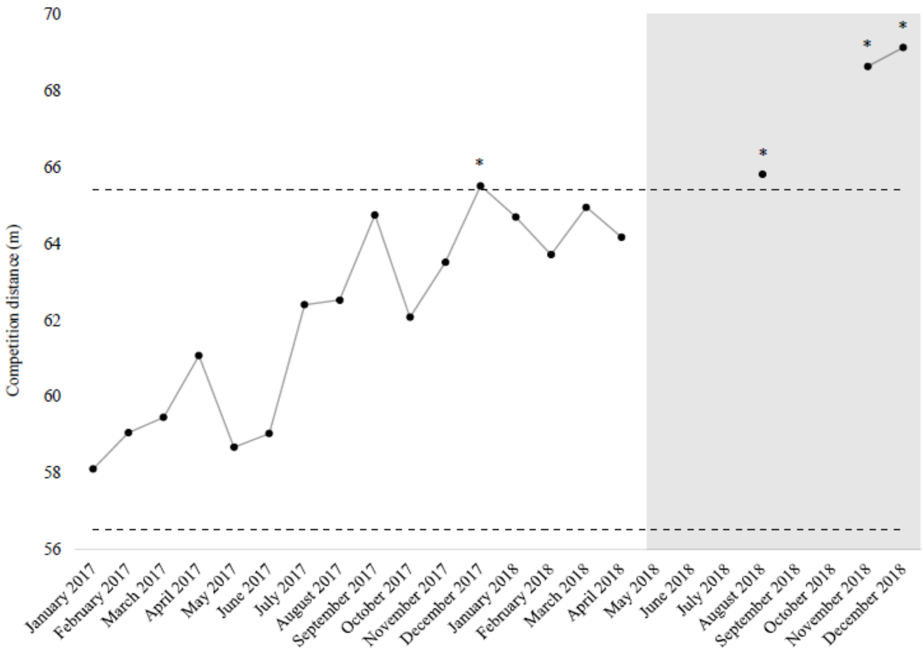

Figure 11. 6. Competition performance during the 11 months prior to and during the 12 months of the investigation period. * denotes change 2 standard deviations above the mean, $^{\#}$ denotes change 2 standard deviation below the mean.

11.8.2 Biomechanical variables

Release velocity can be observed in Figure 11.7. A visual downward trend from the second December testing occasion to a statistical decrease in February 2018 and May 2018 (i.e., two SD below pre-test mean) was observed. Release velocity then trended upwards from May through to a statistical increase in October 2018, December 2018, and February 2019 (i.e., two SD above pre-test mean). Between May and February 2019, release velocity increased by 13.2%.

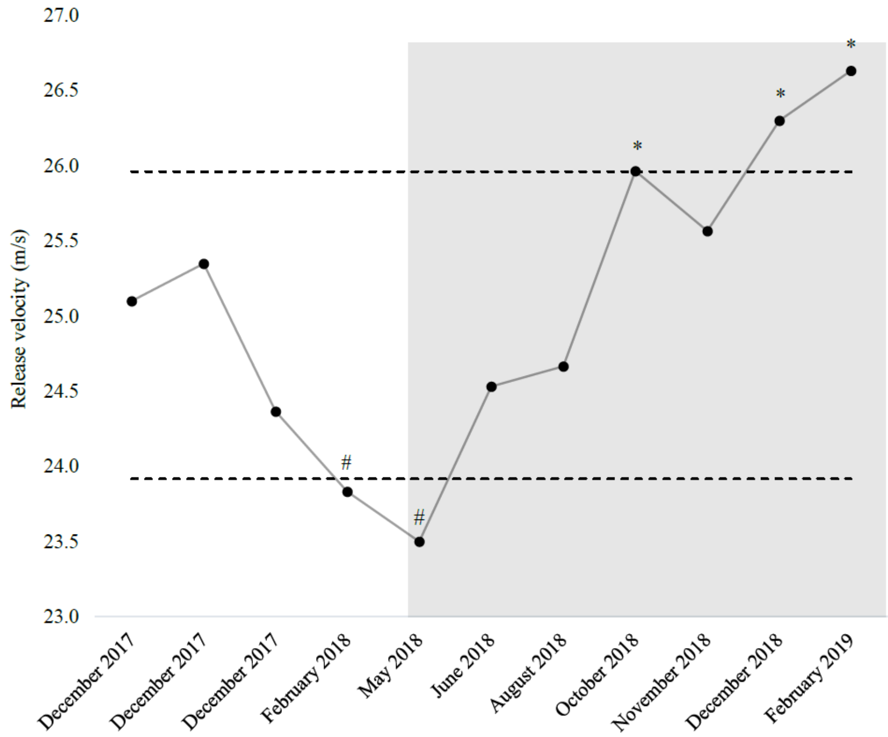

Figure 11. 7. Release velocity during the 12 months of the investigation period. Dashed lines show ± 2 standard deviation bandwidth. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Changes in velocity at each turns are reported in Table 11.1. Statistically greater hammer ball velocities were observed at the majority of foot contacts from August 2018 to February 2019. Visual analysis showed that ball velocity at each foot contact of each turn changed with similar magnitudes to that of release velocities between May and February 2019 (9.7 to 11.6%). Ball velocity at right foot down in Turn 1 changed in a similar pattern to that of release velocity from May to February 2019.

Table 11. 1. Hammer velocities at right foot down (RD) and right foot off (RO). Two standard deviation (2SD) bandwidth values are provided.

	First RO	**Turn 1 (m/s)**		**Turn 2 (m/s)**		**Turn 3 (m/s)**		**Turn 4 (m/s)**	
		RD	**RO**	**RD**	**RO**	**RD**	**RO**	**RD**	**Release**
Elite	**16.2**		**19.8**		**21.9**		**23.7**		**28.2**
	14.6	14.1	18.5	17.2	21.1	19.1	22.6	20.2	25.1
December 2017	14.3	13.8	17.5	16.5	20.4	18.6	21.7	19.3	25.4
	14.3	13.7	17.7	16.3	20.4	18.5	21.8	19.6	24.4
+2SD	14.7	14.3	19.0	17.6	21.4	19.4	23.0	20.7	26.0
-2SD	14.1	13.4	16.8	15.7	19.8	18.1	21.0	18.7	23.9
				Intervention period					
February 2018	*14.4*	*14.0*	*17.8*	*16.7*	*20.1*	*18.3*	*21.6*	*19.4*	*23.8#*
May 2018	*14.6*	*14.5**	*18.0*	*16.8*	*20.1*	*18.3*	*21.4*	*19.2*	*23.5#*
June 2018	*14.7*	*14.5**	*18.5*	*17.4*	*20.8*	*18.6*	*21.8*	*19.6*	*24.5*
August 2018	15.9*	15.6*	19.9*	18.7*	22.5*	20.2*	23.2*	21.1*	24.6
October 2018	15.3*	15.7*	18.5	18.9*	22.3*	20.3*	23.6*	21.2*	26.0*
November 2018	15.2*	15.1*	18.2	17.6*	21.4*	19.6*	22.8	21.3*	25.6
December 2018	15.4*	15.7*	19.0*	18.0*	22.2*	20.3*	23.8*	20.7*	26.3*
February 2019	16.3*	15.9*	19.8*	18.3*	22.4*	20.0*	23.5*	21.1*	26.6*

Notes. Elite values are those reported by Isele and Nixdorf (94) from the 2009 IAAF World Championships. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Changes in azimuth angle are reported in Table 11.2 for the athlete, as are reference values taken from elite performers. Azimuth angles fluctuated throughout the investigation, but only reached a level of statistical change at first right foot off (first RO) from May to June 2018, and at 0° to right foot off in Turn 1 from May 2018 to February 2019 (statistical decrease). When compared to elite throwers, right foot down (RD 0°) occurred earlier from Turn 2 to Turn 4 (angles greater than elite denoted earlier) from February 2018 to February 2019, and right foot off (RO) occurred later. No azimuth angles trended up or down with release velocity over the intervention period or through the May 2018 to February 2019 period.

Table 11. 2. Azimuth angles at right foot down (RD) and right foot off (RO) over the intervention period. Two standard deviation (2SD) bandwidth values are provided.

	Release velocity (m/s)	**First RO (°)**	**Turn 1 (°)**		**Turn 2 (°)**		**Turn 3 (°)**		**Turn 4 (°)**	
			RD - 0	**0 - RO**	**RD - 0**	**0 - RO**	**RD - 0**	**0 - RO**	**RD - 0**	**0 - Rel**
Elite	**28.2**	**50.7**	**155.3**	**50.7**	**127.6**	**51.0**	**119.7**	**51.8**	**107.6**	**104.0**
	25.1	49.03	152.63	70.17	135.50	84.97	115.20	85.90	100.77	106.33
December 2017	25.4	42.75	141.55	72.65	145.65	86.05	119.50	85.35	104.75	112.55
	24.4	45.47	149.17	64.40	146.57	70.50	132.60	60.20	122.83	107.67
+2SD	26.0	52.05	159.12	77.54	154.86	97.87	140.56	106.51	132.97	115.40
-2SD	23.9	39.45	136.44	60.61	130.29	63.14	104.31	47.79	85.93	102.30
				Intervention period						
February 2018	23.8$^{\#}$	40.73	161.00*	53.83$^{\#}$	151.17	70.20	128.07	78.10	115.00	105.07
May 2018	23.5$^{\#}$	38.10$^{\#}$	156.47	59.77$^{\#}$	145.03	68.00	129.13	81.97	115.20	105.50
June 2018	24.5	37.10$^{\#}$	160.07*	56.77$^{\#}$	139.93	68.63	123.83	69.17	120.90	103.77
August 2018	24.7	37.63$^{\#}$	154.23	54.63$^{\#}$	145.23	62.40$^{\#}$	121.20	73.03	110.07	110.53
October 2018	26.0*					82.90	123.40	92.20	104.90	106.10
November 2018	25.6	47.40	139.60	57.95$^{\#}$	158.80*	61.90$^{\#}$	127.15	59.63	120.07	106.20
December 2018	26.3*	47.67	171.07*	66.50	149.27	64.07	135.20	50.93	134.73*	95.90$^{\#}$
February 2019	26.6*	46.40	154.60	52.30$^{\#}$	158.93*	47.80$^{\#}$	146.60*	47.83	124.25	110.03

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

11.8.3 Neuromuscular variables

Changes in inertial load ergometer optimal cadence and peak power can be observed in Figure 11.8 (A and B, respectively). Both optimal cadence and peak power fluctuated throughout the duration of the investigation but did not trend with release velocity. Due to equipment malfunction, inertial load data during October and November 2018 were not recorded.

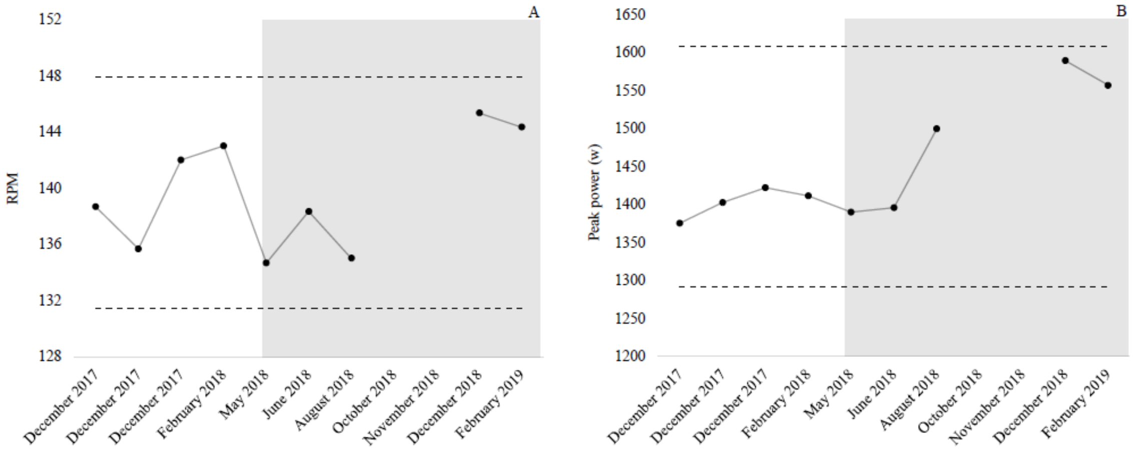

Figure 11. 8. Inertial load ergometer (A) optimal cadence, and (B) peak power.

Changes in vertical jump height and body mass are reported in Figure 11.9 (A and B, respectively). Vertical jump height significantly decreased in May 2018 and again in August and February 2019. Change in vertical jump height were not concurrent with changes in release velocity. Body mass increased throughout the observational period from baseline testing in December 2017 through to February 2019.

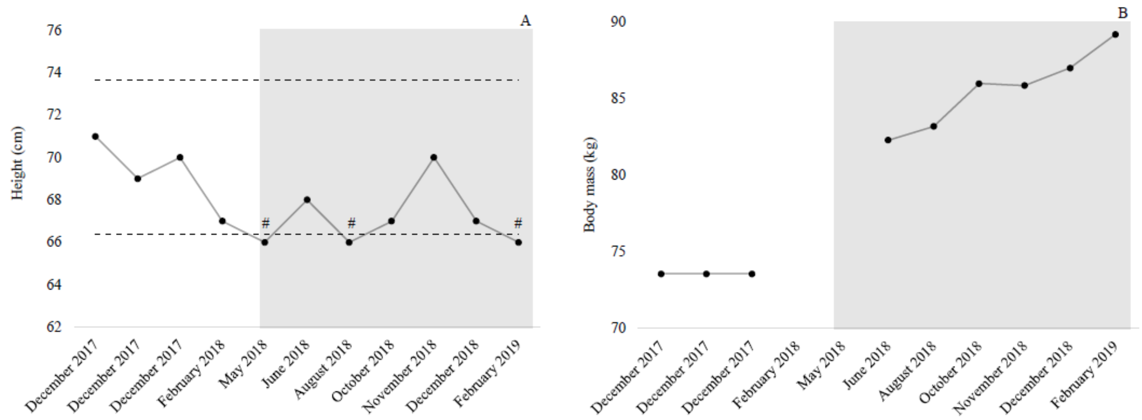

Figure 11. 9. (A) Jump height, and (B) and body mass (8b). * denotes change 2 standard deviations above the mean, [#] denotes change 2 standard deviation below the mean.

Peak bar velocities of all movements are reported in Figure 11.10 (A to D). Countermovement jump bar velocity over the intervention period is reported in Figure 11.10A. Significant increases in bar velocity during the countermovement jump were only observed at the heaviest load in February, May, August, and October 2018. From May 2018 to February 2019 where release velocity trended upwards (Figure 11.7) , decreases of -2.0%, -0.4%, -5.4%, and -3.5% in 20, 40, 60, and 80 kg countermovement jump peak bar velocity were noted. Bench throw bar velocity over the intervention period is shown in Figure 11.10B. Significant increases were observed from June 2018 to February 2019 at the two heaviest loads. Peak bar velocity increased 8.0%, 16.3%, and 16.7% with the 20, 40, and 60 kg loads during May 2018 to February 2019. The time course of the bench pull bar velocity is shown in Figure 11.10C. Bar velocity significantly increased in the 60 kg load condition only from October 2018 to February 2019. From May to February 2019, peak bar velocity changed -1.2%, 6.6%, and -4.3% with the 20, 40, and 60 kg loads. The cable rotation velocity profile of the athlete is presented in Figure 11.10D. Cable rotation velocity significantly decreased through the majority of months between February and October 2018 before statistically increasing above baseline from November 2018 to February 2019 in the lightest load (12 kg). Visual analysis suggested that velocity tended to decrease in the heaviest load from November 2018 to February 2019. From May 2018 to February 2019, an increase of 13.1% and 5.0% was seen with the 12 and 24 kg loads, and a decrease of -2.9% with the 36 kg load. Although increases and decreases in bar and cable velocity across loads were observed, bar and cable velocity did not trend up and down with release velocity.

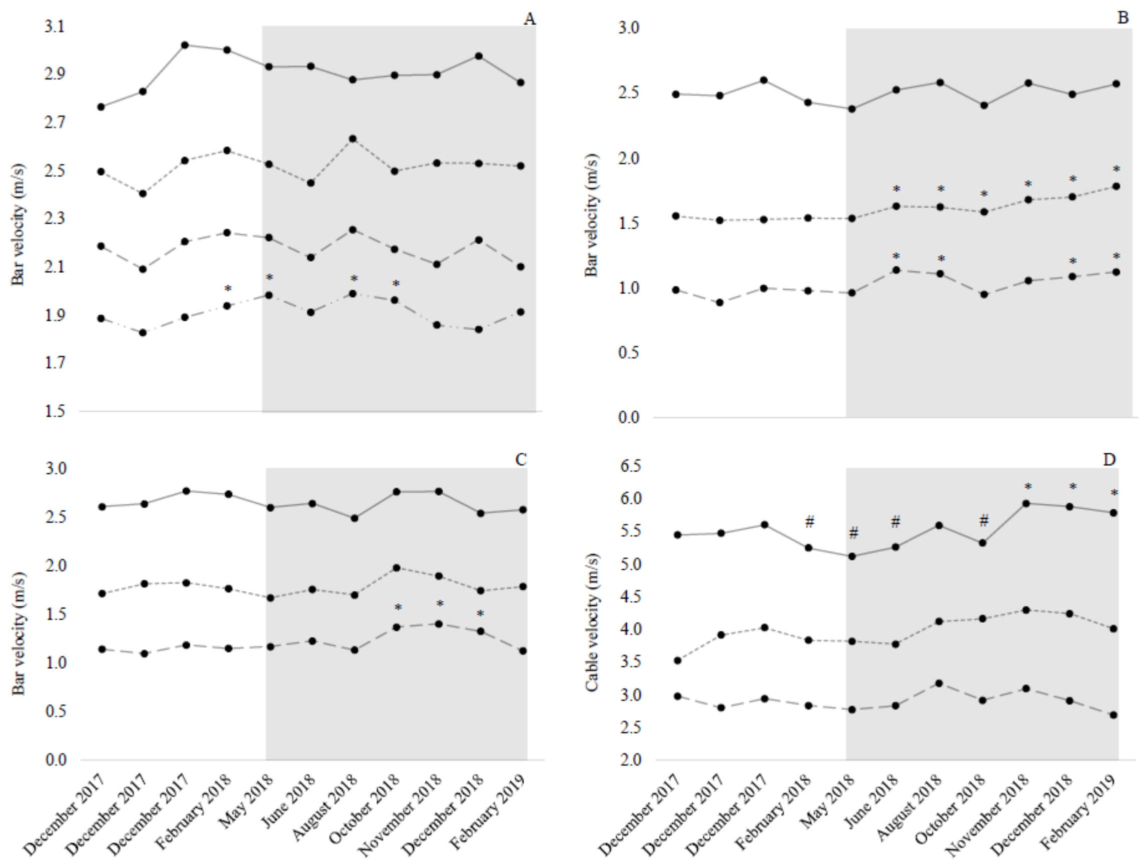

Figure 11. 10. Peak barbell velocity during a loaded (A) countermovement jump, (B) bench throw, and (C) bench pull at 20 kg (—), 40 kg (····), 60 kg (- - -) and 80 kg (·· —), and (D) cable rotation at loads of 12 kg (—), 24kg (····) and 36 kg (- - -). * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Countermovement jump ECC100 and CON100 over the intervention period are reported in Table 11.3. Statistical increases in both ECC100 and CON100 measures were observed from October 2018 to February 2019 in the 20 kg condition, and for all loads in December 2018 and February 2019. When graphed against release velocity, 20 kg ECC100 visually trended in a similar fashion over the entire intervention period (Figure 11.11). From May 2018 to February 2019 where release velocity trended upwards, ECC100 and CON100 increased 48.9% and 18.8%, respectively.

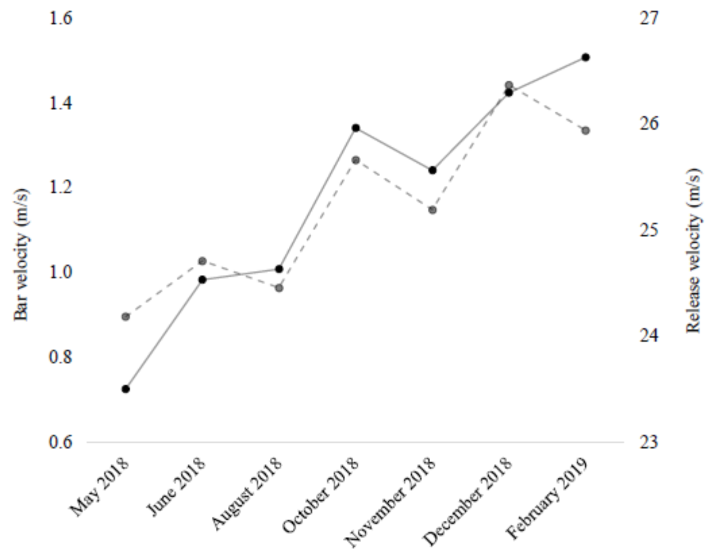

Figure 11. 11. Countermovement jump eccentric bar velocity (ECC100) with 20 kg (---) and release velocity (—) from May 2018 to February 2019.

Table 11. 3. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during countermovement jump at four loads.

	20 kg		40 kg		60 kg		80 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-0.95	1.05	-0.77	0.82	-0.46	0.51	-0.37	0.43
December 2017	-0.87	0.94	-0.57	0.59	-0.30	0.40	-0.29	0.33
	-1.00	1.03	-0.63	0.66	-0.45	0.51	-0.35	0.37
+2SD	-1.07	1.12	-0.87	0.93	-0.59	0.61	-0.42	0.48
-2SD	-0.81	0.89	-0.45	0.46	-0.22	0.34	-0.25	0.27
				Interventional period				
February 2018	-1.03	1.04	-0.85	0.82	-0.54	0.58	-0.41	0.40
May 2018	-0.90	1.12	-0.75	0.81	-0.47	0.50	-0.39	0.45
June 2018	-1.03	1.04	-0.64	0.68	-0.50	0.51	-0.40	0.42
August 2018	-0.96	0.91	-0.68	0.80	-0.49	0.55	-0.37	0.45
October 2018	-1.27*	1.13*	-0.64	0.61	-0.53	0.54	-0.39	0.44
November 2018	-1.15*	1.15*	-0.77	0.86	-0.51	0.53	-0.32	0.31
December 2018	-1.44*	1.31*	-1.11*	1.07*	-0.90*	0.82*	-0.69*	0.63*
February 2019	-1.34*	1.33*	-0.99*	1.09*	-0.70*	0.67*	-0.31	0.32

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Change in bench throw ECC100 and CON100 are shown in Table 11.4. With regard to the heaviest load, significant decreases in ECC100 and CON100 were observed from June to October 2018 and in December 2018. In the 40 kg load, CON100 significantly increased in February, March, and June 2018. CON100 significantly decreased at the lightest load (20 kg) in May, October, and November 2018 before increasing in February 2019, which occurred in parallel with an increase in ECC100 (May 2018 to February 2019, 43.2% increase).

Table 11. 4. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench throw at three loads.

	20 kg		40 kg		60 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-1.33	1.23	-1.08	0.73	-0.81	0.50
December 2017	-1.58	1.30	-0.74	0.63	-0.67	0.49
	-1.45	1.43	-0.90	0.65	-0.74	0.50
+2SD	-1.71	1.52	-1.24	0.77	-0.88	0.51
-2SD	-1.19	1.12	-0.57	0.57	-0.60	0.49
Interventional period						
February 2018	-1.68	1.23	-1.11	0.84*	-0.64	0.52
May 2018	-1.50	1.11#	-0.90	0.71	-0.80	0.60*
June 2018	-1.55	1.47	-1.03	0.87*	-0.57#	0.47#
August 2018	-1.32	1.18	-0.79	0.63	-0.50#	0.41#
October 2018	-1.33	1.03#	-0.65	0.66	-0.54#	0.42#
November 2018	-1.23	1.09#	-0.80	0.75	-0.66	0.51
December 2018	-1.25	1.19	-0.85	0.72	-0.40#	0.33#
February 2019	-1.83*	1.59*	-1.09	0.91*	-0.73	0.57*

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

No significant change in ECC100 and CON100 bench pull bar velocity was observed (Table 11.5). Visual analysis shows a trend of increasing ECC100 and CON100 from October 2018 to February 2019 at 20 kg and 40 kg loads.

Table 11. 5. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench pull at three loads.

	20 kg		40 kg		60 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-0.53	0.37	-0.32	0.18	-0.04	0.15
December 2017	-1.17	0.53	-0.18	0.06	-0.52	0.40
	-1.51	1.31	-1.05	0.81	-0.73	0.57
+2SD	-2.07	1.75	-1.46	1.16	-1.14	0.80
-2SD	-0.07	0.00	0.00	0.00	0.00	0.00
			Interventional period			
February 2018	-1.05	0.71	-0.89	0.67	-0.70	0.50
May 2018	-1.35	0.96	-0.83	0.58	-0.66	0.47
June 2018	-1.47	1.32	-0.96	0.67	-0.84	0.57
August 2018	-1.39	1.00	-0.71	0.59	-0.44	0.34
October 2018	-0.22	0.45	-0.36	0.13	-0.08	0.26
November 2018	-0.87	0.86	-0.65	0.54	-0.31	0.32
December 2018	-1.25	0.85	-0.82	0.53	-0.57	0.50
February 2019	-1.83	1.59	-1.09	0.91	-0.73	0.57

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

11.9 Discussion

Coaches and athletes seek to enhance competition performance by enhancing both biomechanical and neuromuscular variables relating to their throwing events. One method of identifying factors important to enhancing performance is to map positive changes in throwing performance alongside those factors that change in a similar manner over a given training period. Using this approach, positive changes in competition throwing performance and release velocity were noted from approximately May 2018 to February 2019. This period (May 2018 to February 2019) was identified as the period of interest and highlighted throughout the results section.

In terms of the performance and biomechanical analyses, the main findings were: 1) hammer throw performance increased by 7.7% between May 2018 and February 2019, with the increase being statistically significant from August 2018 onwards; 2) release velocity increased by 13.2% from May 2018 to February 2019, with the increase being statistically significant in October 2018, December 2018, and February 2019; 3) hammer ball velocity at right foot down and right foot off events increased by 8.9 to 11.6% from May 2018 to February 2019, with a similar pattern noted for release velocity; and 4) no clear trends were observed for azimuth angles, although significant changes from baseline were observed throughout the tracking period.

With regards to the neuromuscular variables during the period of interest, the main findings were: 1) optimal cadence and power increased by 7.2 and 12.0%, respectively, but changes were not statistically significant; 2) vertical jump height decreased in a significant manner; 3) body mass significantly increased by 8.4% from baseline; 4) peak bar and cable velocities across movements significantly changed, but were not concurrent with hammer ball velocity; and, 5) late eccentric (ECC100) 20 kg countermovement jump bar velocity increased 43% from May 2018 to February 2019, fluctuating concurrently with release velocity and reaching levels of significant change from October 2018 to February 2019.

Athletics coaches and athletes seek to enhance performance by adapting technical and physical loads through a planned training programme that should culminate in the highest level of performance during the competitive athletics season. Our data show hammer performance significantly increased from August onwards (7.7% between April 2018 and December 2019). The increases in competition performance exceeded the predicted distance from the 11 months prior to this investigation. November/December corresponds with the start of the competitive athletics season for the current athlete. The current periodisation plan led to improved performance with associated enhanced biomechanical and neuromuscular variables. The periodisation plan and training programmes were monitored until February 2019. However, since no competitions were undertaken with the 6 kg implement between December 2018 to February 2019, it is unknown whether competitive performance continued to increase. That said, release velocity is the primary predictor of performance (2, 94) and tended to increase with performance during the investigation period, reaching its highest level in February 2019 (13.2 % increase from May 2018 to February 2019). Increased release velocity throughout this period was concurrent with increased ball velocities through the preceding turns and foot contacts (Table 11.1). Of the foot contacts and turns, ball velocity at right foot down in Turn 1 mirrored the changes in release velocity best. One of the coaching directives used in the second part of the periodisation plan was to increase ball velocity at first right foot off to get closer to that of elite throwers (Table 11.1) (94). Significant increases in ball velocity at first right foot off was observed in this athlete from August 2018 to February 2019, with increases in ball velocity at each foot contact at each turn as well as release velocity in October 2018, December 2018, and February 2019. The coaching directives and cues in this instance appeared to have been effective and well implemented by the athlete.

Changes in azimuth angles did not mirror that of release velocity over the intervention period. Accordingly, the changes in hammer velocity are likely to do with the magnitude of force applied rather than the time over which it was applied. Based on the findings of Rojas-Ruiz and Gutierrez-Davila (104) who reported a negative correlation between angular displacement (pooled azimuth angles, RD + RO) in the antepenultimate ($r = -0.503$, $p < 0.01$) and penultimate ($r = -0.386$, $p < 0.05$) turns and hammer velocity, greater azimuth angles were thought to be associated with slower ball velocities. In contrast, we observed total angular displacement to be maintained as release velocity increased, and the greatest azimuth angles to occur in Turn 3 with ball velocities similar to those of elite male throwers (94). The high azimuth angles observed at high velocities are indicative of the technical proficiency of this hammer thrower and that hammer ball velocity can increase and decrease independent of changes in azimuth angle over a longitudinal period.

When considering the neuromuscular qualities alongside the release velocity, peak bar velocities did not change concurrently with release velocity during the countermovement jump, bench throw, bench pull, and cable rotation at any of the assessed loads. Judge et al. (120) reported a weak positive correlation between back squat 1RM and throwing performance ($r = 0.33$, $p = 0.001$). In contrast, peak bar velocity during CMJ across loads decreased from 0.4 to 5.4% as release velocity of throwing tended to increase (May 2018 to February 2019). However, the bar velocity during the CMJ in the ECC100 phase between May 2018 and February 2019 corresponded with that of release velocity. CON100 CMJ bar velocity also increased, but did not mirror release velocity as closely. Bourdin et al. (124) reported a strong correlation ($r = 0.73$, $p < 0.01$) between drop jump stiffness and hammer performance in male throwers. Stiffness is a composite of eccentric and concentric performance within short contractile windows. Collectively, Bourdin et al. (124) and our data suggest that male hammer performance is related to, and increases with, neuromuscular performance in short contractile windows (i.e., 0 to 200 ms) and stretch-shortening cycle properties.

During the May 2018 to February 2019 period, body mass, optimal cadence, and peak power increased 8.4%, 7.2%, and 12.0%, respectively, as release velocity increased 13.2%. Terzis et al. (122) observed a strong association between total body mass ($r = 0.81$, $p < 0.05$), muscle fibre cross sectional area ($r = 0.90 – 0.96$, $p < 0.01$), and throwing performance. The increase in body mass was a coaching directive to allow for more efficient countering of the hammer. Greater body mass was thought to decrease the required vertical displacement of the centre of mass to resist the pulling forces of the hammer (7, 96). Further research is required to confirm this premise as centre of mass displacement was not tracked in the current investigation.

Increased peak power at an increased cadence shows an enhanced ability to produce force at high velocities, a desirable trait in athletic throwing athletes. The CMJ ECC100 and CON100 data at the 20 kg load suggest that our athlete increased his ability to produce force within short contractile windows. Increased neuromuscular performance at high velocities and within short contractile windows corresponds with the temporal and kinematic requirements of hammer throwing (2, 7, 94). During a hammer throw, elite athletes lower their centre of mass in single support (220 to 380 ms), a pattern that must be reversed during double support [180 ms to 320 ms in elite hammer throwers (7, 94)] to effectively accelerate the hammer (7). Furthermore, as hammer velocity increases, the athlete is required to produce propulsive force at increasing velocities. To generate maximum performance, an understanding of the biomechanics and neuromuscular variables that underpin higher levels of performance is important in an informed approach to resistance training planning.

The model of periodisation targeted increasing neuromuscular qualities associated with early force – time and high velocity force application, aiming to peak in the December 2018 to February 2019 period. Early force – time and high velocity force application has been related to tendon stiffness (18), fibre type (17, 26), and peak force (17, 19). Therefore, strength and power resistance training was included from March to mid-July 2018 to increase general strength and power qualities. As a result of strength training, a decrease in IIx fibre type expression can occur (184). For this reason, an eccentrically dominated programme was introduced from late July to mid-October 2018 to increase fast fibre type expression, fibre cross sectional area, and stiffness (23, 195). Further increases in fast fibre type expression have been observed during detraining periods lasting greater than three weeks, but peak force and tendon stiffness decrease concurrently (117, 155). For this reason, a retraining period including short periods of eccentric, ballistic, power, and velocity based training were included to maintain fibre type, while enhancing peak force and tendon stiffness (23, 185, 191, 195). Optimal cadence, as a proxy for fibre type (26), largely followed this prediction in fibre type qualities as a decrease in optimal cadence was observed following strength-based training and an increase following the eccentrics – detraining – retraining blocks (7.2% increase). Furthermore, light load rotation remained significantly lowered until the detraining period. Similarly, Andersen et al. (117) observed light load kinetics to be enhanced following a detraining period that were concurrent with a fibre type shift towards faster fibre types (i.e., IIa to IIx). As such, it is not necessarily surprising that changes in inertial load ergometer optimal cadence and peak power did not mirror changes in throwing performance given that these changes are more akin to fibre type. However, there were considerable missing data points during the period of interest for the cycle ergometer testing because of equipment malfunction that limit our ability to draw conclusions.

With regard to strength, 1RM was not directly tracked, however heavy load countermovement jump, bench press, bench pull, and cable rotation peak velocity was tracked as a proxy for strength. Changes across the longitudinal period with training varied across these exercises. Whereas loaded countermovement jump followed a more predictable pattern of adaptation; bench throw, bench pull, and cable rotation did not. These observations maybe suggestive of adaptive "layering" from the sequencing of training modes over a longitudinal period. In support, Staron et al. (20) observed women to exhibit a greater percentage of fast fibre types with similar levels of peak force to that observed following strength training when detraining and retraining periods were undertaken. Few investigations have sought to understand the effect of multiple sequenced training modes of adaptations relating to early force – time and high velocity force application. It also needs to be acknowledged that direct measures of neuromuscular qualities, such as fibre type and strength were not quantified in this study. The proxy measures used herein may not accurately reflect the underlying morphological and physiological changes.

11.10 Conclusions

Competition performance and release velocity statistically (± 2SD) increased over the course of this longitudinal investigation. Changes in release velocity corresponded with increased hammer velocity through preceding turns at right foot down and right foot off in agreement with the coaching directives, but not with changes in azimuth angles. With regard to neuromuscular qualities, bar velocity 100 ms prior to (ECC100) and post (CON100) concentric onset of a CMJ showed the greatest correspondence with change in release velocity. That said, concurrent increases in body mass and inertial load bike variables of peak power and optimal cadence were observed during periods of high release velocity, with the latter indicating a higher fast twitch fibre type percentage. The high correspondence between CMJ ECC100 and release velocity when compared to CMJ peak bar velocities suggests that these metrics are more related to hammer biomechanics and should be tracked preferentially. Clearly, the observed associations and trends in the data need to be validated in a larger sample of athletes. Future research would benefit from reporting impulse, rate of force development, and early contraction bar velocities during loaded countermovement jumps; however, a larger body of research is needed to confirm the utility of these measures.

Our data suggest the possibility of sequencing training modes to generate an adaptive profile that corresponds to enhanced early force – time and high velocity force application. However, this is one of first investigations to track throwing biomechanics and force – velocity and force – time variables over a longitudinal period against a periodisation model. It is highly probable that the current model is individual dependent, with different associations found based on an athlete's strength and weaknesses, as well as coaching directives.

Chapter 12

The integration of biomechanics and resistance training in female hammer throwing: A case study

12.0 Prelude

In the previous Chapter, an elite junior male hammer thrower was tracked over a 16-month period using testing methods and a periodisation model outlined in prior Chapters. It was found that no kinematic variable concurrently adapted with release velocity, however late eccentric velocity in a countermovement jump (neuromuscular variable) corresponded with changes in release velocity. To extend the body of knowledge and inform practice, further investigations are required given that results from a single subject are likely not generalisable. It is important to consider adaptive responses of individuals with different training history, sex, and/or throwing backgrounds. Thus, this Chapter investigated the changes in hammer throwing biomechanics, neuromuscular status and competition performance over a longitudinal period in a sub-elite senior female hammer thrower. Like the previous Chapter, the methods discussed in Chapters 8, 9, and 10 were integrated along with the periodisation model developed in Chapter 6.

12.1 Introduction

The hammer throw is one of the four throwing events within the Olympic track and field programme. Competitive athletes perform three to four rotations holding onto the hammer with the objective of generating maximal hammer ball velocity in each turn to throw the furthest distance. The four rotations must be performed within a 2.135 m circle and the hammer ball must land within the throwing sector to be an official result (1). The hammer itself weighs between 3.00 and 7.26 kg and is 1195 to 1215 mm in length, depending on age and sex of the thrower. Increasing competition distance is predominantly a function of increasing release velocity, with elite male and female throwers releasing the hammer at 27.6 m/s (94). As such technical coaches and strength coaches seek to change and adapt variables related to increased hammer ball velocity.

To develop high magnitudes of ball velocity the athlete must apply large net propulsive tangential forces to the hammer handle (2). Thus, biomechanical and neuromuscular capabilities related to hammer throwing need to be developed in tandem. Biomechanically, increasing propulsive tangential force arises from torque produced in double support and by moving in a parametrically oscillating pattern with the hammer (2, 7). Alternatively, decreasing retarding tangential force by decreasing the time that is spent in single support is advocated. Thus, shoulder – hammer angles, azimuth angles, hip height change, and ball velocity through the throw are suggestive of increased propulsive force, increased time of force application, and the effectiveness of the athlete on influencing the ball (100, 111). Such variables although acutely related to performance have not been regularly tracked over a longitudinal period to understand their impact on changing release velocity. With reporting of biomechanical change, technical change directives of the coach and athlete over such periods provides context to understanding changes in the deterministic variables. Previous coaching directives and qualitative biomechanics have been reported in the absence of quantitative biomechanical data (16). Understanding quantitatively the change in factors related to increased performance that relate to coaching instruction provides valuable insight into understanding performance change.

Another avenue to enhance performance is through resistance training and it has been suggested that high magnitudes of lower body strength and power are important predictors of performance (119, 122). However other researchers have found the influence of strength and power training on hammer throw performance to be less conclusive (14, 16, 22). Longitudinal literature does however show a trend towards performance increasing with increasing throwing volume, and as throwing is specific resistance training, planning of gym based resistance training needs to be undertaken with consideration for its affects acutely (i.e. resulting fatigue, DOMS) on throwing performance (14, 22). That said, what is obvious from the literature reviewed is that no studies have regularly monitored the influence of resistance training and technique training over extended periods of time. The purpose of this investigation was therefore to monitor the influence of a resistance training and throwing programme on hammer performance, using biomechanical and neuromuscular markers over an extended period.

12.2 Participant description and performance history

One sub-elite senior female hammer thrower (25 years old at the initiation of this investigation) was recruited. Senior female hammer throwing performance using a standard competition implement (mass: 4.00 kg, length: 1195 mm, and ball diameter 95 to 110 mm) was prospectively tracked for a year as part of this longitudinal case study. Alongside throwing performance, the High Performance Team granted access to throwing and resistance training workouts. The athlete had not, and was not, taking performance enhancing substances (WADA 2018) through the duration of this investigation. Average distance thrown during the 11-month period prior to the investigation was 58.67 ± 2.18 m with an improving performance trend. This performance trend was verified by a linear regression conducted on the performances recorded in the 12 months prior to the investigation predicting that the athlete would throw 62.49 m in 12-months time.

12.3 Biomechanical testing

12.3.1 Warm-up and testing

An individual competition warm-up was performed prior to the throw's biomechanics test. The warm-up consisted of 5 minutes of stationary ergometer cycling at a self-selected pace, dynamic stretching, any prescribed pre-habilitation exercises, and two throws at a self-selected intensity. Six throws were performed at a competition intensity within a competition circle. Strong verbal encouragement was provided, and more than 120 s of rest was given between attempts to ensure adequate recovery. The three 'best' throws based on coach and athlete feedback were kept for further analysis, and the average was presented. To avoid diurnal effects on performance, all testing was performed at the same time of day [7:00 to 9:00 am] throughout the duration of this investigation. To avoid the impact of environmental conditions on performance, all testing was performed indoor with ambient temperatures controlled at ~22°.

12.3.2 Three dimensional analysis

All throwing analysis was performed indoors in the HPSNZ/Athletics New Zealand throws room. The athlete and hammer were recorded using three electronically synchronised Vision Prosilica GX1050C cameras sampling at 70 frames per second (fps) with shutter speeds of 1/1000. The cameras were positioned above (Figure 12.1, camera 1), to the rear (Figure 12.1, camera 2), and laterally to the right (Figure 12.1, camera 3) of the athlete. Prior to testing all cameras were calibrated to known positions within the frame of view according to manufactures specifications.

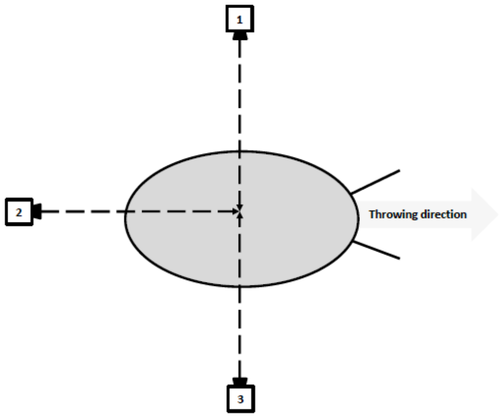

Figure 12. 1. Throws room. Athlete cameras (1 – 3) are positioned on 3 dimensional axes perpendicular to one another and collect athlete movement.

The centre of the hammer, handle, and known points defining the centre front and rear of the circle were manually digitised in custom written software that used a least squares approach to generate coordinates in three-dimensional space. Our laboratory has previously shown manual digitisation of throwing kinematics to have high degrees of test-retest (CV: 2.75 to 8.38%, ICC: 0.82 to 0.95) and intra-rater (CV: 0.12 to 4.98%, ICC: 0.92 to 1.00) digitisation reliability (refer to Chapter 9). All velocity data were filtered using an Butterworth filter with an 8 Hz cut-off frequency that was determined by residual analysis [355].

12.3.3 Parameters

The two main throwing parameters of interest were hammer velocity (m/s) and azimuth angle (°). To generate hammer velocity profiles, the centre of the hammer was manually digitised in all frames prior to the first right foot off and throughout the duration of the throw until it left the field of view of two cameras. Azimuth angles were calculated from the intersection of the sector (a line joining the back to the front of the circle centre corresponding with the throwing direction) and hammer (a line joining the hammer ball and handle centres) lines. Hammer velocities and azimuth angles were recorded at right foot contacts, as determined from the rear and side view cameras, as the first and last point of contact of the right foot with the ground through each turn.

12.4 Neuromuscular testing

12.4.1 Warm-up and testing

Neuromuscular testing was performed following the throws testing [8:00am – 10:00am]. Five minutes of rest between the final throw and first vertical jump was given. The participant was familiarised with all tests prior to the initial testing occasion and had prior experience with all tested movements. Jumping, rotational, and explosive upper body pushing and pulling movements formed an essential part of weekly training programmes; hence, a certain level of familiarisation to testing procedures was maintained throughout the longitudinal tracking period. The order of testing was kept consistent for the duration of this investigation: vertical jump, inertial load bike, cable rotation, bench pull, bench throw, and countermovement jump. A submaximal warm-up set was performed before each assessment, after which verbal encouragement to perform each exercise with maximal intent was given. To control for the influence of environmental factors all testing was performed with ambient temperatures controlled at ~22°.

12.4.2 Vertical Jump

Six maximal effort vertical jump trials were completed with more than 120 seconds rest between trials. Data from the best trial were used for analysis as the coach wanted data to compare with historical data. Vertical jump testing was performed using a Vertec (Swift Performance, QLD, Australia) following previously reported protocols (380). Standing reach was measured initially as the highest point reached on the dominant side with the heels in contact with the ground. The athlete then performed a countermovement jump for maximal vertical height, squatting to a self-selected depth from an erect stance, immediately concentrically jumping explosively to tap the vanes on the Vertec. This assessment method has previous been shown to be reliable for quantifying vertical jump height (CV: 4.6 to 7.6%, ICC: 0.87 to 0.94) (381).

12.4.3 Inertial load bike

Three continuous maximal effort inertial load bike trials were completed with more than 120 seconds rest between trials. The average from the three trials was used for analysis. The inertial load bike trial involved 8 maximal effort revolutions seated on a fixed-weight flywheel cycling ergometer. Flywheel weight was fixed at 30 kg with a moment of inertia of 1.08 $kg \cdot m^2$ and 165 mm crank length. Based on the results of Hautier et al. (26), optimal cadence was used as a quasi-measure of muscle fibre type. This assessment method has previously been shown to be reliable for assessing optimal cadence in power trained athletes following multiple familiarisations within our laboratory (Days 1 vs 2, CV: 3.8%, ICC: 0.69; Days 2 vs 3, CV: 2.2%, ICC: 0.92).

12.4.4 Load velocity profiling

Three maximal effort trials at each load were completed across movements (i.e. cable rotation, bench pull, bench throw and countermovement jump) with more than 120 seconds of rest between each load. The average of the three trials was used for analysis. The cable rotation involved 12, 24, and 36 kg loads, and the bench pull, bench throw, and countermovement jump involved 20, 40, and 60 kg loads. An additional 80 kg load was used during the countermovement jump. More than 120 s of rest was given between each attempt to ensure recovery. All tested loads followed a lightest to heaviest progression. Absolute loads were chosen as they are more ecologically valid to throwing as implement weight is fixed regardless of strength level. Furthermore the cable rotation loads are consistent with those observed to be reliable (see Chapter 8). Bench press and bench pull loads are consistent the loads used in Chapter 10 whereby bar velocity was related to seated putting performance.

12.4.5 Cable rotation

A box modified to fixate the hip was secured in front of a line bisecting two cables (Figure 12.2), allowing the sacrum to be positioned on the bisecting line. To fixate the hip, two adjustable rigid sides adjusted to pelvis width were added to the box. The cable was set at a height corresponding to seated shoulder height. Facing forward in an upright posture, the athlete held the cable handle in two hands with both elbows extended. Starting from neutral (Figure 12.2), the athlete rotated towards the cable pulley machine and immediately rotated concentrically in the opposite direction. Poles corresponding to 45° of rotation bilaterally were set to define the range of motion. Countermovement speed was self-selected and only trials where extension in both arms was maintained were analysed. Trials where 45° of rotation was not achieved or where visible elbow flexion was present were terminated and repeated. Only counter clockwise (dominant side) rotations were assessed. This assessment method has previously been shown to be reliable for assessing peak velocity (m/s, CV: 3.30 to 6.90%, ICC: 0.93 to 0.99) (382).

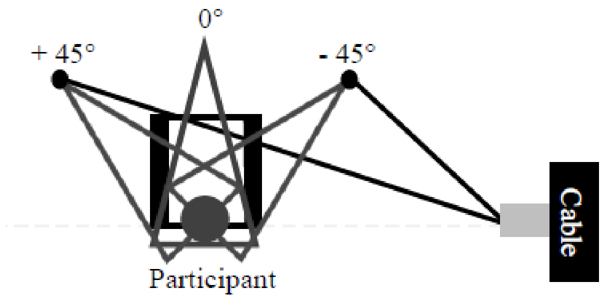

Figure 12. 2. Seated rotation set up.

12.4.6 Prone bench pull

A countermovement bench pull consistent with the methods of Sanchez-Medina et al. (307) was performed without the use of a Smith machine. Lying prone on a high-pull bench with a self-selected hand width, the athlete lowered the bar to an extended arm position and pulled the bar into the bench contacting a point coinciding with the xyphoid process. The bar was then lowered for the ensuing repetition that was immediately performed from full extension. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xyphoid process due to the steel frame. Instructions and verbal encouragement to contact the bench as forcefully as possible were given and only trials where contact was made were counted. Trials during which the chest or hips lifted off the bench were disregarded and repeated. The reliability of load velocity profiling in the bench pull has previously been documented (ICC: 0.81 to 0.90, CV: 5.19 to 6.89%) (383).

12.4.7 Bench throw

A countermovement bench throw was employed consistent with previous methods (226, 306, 384). Lying supine on a bench press, the bar was lowered to the chest at a self-selected speed, which was followed immediately by a concentric throw. The athlete was instructed that the bar should make light contact with the lower portion of the chest. Trials during which the head, shoulders, hips, or feet lost contact with their respective surfaces or bouncing of the bar off the chest was observed were disregarded and repeated. Instructions and verbal encouragement to throw the bar as high as possible were given. The reliability of peak bar velocity at similar loads during a bench throw has been previously documented (ICC: 0.86 to 0.96, CV: 1.80 to 3.55%) (384).

12.4.8 Countermovement jump

A countermovement jump consistent with previous investigations (308, 309) was used to quantify bar velocity. Starting in an erect position with an Olympic bar resting on the upper back, the athlete squatted down to a self-selected depth (310) and completed a concentric jump as explosively as possible. Instructions and verbal encouraged to jump as high as possible were given. The reliability of countermovement jump peak bar velocity has previously been demonstrated (ICC: 0.84 to 0.93, CV: 3.4%) (385).

12.4.9 Equipment and data analysis

All movements were analysed using a PT5A (Fitness Technologies, SA, Australia) LPT connected to the cable stack or bar. Displacement – time data was captured via a custom written LabVIEW programme at 1000 Hz. Manufactures recommendations for calibration were followed.

Displacement – time data from the LPT were analysed using a custom script written in MatLab (v2018a, MA, USA). Cable rotation LPT displacement data were multiplied by 1.8 to account for the 1.8:1 cable pulley gearing ratio and all data were filtered at 100 Hz using a 4th order Butterworth low-pass filter.

A peak detection algorithm was implemented to identify each repetition. Peaks were required to reach 80% of the maximum distance, and multiple peaks within one second were counted as a single repetition. The start of each repetition (concentric onset) was identified by finding the minimum displacement with an additional 1% added to exclude minor movements between repetitions. For each repetition across all movements peak velocity was calculated. For each repetition during the bench pull, bench throw, and countermovement jump peak velocity 100 ms pre (ECC100) and post (CON100) concentric onset was also calculated. One hundred millisecond windows pre and post concentric onset were chosen as they are consistent with contractile windows observed in elite throwing (9, 100, 386).

12.5 Resistance training and throwing periodisation

Resistance training and throwing training from November 2017 to March 2019 followed a periodised plan (Figure 12.3 and Figure 12.4). Throwing periodisation was planned in conjunction with the resistance training methods with a throws-driven focus. Throws-driven meant that throwing was prioritised over resistance training. Therefore, the resistance training programmes were designed to maximise adaptation with minimal residual fatigue which allowed for the completion of throwing trainings with maximal effort. A throws-driven resistance training method was chosen based on the association between hammers thrown and years throwing reported by Judge et al. (120), and the connection between throwing and performance observed in prior case studies (14, 22). During periods of heavy throwing (i.e., more volume and heavy hammer weights), more fatiguing modes of resistance training were integrated. In contrast, during lighter throwing periods, a detraining resistance training mode was integrated.

The resistance training periodisation was based on a theoretical model of periodisation (see Chapter 6). Briefly, the periodisation model aimed to increase early force – time and high velocity force application by cycling resistance training modes to conserve or increase fibre type qualities, enhance tendinous qualities, and increase peak force. Resistance training programmes generally consisted of 3 to 5 sets of 2 to 6 repetitions of compound type movements. Thereafter, eccentric training at various speeds and ballistic weeks were cycled. Eccentric training was performed with supra-maximal loads of ~3 s (slow, S ECC), ~2 s (moderate, M ECC) or less than 1 s (fast, F ECC) (Figure 12.4). Throughout the programme, loads were adjusted to modulate the eccentric duration. Similarly, modes were modulated to ensure movements were ballistic in nature during ballistic periods.

General	Year	2017								2018																										
	Month	November				December				January					February				March				April					May				Jun				July
		6/11/2017	13/11/2017	20/11/2017	27/11/2017	4/12/2017	11/12/2017	18/12/2017	25/12/2017	1/01/2018	8/01/2018	15/01/2018	22/01/2018	29/01/2018	5/02/2018	12/02/2018	19/02/2018	26/02/2018	5/03/2018	12/03/2018	19/03/2018	26/03/2018	2/04/2018	9/04/2018	16/04/2018	23/04/2018	30/04/2018	7/05/2018	14/05/2018	21/05/2018	28/05/2018	4/06/2018	11/06/2018	18/06/2018	25/06/2018	2/07/2018
	Days training	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6						6	6	6	6	6	6	6	6	6	6	6	6
	Weekly intensity (H-M-L)	H	H	L	M	H	H	L	H	H	L	M	M	L	M	H	H	L	M						M	H	H	L	M	H	H	L	L	M	H	H
Throwing	Throws sessions/week	7	7	5	6	7	7	5	6	6	6	6	6	5	7	7	7	5	6						6	6	6	4	7	7	7	5	5	7	7	7
	Total throws	180	80	120	160	180	80	120	160	180	80	80	80	80	80-100	100-140	100-140	60-80	80-100						80-100	>120	>130	<100	100-120	>140	>150	<100	<100	100-130	>150	>160
	Rep range	1	1	1	1	1	1	1	1	1	1	1	1	1-2	1-2	1-2	1-2	1	1						1-3	1-3	1-3	1-2	1-3	1-3	1-3	1-2	1-2	1-3	1-3	1-3
	Percentage of volume spent with implement: 3kg																																			
	3.5kg																																			
	4kg short																																			
	4kg	Daily fluctuation to throw 60-67m. Split into 60-62m, 62-65m, 65-67m								Daily fluctuation in loads to throw 65 - 70m+. Split into technical days and 67-70m and 70m+										On break																
	4kg long																																			
	4.5kg																																			
	5kg																																			
	5.5kg																																			
	6kg																																			
Resistance	Gym sessions/week	3	3	2	3	3	3	2	3	3	3	2	2	3	3	3	3	2	2						3	3	3	2	3	3	3	2	2	3	3	3
	Programing specifics: Primary	F ECC		Pwr	F ECC			VBT						Pwr											Strength				S ECC			Pwr		F ECC		
	Secondary	VBT			VBT			Plyo																	Pwr				Strength			Plyo		Pwr		

Figure 12. 3. Throwing and resistance training periodisation from November 2017 to July 2018. H – M – L, high – moderate – low; Pwr, power training; VBT, velocity based training; Plyo, plyometric training; S ECC; slow velocity eccentric training; F ECC, fast velocity eccentric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

		Year	2018																									2019										
General		Month	July				August				September				October					November				December				January					February				March	
			9/07/2018	16/07/2018	23/07/2018	30/07/2018	6/08/2018	13/08/2018	20/08/2018	27/08/2018	3/09/2018	10/09/2018	17/09/2018	24/09/2018	1/10/2018	8/10/2018	15/10/2018	22/10/2018	29/10/2018	5/11/2018	12/11/2018	19/11/2018	26/11/2018	3/12/2018	10/12/2018	17/12/2018	24/12/2018	31/12/2018	7/01/2019	14/01/2019	21/01/2019	28/01/2019	4/02/2019	11/02/2019	18/02/2019	25/02/2019	4/03/2019	11/03/2019
	Days training #		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6																		
	Weekly intensity (H-M-L)		L	M	L	L	H	H	L	M	H	H	L	M	H	H	L	M	H	H	L	L	L	L	L	L	L	M	H	L	L	H	H	M	L	L	L	
Throwing	Throws sessions/week		6	7	5	6	7	7	5	7	7	7	5	7	7	7	5	7	7	7	7	8	8	8	8	8	8	7	7	8	8	8	8	8	8	8	6	
	Total throws		100-120	100-120	<100	<100	>140	>160	<100	100-120	>150	>160	<100	>150	>180	120-150	<100	>150	>180	120-150	<100	100-150	100-150	100-150	100-150	100-150	100-150	>150	>180	120-150	<100	120-150	120-150	<100	<100	<100	<100	
	Rep range		1	1	1	2	1-3	1-3	1-2	1-2	1-3	1-3	1	1	1-3	1-3	1-2	1-2	1-3	1-3	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2	1-2			
	Percentage of volume spent with implement	3kg																																				On Break
		3.5kg																																				
		4kg short																																				
		4kg																																				
		4kg long																																				
		4.5kg																																				
		5kg																																				
		5.5kg																																				
		6kg																																				
Resistance	Gym sessions/week		2	2	2	2	3	3	2	3	3	3	2	3	3	3	2	3	3	3	1	1	1	1	1	1	1	3	3	2	2	3	3	2	1	1	1	
	Programing specifics	Primary	Pwr				M ECC	F ECC	VBT	VBT	M ECC	M ECC	VBT	VBT	M ECC	M ECC	VBT	VBT	F ECC		VBT																	
		Secondary	Plyo						F Iso	Plyo				Plyo				Plyo			Pwr/Plyo																	

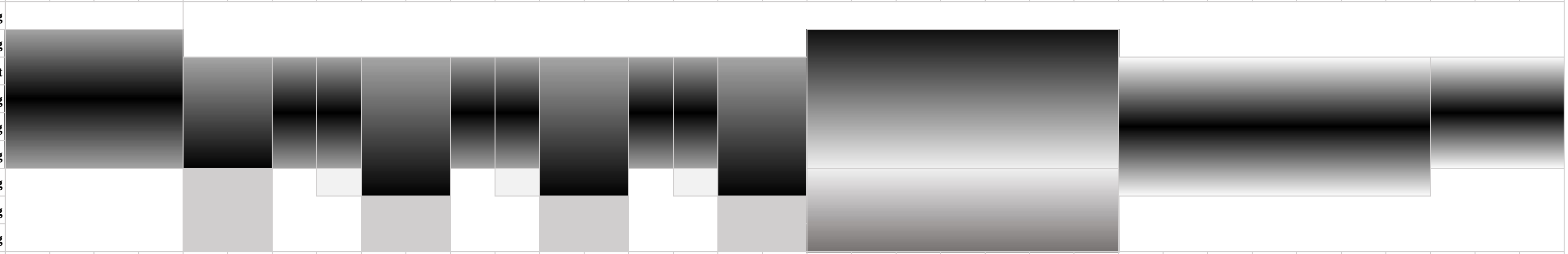

Figure 12. 4. Throwing and resistance training periodisation from July 2018 to March 2019. H – M – L, high – moderate – low; Pwr, power training; VBT, velocity-based training; Plyo, plyometric training; S ECC, slow velocity eccentric training; M ECC, moderate velocity eccentric training; F ECC, fast velocity eccentric training; F Iso, fast isometric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

12.6 Coaching directives

There were two main periods with three main coaching directives. The coaching directives were:

- Catching the hammer earlier (increasing the azimuth angle at right foot down)
- Increasing length (throwing with full shoulder protraction)
- Ascending rhythm (starting with high hammer ball speed and increasing it through the turns)

Throughout the tracking period, the three directives were emphasised at different time points. The third directive of ascending rhythm was often emphasised leading into the competition season. The former two, catching the hammer earlier and increasing length, were emphasised primarily outside of the competitive season.

12.7 Statistical analysis

Longitudinal change was quantified using a mixed statistical and visual analysis method (387) to allow for the quantification of large changes in the analysed variables (388). The two band SD method was used for the purpose of this investigation due to its agreement with the C statistic and split method of trend estimation (388). Within this method, numerical changes were tracked via graphs with significant change quantified by a clear set of rules. The graphs have two bands that indicate two SD above (upper band) and two SD below (lower band) the pre-test mean. Post-test data points on the graph that fall outside either bands define a significant change. Changes are considered more meaningful when consecutive or numerous data points fall outside the SD lines (Figure 12.5) (388). Visual analysis was used to identify trends in the data and was defined as two or more data points trending in the same direction (Figure 12.5). Furthermore, neuromuscular and biomechanical variables were mapped against the criterion performance variable to identify concurrent changes over prolonged periods. Additionally, to provide comparison between distinct data points where performance or release velocity showed large changes, raw (and percentage) change in variables was quantified and presented as mean ± SD. This gave the ability to compare biomechanical and neuromuscular status between data points.

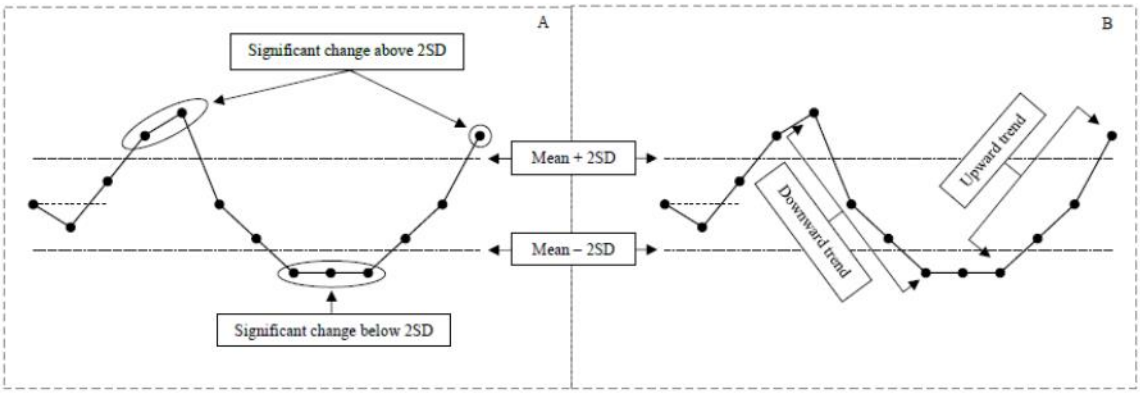

Figure 12. 5. (A) Statistical, and (B) visual analysis methods used.

12.8 Results

12.8.1 Throwing performance

Competition performance change can be observed in Figure 12.6. A significant increase in performance was observed in both December 2017 and January 2018 and again in January and February 2019. From January 2019 to March 2019 a downward trend in performance was observed. Due to the lack of competitions undertaken between February 2018 and January 2019, no trends could be identified.

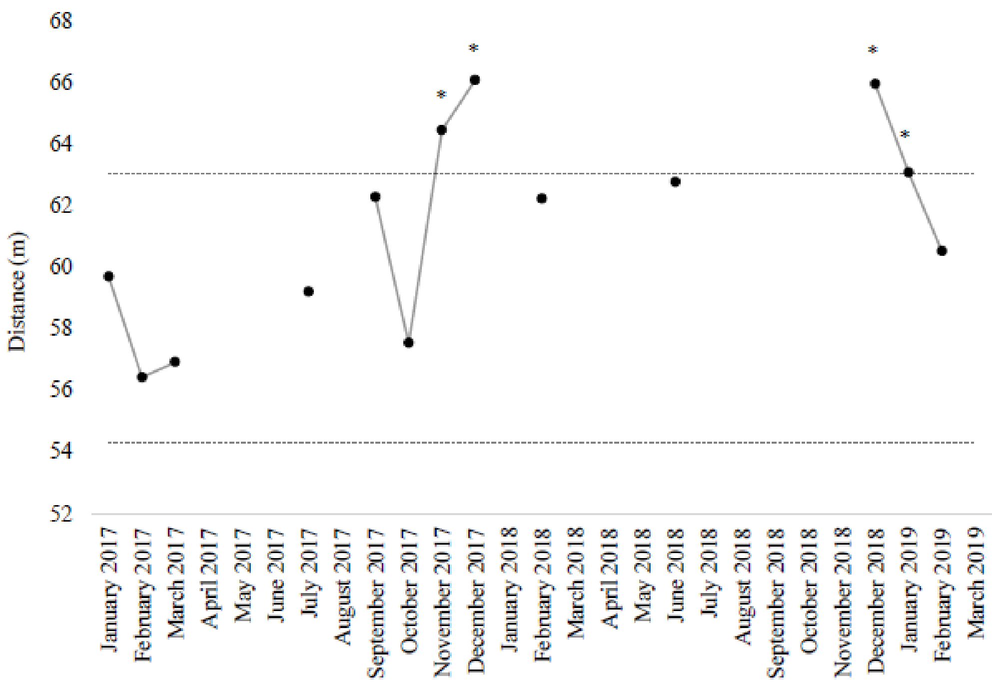

Figure 12. 6. Competition performance pre and during the investigation period (November 2018 to March 2019). * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

12.8.2 Biomechanical variables

Release velocity can be seen in Figure 12.7. Significant increases in release velocity were observed in February 2018 and from August 2018 to January 2019. After dropping below the +2SD bandwidth in May 2018, release velocity trended upwards to a peak in September 2018 (7.6% increase between May and September 2018) and then declined through to January 2019. The period from May to September 2018 was defined as the period of interest and chosen for further analysis as a progressive rise in release velocity was observed.

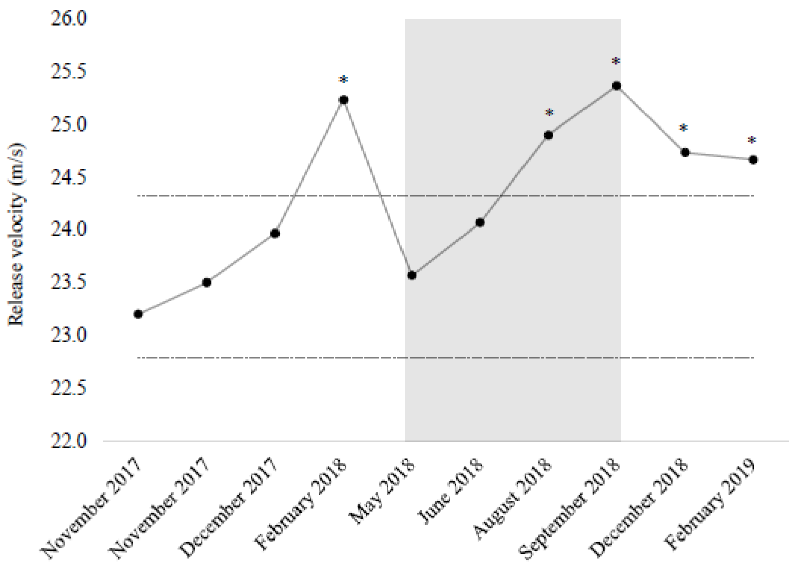

Figure 12. 7. Release velocity during the investigation period. Dashed lines show ± 2 standard deviation bandwidth. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Hammer velocity at right foot down and right foot off during the investigation period is presented in Table 12.1. A significant decrease in hammer velocity was observed in Turn 1 at right foot down in June 2018, but did not correspond with further decreases in hammer ball velocity. Significant increases in hammer velocity during early foot contacts corresponded with significant increases in all proceeding contacts. Hammer velocity at all foot contacts and events following Turn 1 right foot off trended up from May to September 2018, and downward from September 2018 to February 2019. When comparing May 2018 to September 2018, hammer velocity at each foot contact increased. Velocity at each event systematically increased with each turn (RO = 0.2% to 7.64%, RD = 1.8 to 9.5%).

Table 12. 1. Hammer velocities at right foot off (RO) and right foot down (RD). Two standard deviation (2SD) bandwidth values are provided.

	First RO	Turn 1 (m/s)		Turn 2 (m/s)		Turn 3 (m/s)		Turn 4 (m/s)	
		RD	RO	RD	RO	RD	RO	RD	Release
November 2017	14.9	14.2	18.3	17.4	20.5	19.0	22.1	19.8	23.2
November 2017	14.3	14.0	16.5	16.0	19.2	18.0	20.9	19.3	23.5
December 2017	15.1	14.8	18.1	17.4	20.2	19.5	21.5	20.2	24.0
+2SD	15.6	15.1	19.6	18.6	21.4	20.4	22.7	20.7	24.3
-2SD	13.9	13.5	15.7	15.3	18.5	17.3	20.3	18.8	22.8
Intervention period									
February 2018	14.8	14.3	18.8	18.2	21.2	20.0	22.9*	20.9*	25.2*
May 2018	14.9	14.5	18.0	17.6	20.2	18.6	21.4	20.0	23.6
June 2018	14.4	13.5#	17.8	17.5	20.8	19.6	22.4	20.2	24.1
August 2018	14.7	14.6	17.7	17.4	21.1	19.7	23.0*	20.8*	24.9*
September 2018	14.9	14.8	18.5	18.0	21.4*	20.4*	23.0*	21.9*	25.4*
December 2018	14.5	14.5	17.6	17.6	20.3	19.7	21.7	20.1	24.7*
February 2019	14.4	14.1	16.5	15.6	19.6	18.1	21.8	19.5	24.7*

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Changes in azimuth angles are reported in Table 12.2. Azimuth angles from December 2017 first right foot off trended downwards, reaching statistical significance from September 2018 to February 2019. With a significant decrease in first right foot off angle was a significant increase in right foot down, Turn 1 azimuth angle. During Turn 2, a change was observed from September 2018 to February 2019 with increases in right foot down azimuth angles being significant in September 2018 and February 2019. Turn 2 right foot off azimuth angle fluctuated, reaching a level of statistical decrease in February 2018, September 2018, and December 2018. Turn 3 right foot down azimuth angle trended upwards from June 2018, reaching a level of statistical increase from September 2018 to February 2019. Right foot off azimuth angle during Turn 3 fluctuated, but generally trended downward from December 2017. In contrast, right foot down showed an opposite trend during the same time period. Release azimuth angle increased in June 2018, thereafter tended to decrease, reaching statistical significance from September 2018 to February 2019. When comparing between May and September 2018, both increases and decreases in azimuth angle were observed. Right foot off in each turn (First RO to Turn 3) decreased 10.1% to 42.7% between time points. In contrast, right foot down increased 2.2% to 23.1% between Turns 1 to 3, but decreased 4.9% in Turn 4.

Table 12. 2. Azimuth angles (°) at right foot off (RO) and right foot down (RD) during each turn across the intervention period. Two standard deviation (2SD) bandwidth values are provided.

	First RO	Turn 1 (°)		Turn 2 (°)		Turn 3 (°)		Turn 4 (°)	
		RD - 0	**0 - R0**	**RD - 0**	**0 - R0**	**RD - 0**	**0 - R0**	**RD - 0**	**0 - R0**
November 2017	95.9	112.0	82.6	111.1	74.7	111.0	54.4	117.5	116.8
November 2017	85.6	113.2	101.0	100.6	85.2	106.4	67.2	111.4	123.4
December 2017	100.0	101.2	94.2	110.1	90.2	97.2	85.7	88.1	121.7
+2SD	108.6	122.0	111.3	118.9	99.2	119.0	100.6	136.8	127.5
- 2SD	79.0	95.6	73.9	95.7	67.6	90.7	37.6	74.6	113.8
				Intervention period					
February 2018	98.9	111.1	86.1	108.7	66.6#	96.0	70.1	99.6	124.1
May 2018	96.5	113.3	93.2	101.8	83.9	118.9	66.0	116.4	120.4
June 2018	93.1	118.3	92.3	99.6	84.8	103.9	77.1	96.3	130.9*
August 2018	86.7	101.3	96.8	99.5	73.5	113.5	49.8	120.0	120.0
September 2018	55.3#	139.5*	79.1	120.1*	58.5#	121.5*	59.3	110.7	113.5#
December 2018	74.5#	134.0*	94.4	118.5	65.1#	125.6*	38.1	129.1	111.5#
February 2019	75.9#	131.0*	86.0	119.7*	71.6	125.4*	40.5	129.8	108.9#

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

12.8.3 Neuromuscular variables

Inertial load bike optimal cadence and peak power is presented in Figure 12.8. Optimal cadence initially fluctuated before significantly decreasing between August and December 2018, following which a significant increase was observed. Peak power significantly decreased in May 2018, then trended upwards reaching a significant increase in August 2018 and September 2018 before significantly decreasing in December 2018. Changes in peak power from May to September 2018 were concurrent with release velocity during the same period. When examining May 2018 to September 2018, a period during which release velocity trended up, optimal cadence decreased 3.1% whereas peak power increased 13.1%.

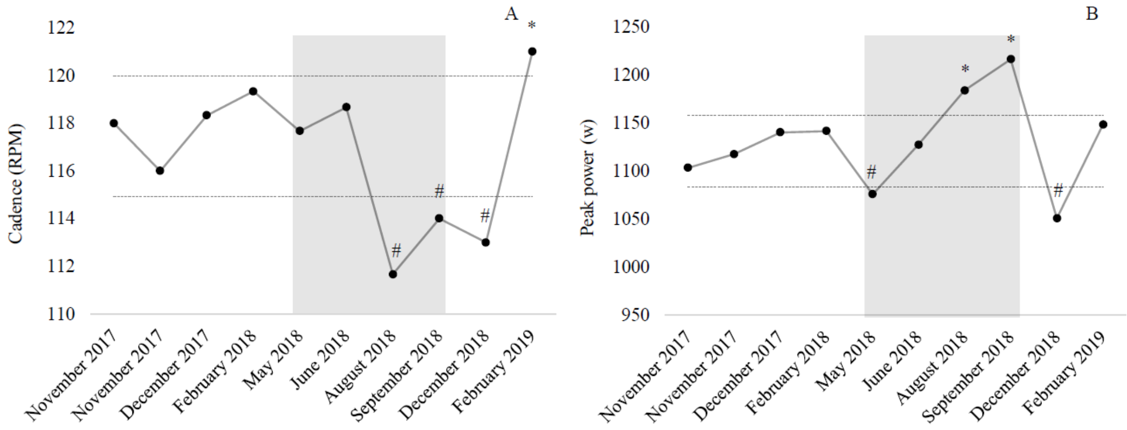

Figure 12. 8. Inertial load bike (A) optimal cadence, and (B) and peak power.

Jump height and body mass are presented in Figure 12.9 (A and B, respectively). Following baseline testing (November to December 2018), jump height significantly declined from February 2018 to February 2019. In contrast, body mass trended up from February 2018 to February 2019. From May 2018 to September 2018, vertical jump decreased 2.1% while body mass increased 1.7%.

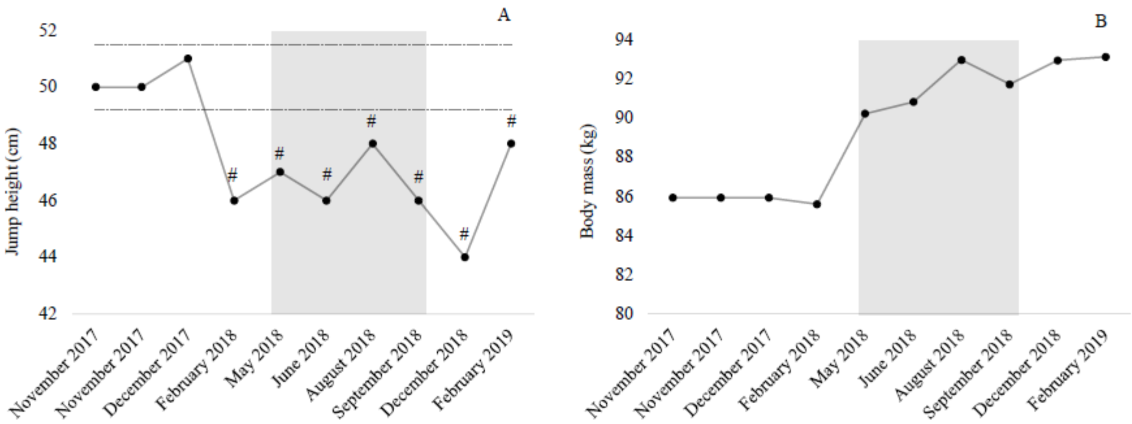

Figure 12. 9. (A) Vertical jump height, and (B) body mass. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Peak bar velocities of all movements are reported in Figure 12.10 (A to D). Countermovement jump peak bar velocity (Figure 12.10A) significantly decreased from May 2018 to February 2019 in both 60 kg and 80 kg conditions, and from August 2018 to February 2019 in the 40 kg condition. A significant decrease was observed only in December 2018 in the 20 kg load; however, a downward trend from August to December 2018 was observed. When comparing peak velocity between May and September 2018, decreases of 2.1%, 4.2%, and 1.1% were observed with 20, 40, and 60 kg, but no change was observed with 80 kg.

Bench throw peak bar velocity (Figure 12.10B) at 60 kg significantly decreased from February 2018 to June 2018 and in August 2018, December 2018, and February 2019 as no repetitions were completed. At the 40 kg load, significant decreases were observed in February 2018, August 2018, December 2018, and February 2019. With regard to the 20 kg condition, peak bar velocity significantly decreased from February 2018 to February 2019. When comparing May to September 2018, peak velocity increased 2.1%, 3.9%, and 33% with 20 kg, 40 kg, and 60 kg respectively.

Bench pull bar velocity (Figure 12.10C) significantly decreased in the 60 kg condition from September 2018 to February 2019. With regard to the 40 kg load, peak bar velocity trended downward from August 2018 to February 2019 reaching statistical significance in February 2019. With regard to the 20 kg load, a significant decrease was observed only in May 2019. When comparing May and September 2018, peak bar velocity increased 36.0% and 11.2% with 20 and 40 kg loads, but decreased 11.1% with the 60 kg load.

With regard to the cable rotation, peak velocity trended downward in February 2018 reaching a level of significant decrease in September 2018 at the heaviest load. In the other two loads, fluctuations in peak velocity between months were observed, but no clear trends identified. When comparing May and September 2018, peak velocity increased 7.9% and 6.9% with 12 and 24 kg loads, but decreased 12% with the 36 kg load.

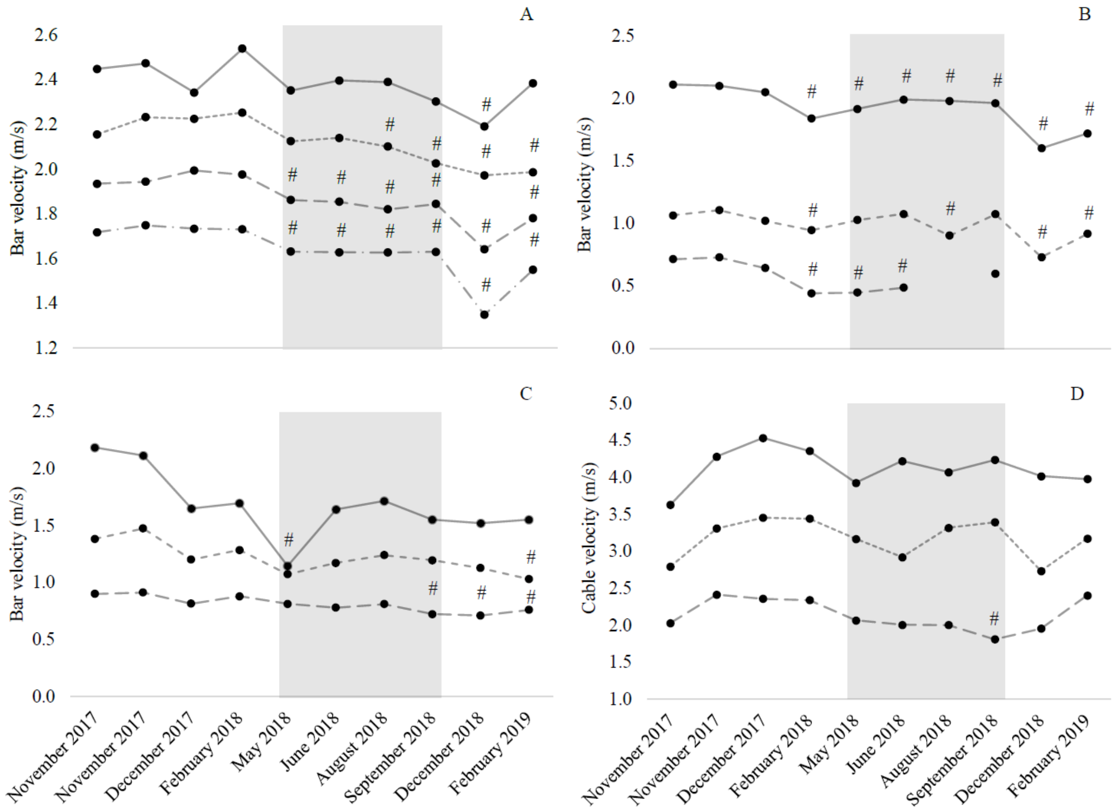

Figure 12. 10. Peak bar velocities during a loaded (A) countermovement jump, (B) bench throw, (C), bench pull at 20 kg (—), 40 kg (····), 60 kg (- - -), and 80 kg (·· —), and (D) cable velocity during the cable put at 12 kg (—), 24 kg (····), and 36 kg (- - -). * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

ECC100 and CON100 during the loaded countermovement jump is reported in Table 12.3. CON100 significantly decreased across the majority of the months (February 2018 to February 2019) and ECC100 significantly decreased from September 2018 to February 2019 with 40 kg, 60 kg, and 80 kg loads. ECC100 bar velocity with 20 kg fluctuated below and above the two SD bandwidths. Significant increases in February 2018, August 2018, and February 2019, and significant decreases in May 2018, September 2018, and December 2018 were observed. CON100 significantly decreased in both September and December 2018 with no trends observed. When comparing May 2018 with September 2018, decreases in both ECC100 (8.2 to 12.1%) and CON100 (7.5 to 13.3%) were observed.

Table 12. 3. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during countermovement jump at four loads.

	20 kg		40 kg		60 kg		80 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-0.94	1.12	-0.74	0.82	-0.61	0.65	-0.48	0.49
November 2017	-0.93	1.06	-0.79	0.82	-0.52	0.58	-0.42	0.46
December 2017	-0.92	1.02	-0.73	0.83	-0.56	0.60	-0.40	0.47
+2SD	-0.95	1.17	-0.81	0.83	-0.66	0.68	-0.52	0.51
-2SD	-0.91	0.96	-0.70	0.81	-0.47	0.53	-0.34	0.44
Intervention period								
February 2018	-1.08*	1.16	-0.76	0.82	-0.55	0.59	-0.43	0.43#
May 2018	-0.91#	1.02	-0.73	0.75#	-0.49	0.53#	-0.36	0.40#
June 2018	-0.94	1.02	-0.71	0.74#	-0.52	0.53#	-0.37	0.43#
August 2018	-0.97*	1.05	-0.77	0.76#	-0.52	0.56	-0.43	0.47
September 2018	-0.80#	0.93#	-0.65#	0.65#	-0.45#	0.49#	-0.32#	0.35#
December 2018	-0.75#	0.79#	-0.60#	0.61#	-0.41#	0.43#	-0.30#	0.28#
February 2019	-0.99*	0.97	-0.67#	0.68#	-0.50	0.49#	-0.33#	0.36#

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Bench throw ECC100 and CON100 is reported in Table 12.4. Both CON100 and ECC100 significantly decreased over the investigation period with the exception of September 2018 in the heaviest load. Significant decreases in ECC100 were observed across multiple months (June, August, December 2018) in the 40 kg condition, but only in December for CON100. With regard to the 20 kg load, significant decreases in CON100 were observed over all months, and ECC100 in May and December 2018. Between May and September 2018 when velocity trended upwards, ECC100 increased 15.4% and 80.6% with the 20 kg and 60 kg loads, respectively; but decreased 4.4% with the 40 kg load. CON100 increased 8.3%, 11.8%, and 120% with 20 kg, 40 kg, and 60 kg, respectively.

Table 12. 4. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench throw at three loads.

	20kg		**40kg**		**60kg**	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-1.52	1.34	-0.91	0.80	-0.70	0.58
November 2017	-1.38	1.27	-0.89	0.78	-0.54	0.46
December 2017	-1.32	1.29	-0.80	0.70	-0.59	0.48
+2SD	-1.62	1.37	-0.97	0.87	-0.78	0.64
-2SD	-1.19	1.23	-0.76	0.65	-0.45	0.37
			Intervention period			
February 2018	-1.36	1.15#	-0.86	0.69	-0.45#	0.36#
May 2018	-1.10#	1.08#	-0.90	0.68	-0.36#	0.25#
June 2018	-1.25	1.18#	-0.75#	0.68	-0.39#	0.32#
August 2018	-1.31	1.15#	-0.73#	0.66		
September 2018	-1.27	1.17#	-0.86	0.76	-0.65	0.55
December 2018	-1.11#	1.00#	-0.66#	0.55#		
February 2019	-1.10#	1.03#	-0.78	0.67		

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Bench pull ECC100 and CON100 is reported in Table 12.5. CON100 over the majority of months significantly decreased across loads. However, ECC100 was significantly decreased in February 2018 (20 kg load), from May to August (40 kg load), and from June to December 2018 (60 kg load). The only significant increases observed was ECC100 in the 40 kg load in September 2018 and February 2019. When comparing May and September 2018 when a large change in release velocity was observed, ECC100 increased 19.3% and 98.3% with 20 kg and 40 kg loads, respectively; but decreased 25.9% in the 60 kg condition. CON100 followed a similar pattern, increasing 51.0% and 86.0% with 20 kg and 40 kg, respectively; but decreased 50.0% in the 60 kg load.

Table 12. 5. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench pull at three loads.

	20 kg		40 kg		60 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-1.64	1.45	-1.11	0.92	-0.64	0.50
November 2017	-1.65	1.37	-1.05	0.97	-0.66	0.55
December 2017	-1.33	1.14	-0.99	0.87	-0.36	0.40
+2SD	-1.90	1.64	-1.16	1.02	-0.89	0.64
-2SD	-1.18	1.00	-0.94	0.82	-0.21	0.33
			Intervention period			
February 2018	-0.64#	0.68#	-1.15	0.75#	-0.43	0.48
May 2018	-1.19	0.51#	-0.60#	0.50#	-0.27	0.36
June 2018	-1.47	1.13	-0.89#	0.67#	-0.19#	0.36
August 2018	-1.36	0.75#	-0.88#	0.78#	-0.05#	0.33#
September 2018	-1.42	0.77#	-1.19*	0.93	-0.20#	0.18#
December 2018	-1.40	1.00#	-1.12	0.84	-0.14#	0.32#
February 2019	-1.44	0.88#	-1.16*	0.71#	-0.25	0.27#

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

12.9 Discussion

Coaches and athletes seek to enhance performance year on year through planned biomechanical and neuromuscular change. Biomechanical and neuromuscular change is sought prior to the competition season to enhance performance during the competitive season. One way in which performance enhancing biomechanical and neuromuscular variables can be identified is to track them longitudinally against competition results and primary predictors of performance. The present investigation also sought to understand the relationship between biomechanical and neuromuscular variables from May to September 2018 as a clear upward trend in release velocity was identified. Furthermore, illness in early December 2018 disrupted progression through the later part of this investigation.

The main findings from a performance and biomechanical perspective were: 1) performance was significantly improved in January 2018 and January 2019, which corresponded with the competitive season; 2) release velocity trended upwards from May to a peak in September 2018; 3) increased release velocity during the May to September 2018 period corresponded with a systematic increase in hammer velocity from Turn 2 RO to release, and 4) azimuth angle did not change concurrently with release velocity, although an overall decrease in RO and increase in RD azimuth angle occurred across the intervention.

The main neuromuscular findings were: 1) inertial load peak power trended upwards reaching statistical significance, with changes corresponding with release velocity changes during the May to September 2018 period; 2) vertical jump height significantly decreased across the intervention; and 3) significant decreases in peak velocity, ECC100 velocity, and CON100 velocity were observed across the majority of movements and loads.

Modulating training so that biomechanical and neuromuscular adaptations peak at targeted events to enhance performance requires careful planning. Our data show that performance was significantly elevated during the competitive season in 2018 and 2019. When comparing between seasons, competition performance decreased 0.2% which is likely related to a significant illness late in 2018. We chose to compare the May to September 2018 period where release velocity trended upwards (Figure 12.7) and was not affected by illness. Increases in release velocity during May to September 2018 corresponded with increased ball velocity during the preceding contacts. Time points where ball velocity increased early in the throw resulted in the greatest release velocity (see Table 12.1, September 2018). The data presented by Isele and Nixdorf (94) suggest what we observed here in our case study, where hammer velocity at Turn 2 tended to differentiate release velocity. Our data show that changes in release velocity do not directly correspond with changes in azimuth angle. Judge et al. (16) and Judge et al. (22) reported a temporal shift toward greater relative time spent in double support to correspond with longer throwing distances. Our data do not support these findings as increases in right foot down azimuth were often seen with decreases in right foot off, resulting in similar total angular displacement in double support and similar relative temporal timings. Our data do however suggest that the angular timing of right foot down azimuth angles might aid in increasing release velocity. The coaching directive during the later periods was to “catch the hammer earlier” (right foot down occurs at a greater azimuth angle) to maximise the effects of gravity on hammer acceleration and to gain a parametric oscillatory hip height to hammer relationship that has been observed in elite throwers (7, 95).

When comparing neuromuscular variables to release velocity, only inertial load bike peak power trended upwards with release velocity during the May to September 2018 time period. Cook (119) reported peak anaerobic power normalised to body mass to significantly correlate to hammer throwing performance. Our results support these findings and suggest that peak power during a bike related test corresponds to increasing hammer velocity, that predicts performance. It should be noted that strong correspondence between inertial load peak power and release velocity was observed during only a portion of the interventional period, following which illness confounded further biomechanical and neuromuscular performance. Thus the ability of inertial load peak power to be predictive of performance requires further longitudinal exploration.

With regard to peak bar velocities, decreases were observed in the majority of loads and movements, both during the interventional period and between May and September 2018 when release velocity was increasing. Similarly, Pilianidis et al. (14) showed heavy load back squat strength does not have a causal role in increasing hammer performance. However, both Judge et al. (16) and Judge et al. (22) reported back squat strength to be greatest when the highest performance was achieved, but strength and power did not to trend accordingly with performance during preceding years. Furthermore, Bourdin et al. (124) observed a significant correlation between bench press power and hammer performance ($r = 0.83$, $p < 0.001$), which is in contrast to our observations. The disagreement between our findings and those of Bourdin et al. (124) could be related to sex as males likely require greater chest strength to accelerate a 7.26kg hammer. Concurrent with peak bar velocities, ECC100 and CON100 velocity across loads and movements decreased during periods of increasing release velocity, as did vertical jump height. In contrast, Bourdin et al. (124) reported a significant correlation ($r = 0.73$, $p < 0.001$) between drop jump reactiveness and male hammer throwing performance, and both Judge et al. (16) and Pilianidis et al. (14) reported increases in light explosive shot put and jumping movements with performance in elite female hammer throwers. The disagreement between our observations and those reported previously is difficult to explain as our results add to the discrepancy within the literature and largely suggest traditional strength measures are relatively unimportant to increase hammer throwing performance. However we did not calculate power that, with the increase in body weight, may have changed differentially to that of velocity. In support of previous literature, it is likely that the volume of hammer throwing resulted in increased hammer specific strength that cannot be quantified by resistance based movement variables (14, 16, 120). Thus, the role of strength and power in hammer throwing remains equivocal. As such future research should look to quantify measures of hammer specific strength. Such metrics are likely derived from rhythmical, multiple rotational movements and not linear resistance-based movements.

With regards to the periodisation model employed in the current investigation, it can be concluded that it resulted in performance enhancements at the planned times; however, adaptive profiles largely diverged from those predicted. The sequence of velocity-based training, eccentric training, ballistic type training, detraining, and retraining was theorised to enhance or maintain fibre type while enhancing peak force. Altogether, the programming should result in increased early force – time and high velocity force application. Fibre type and high velocity force production were tracked via optimal cadence that is a proxy for whole muscle fibre type (26, 389) and peak power. Strength and early force – time application was measured via light and heavy load bar velocities. Maximum strength via a 1RM test could not be performed due to the practical constraints of not being able to test maximal lifts during the season. Our data suggest that the current athlete became weaker and exhibited poorer early force – time ability in response to the periodisation sequence. That said, post the detraining and retraining periods, optimal cadence was significantly elevated suggesting a fibre type adaptation had taken place (26). It is possible that residual fatigue resulting from heavy load eccentrics depressed muscular output from February to September 2018 and then severe sickness in December detracted from subsequent results (390). Furthermore, resistance training was hammer specific where movements were largely performed in postures ecologically associated with hammer throwing. Thus, neuromuscular adaptations from throwing training may not have transferred to bilateral countermovement type movements due to lack of specificity.

Alternatively, our results could be indicative of a non-responder to the current periodisation scheme. Differentiating between lack of specificity and lack of training response is challenging.

12.10 Conclusions

The present investigation shows that performance can peak at targeted periods through structured periodisation plans. The changes in performance were accompanied by increased release velocity that corresponded with hammer velocity increases during Turns 2 to 4, but not with changes in azimuth angles or neuromuscular output measures. Thus, performance in the current female hammer thrower was not predicted by neuromuscular output assessed using countermovement jump, bench throw, bench pull, or cable rotation. Future investigations with larger sample sizes are required to further understand the predictive nature of inertial load bike power in hammer throwing. Such investigations should integrate neuromuscular testing more specific to hammer throwing, considering postures and movements more akin to hammer throwing. Finally, the lack of response or expected response to the current periodisation sequence requires further investigation at an individual level.

Chapter 13

The integration of biomechanics and resistance training in male discus throwing: A case study

13.0 Prelude

The previous two Chapters tracked two hammer throwers (one junior male and one senior female) over a longitudinal period. These Chapters integrated the methods discussed in prior Chapters (6, 8, 9, and 10) to understand which biomechanical and neuromuscular variables related to performance longitudinally. Interestingly, the two case studies showed divergent results. Similar to that of hammer throw, Chapters 2 and 5 identified a paucity of literature detailing the changes in discus biomechanics and neuromuscular status over longitudinal periods. Accordingly, this Chapter sought to understand which biomechanical and neuromuscular variables relate to discuss throwing performance. To ensure comparability between events and Chapters, the same testing was employed apart from the 3D tracking method. Briefly, the periodised model presented in Chapter 6 was included in the yearly training plan, as was the cable rotation and bench pull. A single subject design was adopted where-by one sub-elite (top 2 in New Zealand) senior male discus thrower was tested periodically over a 14-month period.

13.1 Introduction

The discus throw is one of the four throwing events within the Olympic track and field programme. Competitive athletes perform approximately two rotations holding onto the discus with the objective of generating maximal displacement of the discus upon release. Through the throwing motion, the athlete must stay within a 2.5 m circle and the discus must land within the throwing sector to be an official result (1). A male senior discus weighs 2.00 kg and has fixed dimensions (Disc diameter; 219 – 221 mm, depth; 44 – 46 mm, inner plate diameter; 50 – 57 mm, metal rim depth; 12 – 13mm) as specified by the International Athletics Association Federation (IAAF). Discus performance, in addition to projectile motion, is affected by aerodynamic properties (i.e., lift and drag) that are a function of discus orientation relative to atmospheric conditions and laws of projectile motion (6, 28). However, within the variables related to flight distance, release velocity has the greatest impact on the distance achieved (39). As such, technical coaches and strength coaches seek to adapt variables related to increased release velocity.

In principle, increasing release velocity of the discus is a function of impulse, that is the magnitude of force applied and the time over which it is applied. With regard to the magnitude of force applied, direction of force application is important to consider to achieve optimal launch conditions. Therefore, biomechanical factors that determine magnitude, direction, and time of force application as well as neuromuscular factors that enhance the possible magnitude and time of force application need to be considered in athlete preparation to enhance performance.

Throughout each phase of the discus throw, researchers have demonstrated elite throws to exhibit large magnitudes of angular momentum about the vertical axis (34, 39), vertical and horizontal ground reaction forces bilaterally (30), and hip to shoulder and shoulder to arm separations (8, 32, 51). Given that kinematic variables in male discus throwers have not been documented longitudinally, the causative effect of altering mechanics on performance remains largely unknown.

Little data are available in relation to neuromuscular capabilities and discus throwers. The few studies available suggest bench press kinetics (124, 126), lower limb stiffness and power (13, 124), and discus-specific force capabilities (13) are important to throwing performance. Given the paucity of literature, investigating resistance training methods that support the biomechanics and neuromuscular qualities underpinning discus performance is required. Biomechanically, the discus throw exhibits high early force – time and high velocity force application from both lower body and upper body segments. As such non-specific force production needs to span the force-velocity spectrum within time constrained windows. Therefore, resistance training must consider relating mechanisms and movements to increase release velocity. The mechanisms related to early force – time (impulse and/or rate of force development within 200 ms) and high velocity force application are well documented and include peak force (17, 138), muscle fibre type (21, 143), tendon stiffness (18, 137), and neural output (136, 137). A detailed report of resistance training practices driven by biomechanical understanding of the discus throw is not available in the scientific literature. Thus, tracking multiple neuromuscular variables, related to theoretical determinants, and noting biomechanical changes over a longitudinal period could provide valuable insight for coaches and athletes. The purpose of this investigation was therefore to monitor the influence of a periodised resistance training and throwing programme on elite discus performance, using biomechanical and neuromuscular markers over an extended period. The training programme aimed to improve mechanisms related to early force – time and high velocity force application.

13.2 Participant description and performance history

One elite senior male (24 years old at the initiation of this investigation) discus thrower was recruited. Senior-level discus performance using a standard male competition implement (mass: 2.00 kg) was prospectively tracked as part of this longitudinal case study. After giving informed consent, full access to the periodisation of throwing and resistance training workouts was granted. The athlete had not, and was not, taking performance enhancing substances (WADA 2018) through the duration of this investigation. Average distance thrown during the 11 month period prior to the investigation was 53.43 ± 1.76 m. A linear regression conducted on the performances from the 11 months prior to the investigation predicted that the athlete would throw 51.58 m in 12-months time and thus was on a declining trend.

13.3 Biomechanical testing

13.3.1 Warm-up and testing

An individualised competition warm-up was performed prior to the throwing biomechanical assessment. The warm-up consisted of 5 minutes of stationary cycling at a self-selected pace, dynamic stretching, and two throws at a submaximal self-selected intensity. All tested throws were performed at a competition intensity within a competition circle. Verbal encouragement was given and at least 120 s of rest was given between attempts. The three ‘best’ throws based on coach and athlete feedback were taken for further analysis, and the average was presented. To avoid diurnal changes in performance, testing was performed at the same time of day [1:00 – 4:00pm] throughout the duration of this investigation. To avoid the impact of environmental conditions on performance, all testing was performed indoor with ambient temperatures controlled at ~22°.

13.3.2 Three dimensional analysis

Six maximal effort throws with a competition certified discus were performed. All throws were performed at an indoor throwing facility within a discus throwing circle that conformed to the International Athletics Association Federation specifications. A 12 camera infra-red system [9 x T40, 3 x Bonita cameras (Oxford Metrics, Oxford, UK)] sampling at 240 Hz recorded three-dimensional marker coordinate data. Cameras were positioned at varying heights around and above the circle to ensure that all markers could be seen during the throwing motion. The capture volume was calibrated according to the manufacturer's specifications prior to each testing occasion. The origin was set in the centre of the circle with the y axis pointing in the direction of throw, z axis vertical, and x axis perpendicular to both y and z axes. Camera positions and volume origin remained constant across the interventional period via fixed attachments and markings on the floor. Marker coordinate data collection and gap filling were performed within Vicon Nexus software (Oxford Metrics, Oxford, UK). Gaps in marker data were filled individually with the fill type that best fitted the predicted marker trajectory with maximum gap fill length set at 20 frames.

Prior to the execution of the throws, 84 retro-reflective makers were positioned on anatomical landmarks and segments to define 17 segments and 16 joints (Figure 13.1 and Appendix 4 for a detailed description of placement). Four additional markers were placed on the implement (3 marker cluster, 1 singular calibration marker) to define the implement centre. Following the collection of a static pose to define segment parameters, 14 markers were removed from the body and one from the implement. Cluster based tracking was employed to reduce error associated with soft tissue movement artefact (90, 391). Additionally, due to the athlete's anthropometry, clusters were custom designed and positioned in areas with relatively less soft tissue movement artefact (90, 391). All clusters were designed in accordance with the recommendations of Cappozzo, Cappello, Croce, and Pensalfini (392).

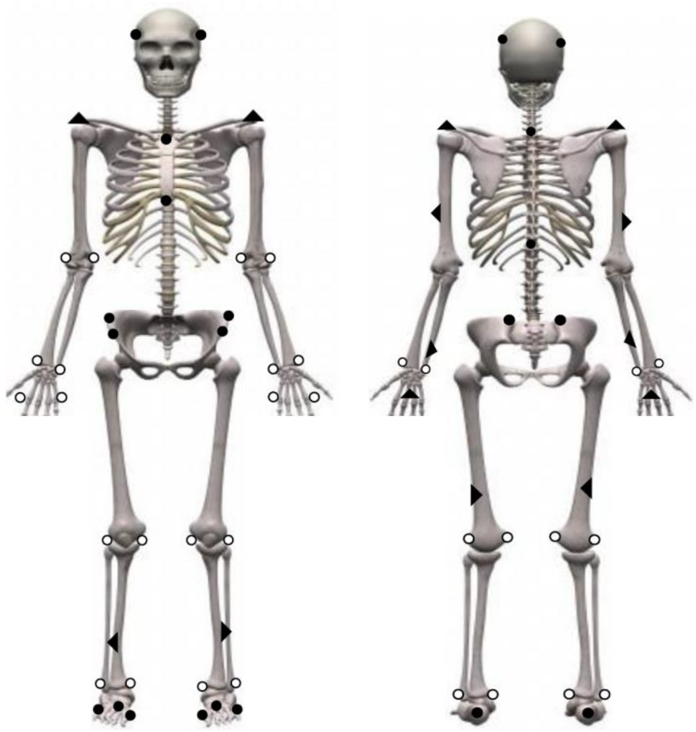

Figure 13. 1. Marker set used for three-dimensional motion analysis. White circles (○) indicate calibration marker, whereas black circles (●) indicate marked used for both calibration and tracking. Black triangles (▶) represent clusters.

Marker coordinate data were exported to Visual3D to derive parameters of interest. The lower body model used a CODA pelvis segment (393) and a thigh, shank and foot segment (394). The upper body model consisted of a Rab, Petuskey, and Bagley (395) trunk segment and a free moving scapulae segment that was used to predict the movement of the shoulder joint centre (396). Upper arm and forearm segments similar to that of Schmidt, Disselhorst-Klug, Silny, and Rau (397) were included. No joint constraints were applied as such the model used had 6 degrees of freedom. No attempt to model scapular movement was made and humorous movement was modelled relative to the thoracic segment. All data was filtered at 12 Hz as determined via residual analysis (362).

13.3.4 Parameters

Five 3D variables were tracked throughout the intervention period based on their relationship to performance. These five variables of interest were: discus velocity (32, 39), hand velocity, hip angular velocity (34), torso angular velocity (34), and hip to shoulder separation (8). Discus velocity was calculated as the instantaneous velocity of the predicted COM of the discus. Hand velocity was calculated as the instantaneous velocity of the predicted centre of the hand. Hip and torso velocity were calculated as the angular velocity of the hip and torso segments about their respective z axes. Hip to shoulder separation was calculated as the relative difference between the hip and thorax about the z axis. Hip to shoulder separation values are reported as negative in sign indicating greater or increased separation. Each variable was calculated from maximum backswing until five frames post release. For simplicity, each parameter was reported at events following maximum backswing. Five events (right foot off, left foot off, right foot down, left foot down, and release) were identified. Foot contacts were determined as the instant in time when vertical separation between the feet and floor occurred or reached an instantaneous minimum. Release was determined as the instant in time when separation between the hand and discus occurred.

13.4 Neuromuscular testing

13.4.1 Warm-up and testing

Neuromuscular testing was performed in a separate session to the throws testing at the same time of day [1:00 to 4:00 pm] within 3 days. The participant was familiarised with all tests prior to the initial testing occasion and had prior experience with all tested movements. Jumping, rotational, and explosive upper body pushing and pulling movements formed an essential part of weekly training programmes; hence, a certain level of familiarisation to testing procedures was maintained throughout the longitudinal tracking period. On arrival to the laboratory, a warm-up was performed that consisted of 5 minutes on a stationary bike and dynamic stretching. The order of testing was kept consistent for the duration of this investigation: vertical jump, inertial load bike, cable rotation, bench pull, bench throw, and countermovement jump. A submaximal warm-up set was performed before each assessment, after which verbal encouragement to perform each exercise with maximal intent was given. To control for the influence of environmental factors all testing was performed with ambient temperatures controlled at ~22°.

13.4.2 Vertical Jump

Six maximal effort vertical jump trials were completed with more than 120 seconds rest between trials. Data from the best trial were used for analysis as the coach wanted data to compare with historical data. Vertical jump testing was performed using a Vertec (Swift Performance, QLD, Australia) following previously reported protocols (380). Standing reach was measured initially as the highest point reached on the dominant side with the heels in contact with the ground. The athlete then performed a countermovement jump for maximal vertical height, squatting to a self-selected depth from an erect stance, immediately concentrically jumping explosively to tap the vanes on the Vertec. This assessment method has previous been shown to be reliable for quantifying vertical jump height (CV: 4.6 to 7.6%, ICC: 0.87 to 0.94) (381).

13.4.3 Inertial load bike

Three maximal effort inertial load bike trials were completed with more than 120 seconds rest between trials. The average from the three trials was used for analysis. The inertial load bike trial involved 8 maximal effort revolutions seated on a fixed-weight flywheel cycling ergometer. Flywheel weight was fixed at 30 kg with a moment of inertia of 1.08 $kg \cdot m^2$ and 165 mm crank length. Based on the results of Hautier et al. (26), optimal cadence was used as a quasi-measure of muscle fibre type. This assessment method has previously been shown to be reliable for assessing optimal cadence in power trained athletes following multiple familiarisations within our laboratory (Days 1 vs 2, CV: 3.8%, ICC: 0.69; Days 2 vs 3, CV: 2.2%, ICC: 0.92).

13.4.4 Load velocity profiling

Three continuous maximal effort trials at each load were completed across movements (i.e. cable rotation, bench pull, bench throw and countermovement jump) with more than 120 seconds of rest between each load. The average of the three trials was used for analysis. The cable rotation involved 12, 24, and 36 kg loads, and the bench pull, bench throw, and countermovement jump involved 20, 40, and 60 kg loads. An additional 80 kg load was used during the countermovement jump. More than 120 s of rest was given between each attempt to ensure recovery. All tested loads followed a lightest to heaviest progression. Absolute loads were chosen as they are more ecologically valid to throwing as implement weight is fixed regardless of strength level. Furthermore the cable rotation loads are consistent with those observed to be reliable (see Chapter 8). Bench press and bench pull loads are consistent with the loads used in Chapter 10 whereby bar velocity was related to seated putting performance.

13.4.5 Cable rotation

A box modified to fixate the hip was secured in front of a line bisecting two cables (Figure 13.2), allowing the sacrum to be positioned on the bisecting line. To fixate the hip, two adjustable rigid sides adjusted to pelvis width were added to the box. The cable was set at a height corresponding to seated shoulder height. Facing forward in an upright posture, the athlete held the cable handle in two hands with both elbows extended. Starting from neutral (Figure 13.2), the athlete rotated towards the cable pulley machine and immediately rotated concentrically in the opposite direction. Poles corresponding to 45° of rotation bilaterally were set to define the range of motion. Countermovement speed was self-selected and only trials where extension in both arms was maintained were analysed. Trials where 45° of rotation was not achieved or where visible elbow flexion was present were terminated and repeated. Only counter clockwise (dominant side) rotations were assessed. This assessment method has previously been shown to be reliable for assessing peak velocity (CV: 3.30 to 6.90%, ICC: 0.93 to 0.99) (382).

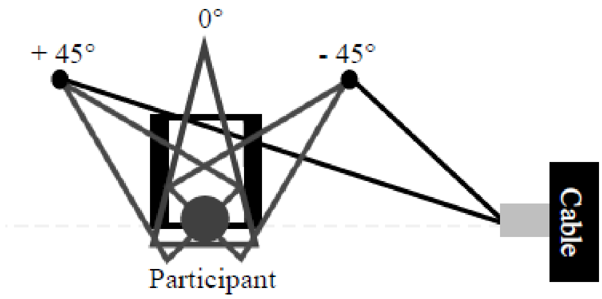

Figure 13. 2. Seated rotation set up.

13.4.6 Prone bench pull

A countermovement bench pull consistent with the methods of Sanchez-Medina et al. (307) was performed without the use of a Smith machine. Lying prone on a high-pull bench with a self-selected hand width, the athlete lowered the bar to an extended arm position and pulled the bar into the bench contacting a point coinciding with the xyphoid process. The bar was then lowered for the ensuing repetition that was immediately performed from full extension. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xyphoid process due to the steel frame. Instructions and verbal encouragement to contact the bench as forcefully as possible were given and only trials where contact was made were counted. Trials during which the chest or hips lifted off the bench were disregarded and repeated. The reliability of load velocity profiling in the bench pull has previously been documented (ICC: 0.81 to 0.90, CV: 5.19 to 6.89%) (383).

13.4.7 Bench throw

A countermovement bench throw was employed consistent with previous methods (226, 306, 384). Lying supine on a bench press, the bar was lowered to the chest at a self-selected speed, which was followed immediately by a concentric throw. The athlete was instructed that the bar should make light contact with the lower portion of the chest. Trials during which the head, shoulders, hips, or feet lost contact with their respective surfaces or bouncing of the bar off the chest was observed were disregarded and repeated. Instructions and verbal encouragement to throw the bar as high as possible were given. The reliability of peak bar velocity at similar loads during a bench throw has been previously documented (ICC: 0.86 to 0.96, CV: 1.80 to 3.55%) (384).

13.4.8 Countermovement jump

A countermovement jump consistent with previous investigations (308, 309) was used to quantify bar velocity. Starting in an erect position with an Olympic bar resting on the upper back, the athlete squatted down to a self-selected depth (310) and completed a concentric jump as explosively as possible. Instructions and verbal encouraged to jump as high as possible were given. The reliability of countermovement jump peak bar velocity has previously been demonstrated (ICC: 0.84 to 0.93, CV: 3.4%) (385).

13.4.9 Equipment and data analysis

All movements were analysed using a PT5A (Fitness Technologies, SA, Australia) LPT connected to the cable stack or bar. Displacement – time data was captured via a custom written LabVIEW programme at 1000 Hz. Manufactures recommendations for calibration were followed.

Displacement – time data from the LPT were analysed using a custom script written in MatLab (v2018a, MA, USA). Cable rotation LPT displacement data were multiplied by 1.8 to account for the 1.8:1 cable pulley gearing ratio and all data were filtered at 100 Hz using a 4^{th} order Butterworth low-pass filter.

A peak detection algorithm was implemented to identify each repetition. Peaks were required to reach 80% of the maximum distance, and multiple peaks within one second were counted as a single repetition. The start of each repetition (concentric onset) was identified by finding the minimum displacement with an additional 1% added to exclude minor movements between repetitions. For each repetition across all movements peak velocity was calculated. For each repetition during the bench pull, bench throw, and countermovement jump peak velocity 100 ms pre (ECC100) and post (CON100) concentric onset was also calculated. One hundred millisecond windows pre and post concentric onset were chosen as they are consistent with contractile windows observed in elite throwing (9, 100, 386).

13.5 Resistance training and throwing periodisation

The periodised plan is shown in Figure 13.3 (December 2017 to July 2018) and Figure 13.4 (August 2018 to March 2019). From December 2017 to February 2018, throwing periodisation was not available due to the coach at the time not planning or reporting throwing sessions. Throwing periodisation from April 2018 through to March 2019 was integrated with the resistance training periodisation. The present periodisation model was targeted at increasing early force – time and high velocity force application, as described in Chapter 6.

From April to November 2018, the model of periodisation was a “resistance-training driven” one. Accordingly, resistance training sessions were prioritised and the detrimental impact of residual fatigue on throwing performance was of lesser concern. Resistance training during this period was targeted at enhancing fibre type qualities (21), tendon stiffness (143), peak force (17), and neural output (158). Training mode was manipulated and velocity based (185), ballistic (192), slow eccentric (23), and fast eccentric (23) training modes were cycled throughout the programme. Acutely, depressed early force – time application has been shown to occur following eccentric type training (390). Therefore, during the weeks of eccentric training, throwing load was increased and throwing speed decreased to decrease the dependence of throwing performance on early force – time application.

From November 2018 to March 2019, the periodisation switched to a “throws driven” model and the fatigue resulting from resistance training was of greater concern. From November 2018 to January 2019 one resistance training session occurred every 10 days, which was implemented to elicit a detraining effect to enhance fibre type qualities (117). During this period, peak force and stiffness were expected to decrease; however, high velocity force application was expected to increase. To match and enhance the expected adaptation, throws volume and load were decreased, resulting in more high intensity throwing sessions from late November 2018 to early January 2019.

From early January to March 2019, velocity based training with plyometrics were used to enhance peak force and stretch shortening cycle ability while maintaining fibre type qualities (185, 193). Movement specificity was increased also to enhance the cross over between resistance training and throwing. Throwing programming revolved around the competition load and was of high intensity.

Schedule	Month	December				January					February				March				April					May				Jun				July				
General	*Week starts*	*4/12/2017*	*11/12/2017*	*18/12/2017*	*25/12/2017*	*1/01/2018*	*8/01/2018*	*15/01/2018*	*22/01/2018*	*29/01/2018*	*5/02/2018*	*12/02/2018*	*19/02/2018*	*26/02/2018*	*5/03/2018*	*12/03/2018*	*19/03/2018*	*26/03/2018*	*2/04/2018*	*9/04/2018*	*16/04/2018*	*23/04/2018*	*30/04/2018*	*7/05/2018*	*14/05/2018*	*21/05/2018*	*28/05/2018*	*4/06/2018*	*11/06/2018*	*18/06/2018*	*25/06/2018*	*2/07/2018*	*9/07/2018*	*16/07/2018*	*23/07/2018*	*30/07/2018*
	Weekly intensity (H-M-L)	L	L	L	L	L	M	M	L	L	L	M	M	M	L				M	H	L	M	H	H	L	M	H	H	L	M	H	H	L	M	H	H
Throwing	Phase	Specific - Competition phase														Time off			Semi - specific																	
	Sessions/week #	Unknown																	5	5	3	5	5	5	3	5	5	5	3	5	5	5	3	5	5	5
	Total throws	Unknown																	80-100	100-120	50-70	100-120	100-120	80-100	50-70	100-120	100-120	80-100	50-70	100-120	100-120	80-100	50-70	100-120	100-120	80-100
	Discs 1.5kg																																			
	Discs 1.75kg																																			
	Discs 2kg	Unknown																																		
	Discs 2.25kg																																			
	Discs 2.5kg																																			
Resistance	Sessions/week #	2	2	2	2	2	4	3	2	2	2	3	3	3	2				4	5	2	3	5	5	2	3	3	5	2	3	3	5	2	3	3	5
	Primary mode	Bal					Pwr												VBT			S ECC			VTB	Bal	S ECC	F ECC	Pwr	Bal	S ECC	F ECC	Pwr	Pwr	S ECC	F ECC
	Secondary mode						F Iso												Pwr			Pwr					Pwr			Pwr				Pwr		

Figure 13. 3. Resistance training and throwing periodisation from December 2017 to July 2018. H – M – L, high – moderate – low; Bal, ballistic type training; Pwr, power training; F Iso, fast isometric training; VBT, velocity-based training; S ECC, slow velocity eccentric training; F ECC, fast velocity eccentric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

Schedule	Month																																
		August				September				October					November				December				Janruary					February				March	
General	*Week starts*	*6/08/2018*	*13/08/2018*	*20/08/2018*	*27/08/2018*	*3/09/2018*	*10/09/2018*	*17/09/2018*	*24/09/2018*	*1/10/2018*	*8/10/2018*	*15/10/2018*	*22/10/2018*	*29/10/2018*	*5/11/2018*	*12/11/2018*	*19/11/2018*	*26/11/2018*	*3/12/2018*	*10/12/2018*	*17/12/2018*	*24/12/2018*	*31/12/2018*	*7/01/2019*	*14/01/2019*	*21/01/2019*	*28/01/2019*	*4/02/2019*	*11/02/2019*	*18/02/2019*	*25/02/2019*	*4/03/2019*	*5/03/2019*
	Weekly intensity (H-M-L)	L	M	H	H	L	M	H	H	L	M	H	H	L	M	H	H	L	L	L	L	L	L	M	M	M	L	L	M	M	M	L	Time off
Throwing	Phase	Semi-specific																Specific															
	Sessions/week #	5	5	5	5	5	5	5	5	3	5	5	5	3	5	5	5	4	5	5	5	4	5	5	5	5	5	5	5	5	5	5	
	Total throws	50-70	80-100	100-120	100-120	50-70	120-150	120-150	80-100	50-70	120-150	120-150	80-100	50-70	120-150	120-150	80-100	80-100	80-100	80-100	80-100	80-100	80-100	100 - 120	100 - 120	80 - 100	80 - 100	80 - 100	80 - 100	80 - 100	80 - 100	80 - 100	
	Discs 1.5kg																																
	Discs 1.75kg																																
	Discs 2kg																																
	Discs 2.25kg																																
	Discs 2.5kg																																
Resistance	Sessions/week #	2	4	5	5	3	4	5	5	2	3	5	5	2	3	5	5	1/10 Days						3	3	2	3	2	3	2	3	2	
	Primary mode	VBT		Strength		VBT		M ECC	F ECC	Pwr		M ECC	F ECC	Pwr		M ECC	F ECC	VBT						VBT									
	Secondary mode			Pwr				Pwr																Bal/F Iso									

Figure 13. 4. Resistance training and throwing periodisation from December 2017 to July 2018. H – M – L, high – moderate – low; Bal, ballistic type training; Pwr, power training; F Iso, fast isometric training; VBT, velocity-based training; S ECC, slow velocity eccentric training; M ECC, moderate velocity eccentric training; F ECC, fast velocity eccentric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

13.6 Coaching directives

There were two main periods where the main coaching directives differed. From April to September 2018, the three key coaching directives were:

- Gain body mass.
- Decrease trunk tilt from right foot down to release.
- Increase the high point of the discus and shift its occurrence in line with the left hand sector line.

From September 2018 to March 2019, the two key two coaching directives were:

- Finish the angular work of the pelvis.
- Increase movement velocity.

13.7 Statistical analysis

Longitudinal change was quantified using a mixed statistical and visual analysis method (387) to allow for the quantification of large changes in the analysed variables (388). The two band SD method was used for the purpose of this investigation due to its agreement with the C statistic and split method of trend estimation (388). Within this method, numerical changes were tracked via graphs with significant change quantified by a clear set of rules. The graphs have two bands that indicate two SD above (upper band) and two SD below (lower band) the pre-test mean. Post-test data points on the graph that fall outside either bands define a significant change. Changes are considered more meaningful when consecutive or numerous data points fall outside the SD lines (Figure 13.5) (388). Visual analysis was used to identify trends in the data and was defined as two or more data points trending in the same direction (Figure 13.5). Furthermore, neuromuscular and biomechanical variables were mapped against the criterion performance variable to identify concurrent changes over prolonged periods. Additionally, to provide comparison between distinct data points where performance or release velocity showed large changes, raw (and percentage) change in variables was quantified and presented as mean ± SD. This gave the ability to compare biomechanical and neuromuscular status between data points.

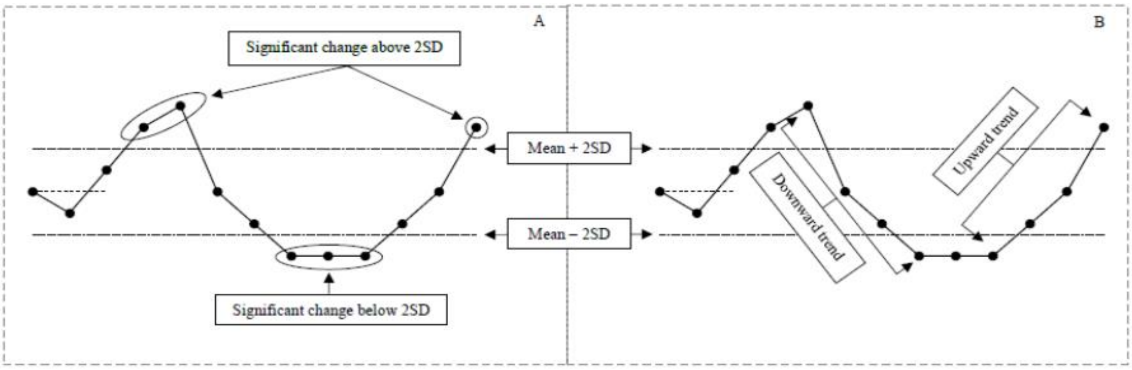

Figure 13. 5. (A) Statistical, and (B) visual analysis methods used.

13.8 Results

13.8.1 Throwing performance

Competition performance is reported in Figure 13.6. Based on the prior 11 months of competition performances, a statistical increase was observed during February and March 2019. No competitions were undertaken between April 2018 and early December 2018. The shaded area in Figure 13.6 extends from February/March 2018 to February/March 2019 and represents the chosen period of interest. February to March represents the major competitive athletics season for a senior athlete. Between seasons (2018 and 2019), a 3.5% improvement in performance was recorded.

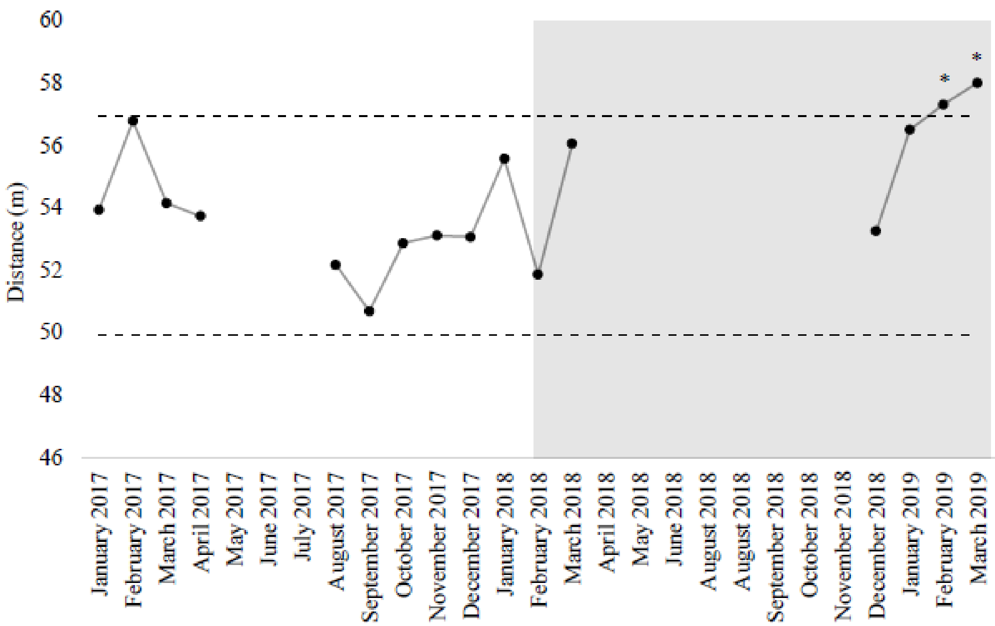

Figure 13. 6. Competition performance for the 11 months prior to the start of the investigation, and throughout the investigation period. Investigational period extended from December 2017 to March 2019.

13.8.2 Biomechanical variables

Changes in discus velocity at each foot contact are presented in Table 13.1. An increase in discus velocity at right foot off was recorded from February 2018 to February 2019; however, increased velocity at right foot off did not always correspond with increased discus velocity at left foot off and right foot down. At left foot down, a statistical change was observed across the majority of months, with the exception of November and December 2018. Increases in velocity at left foot down corresponded with increased release velocity from February 2018 to August 2018. However, due to marker occlusion, release velocity was not able to be calculated in November 2018 and February 2019. Between seasons, discus velocity at right foot off, left foot off, right foot down, and left foot down (March 2018 to December 2019) changed 6.5%, -3.9%, -18.2%, -15.1%, and 5.0%, respectively.

Table 13. 1. Discus velocity (m/s) at each event during the discus throw.

	Right foot off	Left foot off	Right foot down	Left foot down	Release
	4.6	7.4	7.5	7.6	20.7
December 2017	4.5	7.6	7.5	6.8	
	4.5	7.8	7.6	7.4	20.7
+2SD	4.7	8.0	7.7	8.1	20.8
-2SD	4.5	7.2	7.4	6.5	20.6
			Interventional period		
February 2018	5.1*	8.2*	8.6*	9.8*	21.2*
May 2018	4.3#	7.2#	7.3#	8.7*	20.6
June 2018	4.8*	7.7	7.6	9.2*	21.9*
August 2018	4.9*	7.8	7.7*	9.0*	21.5*
November 2018	5.2*	7.9	7.2#	7.6	
December 2018	5.3*	8.0*	7.3#	7.6	22.3*
February 2019	5.5*	7.9	7.3#	8.5*	

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

As discus marker occlusion was observed at release and during the throw, hand COM velocity is presented as it is in direct contact with the discus. Changes in hand COM velocity aligned with disc velocity across the tracking periods. Therefore, hand COM velocity was taken as an appropriate surrogate for changes in disc velocity (Figure 13.7).

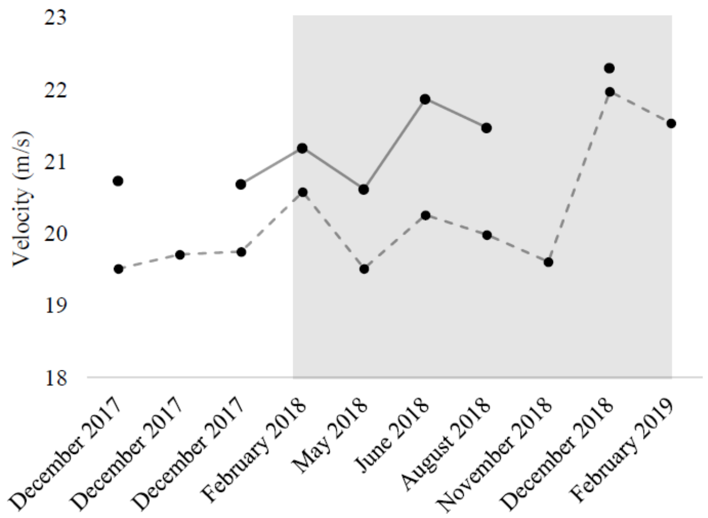

Figure 13. 7. Discus release velocity (black line) and right hand centre of mass velocity (dashed line) over the intervention period.

Statistical increases in hand velocity were observed across the majority of months from February 2018 to February 2019, with the exception of May 2018 during which a statistical decrease in velocity was observed (Table 13.2). Changes in hand COM velocity at right foot off mostly corresponded with the changes in hand velocity observed at left foot off, but not right foot down. As with release velocity, increases in hand velocity at left foot down from February 2018 to August 2018 generally corresponded with increased hand velocity at release. However, the highest hand velocity at release (December 2018) did not correspond with an increase in hand velocity at left foot down. When comparing seasons, a 4.4% increase in hand velocity was observed that coincided with the 3.5% increase in competition performance.

Table 13. 2. Right hand centre of mass (COM) velocity (m/s) at each event during the discus throw.

	Right foot off	Left foot off	Right foot down	Left foot down	Release
	5.0	7.8	8.1	8.5	19.5
December 2017	4.9	8.0	8.2	7.6	19.7
	4.9	8.1	8.3	8.3	19.8
+2SD	5.0	8.3	8.4	9.1	19.9
-2SD	4.8	7.6	8.0	7.2	19.4
			Interventional period		
February 2018	5.5*	8.5*	9.4*	10.5*	20.6*
May 2018	4.7#	7.5#	8.0#	9.4*	19.5
June 2018	5.0*	7.9	8.3	10.0*	20.3*
August 2018	5.3*	8.3*	8.5*	9.9*	20.0*
November 2018	5.7*	8.4*	8.0#	8.5	19.6
December 2018	5.8*	8.4*	8.1	8.7	22.0*
February 2019	5.8*	8.3*	7.9#	9.2*	21.5*

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Pelvic and torso angular velocities are reported in Table 13.3. Angular velocity of the pelvis at right foot off statistically increased from November 2018 to February 2019, which aligned with an increase in torso velocity through the same time period (August 2018 to February 2019).

At left foot off, pelvic angular velocity trended downward initially reaching a level of statistical change in June 2018 before trending up through to February 2019. Torso angular velocity showed large fluctuations, initially increasing in February 2018 prior to statistically decreasing in May and June 2018. Finally, torso angular velocity trended upwards to a level of statistical increase in December 2018.

At right foot down, pelvis angular velocity initially trended upwards from baseline reaching a level of statistical increase in May and June 2018 before trending downward for the remaining months. Torso angular velocity showed greater fluctuations throughout this investigation, reaching a statistical increase in August 2018.

At left foot down, pelvis and torso angular velocities reached a level of statistical increase for the majority of months. However, while above +2SD following June 2018, both the pelvis and torso trended downward. Large fluctuations in pelvis and torso velocities were observed at release. That said, torso velocity trended down from August to February 2019.

When comparing between seasons, pelvic velocity increased at right and left foot off (8.4% and 14.7%, respectively), but decreased at right foot down (-4.6%), left foot down (-27.6%), and release (-104.5%). Similarly, trunk velocity increased 11.3% and 6.9% at right foot off and right foot down, respectively; but decreased -6.0%, -21.1%, and -23.7% at left foot off, left foot down, and release, respectively.

Table 13. 3. Pelvis and torso angular velocity (°/s) about the z axis at each event during the discus throw.

	Right foot off		Left foot off		Right foot down		Left foot down		Release	
	Pelvis	**Torso**	**Pelvis**	**Torso**	**Pelvis**	**Torso**	**Pelvis**	**Torso**	**Pelvis**	**Torso**
	486.8	459.4	637.2	644.3	724.0	515.3	438.6	486.2	492.8	605.9
December 2017	476.3	464.0	604.2	640.6	752.3	538.1	393.5	438.7	356.3	570.4
	448.5	448.4	554.0	624.4	755.2	577.8	413.1	443.5	4.5	448.7
+2SD	510.1	473.3	682.3	657.5	778.3	606.9	460.3	508.4	788.4	706.6
-2SD	430.9	441.2	514.7	615.3	709.4	480.5	369.9	403.9	-219.4	376.7
Interventional period										
February 2018	486.6	484.5*	551.9	675.5*	762.4	533.9	633.3*	648.1*	220.4	586.9
May 2018	478.8	422.3	537.9	509.3#	831.0*	592.3	484.0*	537.1*	82.7	516.0
June 2018	476.8	472.0	512.2#	599.8#	814.0*	578.0	648.4*	611.3*	155.6	546.1
August 2018	487.4	495.9*	552.4	646.8	735.1	615.4*	600.1*	536.0*	301.6	610.4
November 2018	524.4*	529.2*	645.3	652.3	768.8	547.2	572.3*	501.6	107.6	517.4
December 2018	525.1*	521.0*	673.1	675.4*	736.7	530.1	544.4*	519.2*	73.8	518.2
February 2019	527.6*	539.4*	632.7	635.1	727.1	570.8	458.8	511.3*	-10.0	448.0

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Hip to shoulder separations from December 2017 to February 2019 are reported in Table 13.4. At right foot off, large fluctuations can be observed where both statistical changes below (February 2018, June) and above (May, November, December, February 2019) baseline were observed. Visual analysis suggests that hip to shoulder separation trended upwards towards less separation from November 2018 to February 2019.

Large fluctuations were observed at left foot off in hip to shoulder separation, reaching a level of statistical increase in February 2018 and above 2SD in November 2018 and February 2019. Visual analysis showed that left foot off, right foot down, and release followed similar trends, whereby after fluctuations up and down prior to June 2018, they began trending upwards to February 2019. Hip to shoulder separation at left foot down showed much more of a constant pattern, remaining level from December 2017 to February 2019. Between seasons, hip to shoulder separation decreased between 28.9 and 331.9%, showing divergence to that of right hand velocity.

Table 13. 4. Hip to shoulder separation (°) about the z axis at each event during the discus throw.

	Right foot off	Left foot off	Right foot down	Left foot down	Release
	-15.2	-3.7	-14.2	-24.2	-1.4
December 2017	-14.9	0.7	-7.2	-18.0	8.9
	-15.5	-3.2	-5.8	-18.9	6.5
+2SD	-15.8	-6.9	-18.0	-27.0	-6.1
-2SD	-14.7	2.7	-0.2	-13.7	15.4
			Interventional period		
February 2018	-21.0*	-8.8*	-13.1	-21.1	-5.4
May 2018	-14.3#	2.2	-5.3	-18.4	3.7
June 2018	-18.3*	-5.1	-10.5	-19.6	-5.2
August 2018	-14.6	-0.9	-1.3	-17.6	1.2
November 2018	-14.5#	3.4#	-1.6	-19.1	7.6
December 2018	-12.5#	0.9	-3.2	-16.5	8.0
February 2019	-12.2#	3.9#	0.9#	-15.0	12.5

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

13.8.3 Neuromuscular variables

Vertical jump and body mass are reported in Figure 13.8 (A and B, respectively). No statistical change in jump height was observed throughout the investigation period. Note that vertical jump assessments were not undertaken in June and November due to injury. Body mass initially dropped, prior to progressively increasing from February 2018 to February 2019 increasing 10.3% between seasons.

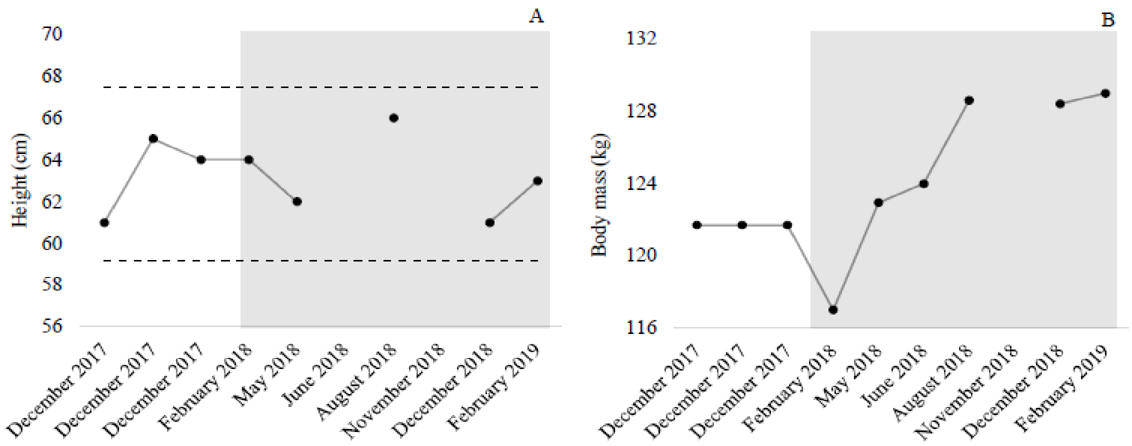

Figure 13. 8. (A) Jump height, and (B) body mass during the investigation period.

Inertial load bicycle optimal cadence and peak power are shown in Figure 13.9 (A and B, respectively). Statistical increases in optimal cadence were observed in February 2018, May 2018, and February 2019, statistical decreases were also observed from June to December 2018. Due to equipment malfunctions, no data were available in November 2018. Peak power dropped significantly in June; but during the remaining months, no significant changes or trends were observed. Between seasons, optimal cadence decreased 0.5% while peak power increased 6.8%.

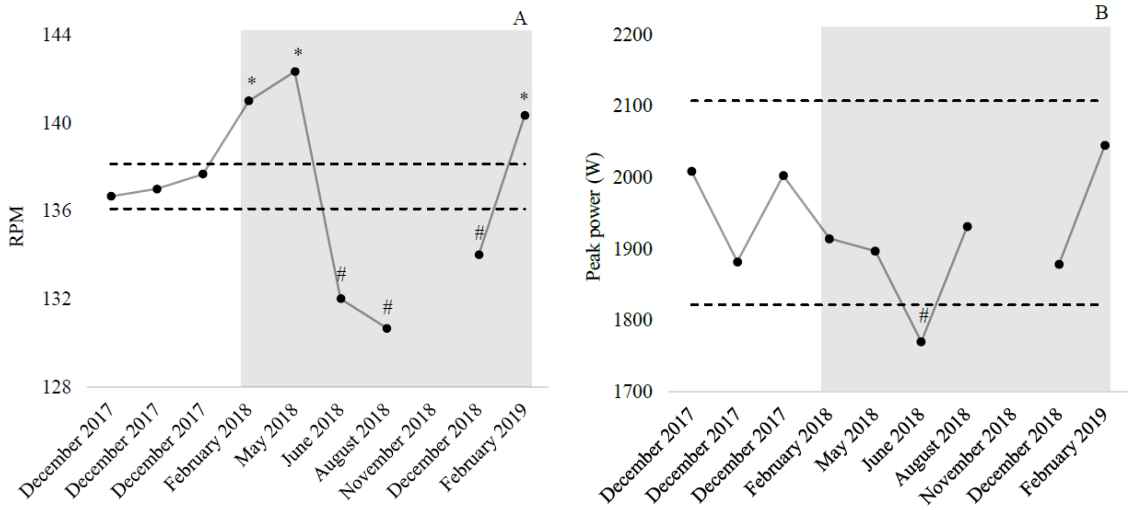

Figure 13. 9. Inertial load bike (A) optimal cadence, and (B) peak power. * statistical increase as determined by +2SD, # statistical decrease as determined by -2SD.

Peak bar velocity during the countermovement jump, bench throw, bench pull, and cable rotation across loads are presented in Figure 13.10 (A to D, respectively). Changes in peak bar and cable velocities were not concurrent with changes in performance. Statistical increases in countermovement jump bar velocity were observed across the majority of loads in February 2018, and from August 2018 to February 2019. Statistical decreases were observed at 60 kg and 80 kg in May 2018 and June 2018, respectively (Figure 13.10A). Between seasons, countermovement jump bar velocity increased 5.1%, 0.1%, and 1.8% at 20 kg, 40 kg, and 60 kg loads, respectively, and decreased 2.6% at 80 kg.

Bench throw bar velocity increased at the majority of loads and data points from May to February 2019 (Figure 13.10B). Between seasons, bench throw peak bar velocity increased 12.7%, 7.6%, and 16.4% with 20 kg, 40 kg, and 60 kg loads, respectively.

Bench pull bar velocity statistically increased in the 20 kg load from November to February 2019. Increases were also observed in February 2018 and November 2018 in the 60 kg loaded condition and decreased in June 2018 at 20 kg. Between seasons, 20 kg bench pull bar velocity increased 9.2%; however, peak bar velocity decreased 4.8% and 9.7% with 40 kg and 60 kg loads, respectively.

The only data point to exceed 2SD during the cable rotation was in the 36 kg load in February 2018. Decreasing trends in peak velocity were observed between December 2017 and June 2018 at 24 kg, and February 2018, June 2018, November 2018 and February 2019 at 36 kg. Between seasons, a 3.8% increase in cable rotation peak velocity was recorded at 12 kg; however a 2.5% and 12.9% decrease in velocity was observed with 40 kg and 60 kg loads, respectively.

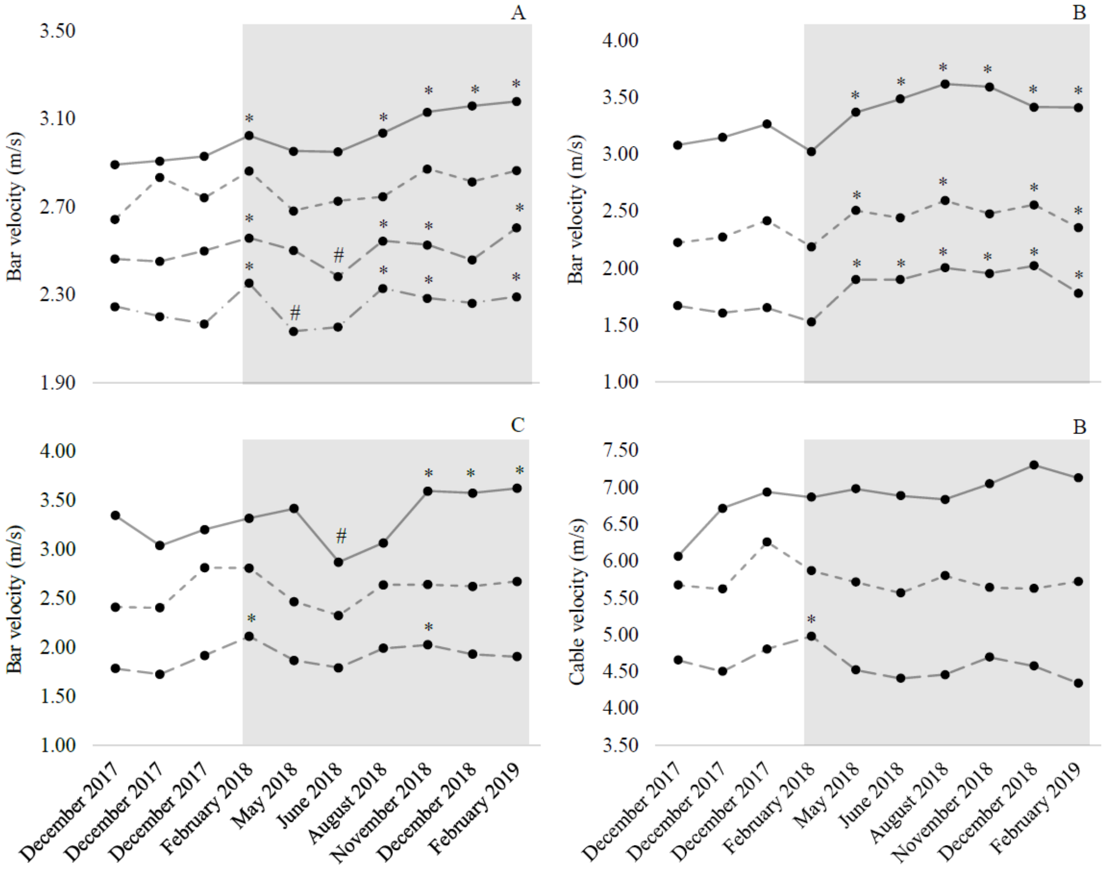

Figure 13. 10. Peak bar velocities during a loaded (A) countermovement jump, (B) bench throw, (C), bench pull at 20 kg (—), 40 kg (····), 60 kg (- - -), and 80 kg (·· —), and (D) cable velocity during the cable put at 12 kg (—), 24 kg (····), and 36 kg (- - -). * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

ECC100 and CON100 during the countermovement jump across loads are reported in Table 13.5. ECC100 statistically increased in December 2018 in the 20 kg loaded condition. Increased CON100 was observed in May 2018 in the 60 kg load, in November 2018 in both 40 kg and 80 kg loads, and in December 2018 in the 20 kg load. When comparing between seasons ECC100 (velocity: 16.2% to 31.5%) and CON100 (velocity: 1.8% to 16.4%) increased across the majority of loads, with the exception of ECC100 that decreased 2% in the 40 kg load.

Table 13. 5. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during countermovement jump at four loads.

	20 kg		**40 kg**		**60 kg**		**80 kg**	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-1.03	1.27	-0.85	1.02	-0.73	0.88	-0.60	0.70
December 2017	-1.21	1.47	-0.98	1.20	-0.83	0.95	-0.66	0.73
	-1.04	1.32	-0.93	1.02	-0.71	0.81	-0.50	0.63
+2SD	-1.30	1.56	-1.05	1.28	-0.88	1.02	-0.75	0.79
-2SD	-0.89	1.14	-0.79	0.88	-0.63	0.73	-0.43	0.58
Interventional period								
February 2018	-1.11	1.33	-1.00	1.10	-0.73	0.82	-0.54	0.65
May 2018	-1.29	1.43	-0.92	1.07	-0.89*	1.00	-0.55	0.65
June 2018	-1.10	1.34	-0.82	0.98	-0.68	0.71	-0.49	0.61
August 2018	-1.14	1.40	-0.93	0.99	-0.73	0.84	-0.53	0.58
November 2018	-1.29	1.49	-1.07*	1.18	-0.87	0.97	-0.72	0.81*
December 2018	-1.47*	1.57*	-1.03	1.11	-0.83	0.85	-0.73	0.72
February 2019	-1.29	1.43	-0.98	1.12	-0.85	0.89	-0.71	0.75

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

ECC100 and CON100 during the bench throw is reported in Table 13.6. Statistical increases in ECC100 were observed from May 2018 to February 2019 across the majority of loads. Increases in ECC100 were mostly concurrent with statistical increases in concentric velocity in the 20 kg and 40 kg, but not 60 kg loads. Statistical decreases in both ECC100 and CON100 were observed in February 2018 across the 20 kg and 40 kg loads. A trend towards increased ECC100 was observed from February 2018 to February 2019 across loads. The same trend was not observed in CON100. When comparing between seasons, ECC100 increased 17% to 64.7% across loads, and CON100 increased 5.2% to 20.6% across loads. The greatest change occurred in the 20 kg condition during this period.

Table 13. 6. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench throw at three loads.

	20 kg		**40 kg**		**60 kg**	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-1.28	2.06	-1.04	1.32	-0.97	1.03
December 2017	-1.44	2.12	-1.27	1.33	-1.10	1.11
	-1.39	2.15	-1.19	1.36	-1.04	0.96
+2SD	-1.54	2.20	-1.40	1.38	-1.17	1.19
-2SD	-1.20	2.02	-0.93	1.29	-0.91	0.88
			Interventional period			
February 2018	-1.09#	1.89#	-1.13	1.25#	-1.06	0.96
May 2018	-1.84*	2.27*	-1.62*	1.46*	-1.34*	1.10
June 2018	-1.57*	2.17	-1.38	1.35	-1.08	1.00
August 2018	-1.72*	2.46*	-1.51*	1.52*	-1.44*	1.25*
November 2018	-1.52	2.35*	-1.44*	1.55*	-1.32*	1.13
December 2018	-1.77*	2.27*	-1.63*	1.54*	-1.59*	1.31*
February 2019	-1.80*	2.28*	-1.55*	1.31	-1.24*	1.07

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

ECC100 and CON100 velocities during the bench pull across loads are shown in Table 13.7. Statistical decreases in ECC100 but not CON100 were observed across the majority of months in the 20 kg load. ECC100 decreased in May 2018 and June 2018 and increased in August 2018, whereas CON100 increased in August 2018, December 2018 and February 2019. With regard to the 60 kg condition, decreases in both ECC100 and CON100 were observed from February 2018 to June 2018, thereafter, increases in ECC100 and CON100 were observed through to February 2019. When comparing between seasons, ECC100 decreased 6.8% in the 20 kg load, but increased 24.7% and 36.2% in the 40 kg and 60 kg loads, respectively, CON100 increased between 25.2% and 39.5% across loads.

Table 13. 7. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench pull at three loads.

	20 kg		40 kg		60 kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
	-1.74	2.12	-1.17	1.38	-0.67	1.00
December 2017	-1.41	1.51	-0.91	1.47	-0.73	1.07
	-1.56	1.94	-1.17	1.34	-0.69	0.97
+2SD	-1.90	2.48	-1.38	1.53	-0.76	1.12
-2SD	-1.24	1.23	-0.78	1.26	-0.63	0.91
Interventional period						
February 2018	-1.27	1.67	-0.94	1.29	-0.63#	0.94
May 2018	-0.12#	1.37	-0.25#	1.29	-0.05#	0.78#
June 2018	-0.60#	1.68	-0.68#	1.40	-0.15#	0.91#
August 2018	-0.05#	1.25	-1.44*	1.71*	-0.95*	1.27*
November 2018	-0.68#	1.74	-0.94	1.52	-0.65	1.17*
December 2018	-1.88	2.29	-1.21	1.75*	-0.88*	1.22*
February 2019	-1.19#	2.09	-1.18	1.80*	-0.83*	1.24*

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

13.9 Discussion

Coaches and athletes seek to enhance biomechanical and neuromuscular variables over longitudinal periods to increase competition performance. One method to identify factors important to performance is to longitudinally track biomechanical and neuromuscular variables alongside competition performance. In doing so, variables that change in the same direction as performance can be identified and used as an indicator of performance. In the current case study, competition throwing performance substantially increased from March 2018 to March 2019. As such, changes in biomechanical and neuromuscular variables were examined between February 2018 and February 2019 as these were the closest testing occasions to competitive performance improvements.

In terms of the performance and biomechanical analysis, the main findings of this investigation were: 1) changes in performance were concurrent with increased disc and right hand velocity at left foot down; 2) between seasons, a change in the velocity pattern of the discus and right hand was observed; and 3) hip and torso velocities and axial separation did not correspond to changes in discus or hand velocity. With regards to the neuromuscular analysis, the main findings were: 1) no single neuromuscular variable adapted concurrently with right hand velocity; 2) optimal cadence and peak power on the cycle ergometer statistically increased during the investigation period, and peak power increased 6.8% between seasons; and 3) increases in loaded countermovement jump, bench throw, and bench pull peak velocity were observed; however, changes in ECC100 and CON100 varied between movements across months.

Athletics coaches and athletes seek to enhance performance by adapting biomechanical and neuromuscular variables through planned longitudinal training interventions. Performance should culminate at the highest level at targeted events or competition periods for the year. Our data show competition performance reached a peak in March 2019 where a personal best of 58.01 m was set at the pinnacle event of the year, representing a 3.5% increase on the previous year. Release velocity has been reported as the primary predictor of performance (39). Thus, it is not surprising that competition performance peaked at the same time as the greatest right hand velocities were recorded (i.e., December 2018 and February 2019). Other than right hand COM velocity, no single biomechanical or neuromuscular variable appeared to correspond with increased release velocity or performance.

Between seasons, a change in discus velocity pattern was noted where an increase in velocity at right foot off and at release was observed; however, decreases in the velocity at all other contacts were observed. Variable patterns of discus velocity change during the throw have been reported in elite throwers (29). However, to the best of our knowledge, this is the first investigation to detail a change in velocity pattern within a thrower over a longitudinal period. Hay and Yu (39) reported a strong correlation between change in discus velocity during flight and distance thrown in female throwers that contrast our observations. In February 2018, an increase in discus velocity during flight was observed; while in February 2019, a decrease in discus velocity in flight was observed alongside a relatively higher right hand velocity at release and increased competition performance (Table 13.2, left foot off to right foot down). The difference between our observations are likely attributable to sex differences that determine the weight thrown. The men's discus has greater inertia and is therefore more resistant to change in velocity when momentum is manipulated in flight (39).

When comparing across the testing occasions, changes in right hand velocity did not correspond with any singular kinematic variable. However, it is possible that a more effective kinematic sequence was present in February 2019. Hip angular velocity decreased 104.5% and torso angular velocity decreased 23.7%, while right hand velocity increased 4.6%. Dapena and Anderst (34) suggested the majority of discus velocity can be attributed to the transference of angular momentum. Angular momentum is a product of moment of inertia and angular velocity, and the moment of inertia is the product of mass and radius squared. Thus, a decrease in hip and torso angular velocities with an increase in right hand velocity possibly represents a greater radius through which the discus is working, resulting in greater angular momentum and discus release velocity. However, the decrease in hip to shoulder separation is likely a technical flaw as elite discus throwers generally are observed to have greater hip to shoulder separations (4, 8, 37).

When comparing changes in neuromuscular variables to release velocity, no singular variable changed concurrently with right hand release velocity. Discus performance has previously been correlated with incline bench press one repetition maximum [$r = 0.96$, $p < 0.01$ (126)] and bench press power [r = 0.65, $p < 0.05$ (124)], but not squat strength or power in sub elite throwers (~48 to 50 m) (124, 126). Our data suggest that change in bench press peak velocity across loads and within specific epochs do not correspond to change in release velocity or hand COM velocity between months; however, bench press peak velocity, ECC100, and CON100 were significantly elevated before and during periods when right hand velocity, discus velocity, and performance increases were observed. This pattern is suggestive of a lag time whereby the expression of enhanced neuromuscular ability within the throwing motion is delayed (297). Thus a maintenance phase should be included into the periodisation following periods of enhanced pressing ability. This period likely allows the athlete to learn how to integrate their new found pressing abilities into the throwing motion resulting in enhanced performance.

Similar to bench press, CMJ peak velocity across loads significantly increased through the investigation; however, few increases in ECC100 and CON100 were observed. Karampatsos et al. (126) and Bourdin et al. (124) observed no significant relationship between back squat strength kinematics and kinetics and performance, which support our findings as both significant increases and decreases in CMJ peak velocity across loads were observed with increases in discus velocity and hand COM velocity. To the best of our knowledge, this is the first investigation to track rotational and pulling type motions concurrently with markers of throwing performance. Due to the relationship between axial separation and throwing performance, and back strength and rotational torque production, we thought these motions might be ecologically valid (371). However, neither bench pull nor torso rotation measures trended concurrently with measures of performance.

Concurrently with periodisation, we were able to report the coach's directives. At present, this is the first investigation the authors are aware of to report the entirety of a discus throwers' programme over a longitudinal period. The reported kinematics were chosen based on prior literature (4, 34) and remained constant throughout the tracking period, and many of the reported kinematics do not reflect coaching directives. The directive of "increasing movement velocity" can be inferred from the data collected. The highest hand velocities were observed during the September 2018 to March 2019 period, primarily later in this period (December/February). Training during this later part corresponded with a decrease in the occurrence of overweight discus's thrown during training and the detraining – retraining period. Similarly, Losch and Bottcher (13) reported increases in competition performance when throwing loads equal to the competition implement had been preceded by periods of heavy throwing and resistance training in an elite female thrower.

The model of periodisation targeted enhancing early force – time and high velocity force application by cycling training modes that maintain or enhance fibre type (23, 155, 185) qualities while trying to increase peak force (23, 185). Loaded CMJ, bench throws, and bench pulls were included as a proxy for maximal strength as they could be assessed at any point during the year.

Our results show increases in heavy load peak velocity across training modes and a maintenance of peak force during a detraining period, which conflict with previous investigations (117, 155). The inclusion of one resistance training session every 10 days combined with 5 throwing sessions during the detraining period may have been enough to maintain peak force across CMJ, bench throw, and bench pull.

With regard to increased fibre type qualities, Hautier et al. (26) showed optimal cadence to closely correspond with fibre type percentage area. As such, we included optimal cadence as a proxy for fibre type. Optimal cadence significantly increased initially (February/May2018), decreased during heavy training periods, and re-increased during a detraining and retraining period. Previous literature has observed an increase in fibre type percentage area (155) and suppressed muscle activation (206) following a detraining period. Pareja-Blanco et al. (185) reported the maintenance of fibre type qualities, but an increase in peak force when velocity loss during each set remained below 10%. In support, our results suggest that the sequence of training, detraining, and retraining enhanced whole muscle fast fibre types.

Enhanced ECC100 and CON100 velocities were observed in the majority of months during the bench throw across loads, but only in a few months for the CMJ, and inconsistently for the bench pull. The differential change in early contraction velocities makes conclusions difficult, but it is suggested that muscle group specific training methods are required to reach similar adaptive responses.

13.10 Conclusion

Effective coaching and preparation for discus throwing involves developing a plan to enhance variables associated with performance. This case study presented a longitudinal periodised plan and tracked competition performance alongside throwing biomechanics and neuromuscular qualities. Competition performance improved between seasons, as did discus and right hand COM velocity that was used as a proxy for performance. However, right hand velocity and discus velocity did not change with any biomechanical or neuromuscular variable, but increases in right hand velocity were observed in periods when multiple neuromuscular variables were significantly elevated. Our results suggest that the variables tracked in the present investigation do not correspond with changes in performance in this particular athlete, leading to three possible conclusions: 1) the periodisation plan was not structured in a manner that would lead to neuromuscular and biomechanical changes, 2) the assessments used in this study do not predict performance gains; and therefore, alternative neuromuscular and biomechanical variables should be explored; and/or, 3) the time taken to integrate an enhanced non-specific neuromuscular state into the throwing motion is delayed, which masks the relationship between biomechanical and neuromuscular variables.

The longitudinal plan cycled training modes to enhance select neuromuscular variables. Although changes were not reflective of performance gains, changes in neuromuscular variables were observed across the investigation period. The observed changes have practical significance for practitioners as similar modes of resistance training result in differential adaptations between movements. Further research is required to validate this concept and understand the variables related to diverging responses between movements. Such research should consist of multiple single subject designs replicating the current methods to provide greater ecological validity to coaches and athletes and provide insight to high performance cohorts.

Chapter 14

The integration of biomechanics and resistance training in female shot putting: A case study

14.0 Prelude

The previous Chapters have sought to understand which biomechanical and neuromuscular variables are important to hammer and discus performance by integrating the content presented in prior Chapters. Few biomechanical or neuromuscular variables have shown any alignment with release velocity longitudinally. To understand if a similar phenomenon is observed in shot put, this final Chapter aimed to apply the prior methodologies for a shot put athlete. Chapter 3 and 5 highlighted a paucity of longitudinal literature showing changes in rotational shot put biomechanics and neuromuscular status. To investigate which biomechanical and neuromuscular variables are important to performance within the scope of this thesis (i.e., high performance throws), a single subject design using a sub-elite to elite athlete was implemented. Accordingly, one elite junior/senior shot putter (ranked 2nd in NZ by Athletics New Zealand) was tracked longitudinally. The theoretical model of periodisation (Chapter 6) was implemented by the coach and athlete to provide resistance training direction.

14.1 Introduction

Men's and women's shot put have been a part of the Olympic track and field programme since 1948. High performance coaches and athletes continuously seek to enhance performance and explore the benefits of various methods of training. For instance, athletes have been seen to use many technical throwing styles in competition over the years, including the shuffle, glide, switch foot glide, and rotational styles. Modern day shot putters mainly use the rotational style.

Two separate, but interrelated, areas are addressed in shot putters to enhance performance: biomechanics and neuromuscular. The former refers to adapting kinematic and kinetic qualities to increase the force applied to the shot during the throwing motion. The second, neuromuscular performance, refers to increasing the absolute force levels the athlete can apply specifically and non-specifically (outside of the throwing motion, e.g., during a bench press). Coaches anticipate that by increasing non-specific force of muscles, these muscles will be able to exert more force and demonstrate greater activation during the shot put motion to ultimately enhance throwing performance.

A paucity of biomechanical literature on shot put is currently available, and more specifically, we could not locate any biomechanical literature documenting changes in kinematic variables with performance over longitudinal timeframes. Cross-sectional biomechanical studies indicate that shot put release velocity is the variable with the strongest predictive ability in terms of performance (62). The required release velocities to reach an elite level have been documented and rely on principles of projectile motion (3). However, between throwers during the throw, numerous velocity patterns have been reported (5, 69), and within an individual, it is unknown whether changes in release velocity longitudinally are underpinned by changes in shot velocity during preceding phases. Furthermore, high magnitudes of angular momentum have been observed in elite shot putters by Byun et al. (5) and later related to performance by Kato et al. (68). However, the effects of changes in angular momentum on shot put performance remains unknown. Furthermore, estimations of angular momentum within athlete groups are likely variant as segment centre of mass locations are inferred predominantly from male cadaver studies of non-athlete groups (398). Thus, based on the mathematical relationship between angular velocity and momentum [T (f x d) x t = I (m x r^2) x angular velocity], angular velocity is likely an important measure to quantify in shot put. However, hip and shoulder angular velocities during shot putting have not yet been documented.

Hip to shoulder separation is often referred to in coaching literature and high magnitudes of separation are often observed in elite throwers (5). Theoretically, increases in hip to shoulder separation increase the time over which the athlete can apply force and torque, potentially promoting a more propulsive kinematic sequence. However, the relationship between changes in hip to shoulder separation and concurrent changes in shot put velocity over time are also unknown.

The second avenue to enhance competition performance is through resistance training. The principle of specificity suggests that there must be similarity between resistance training movements and the required throwing biomechanics. Current cross-sectional literature suggests peak force to be important to performance (118), but peak force has a ceiling effect after which any further improvement seems of little benefit to performance (15). Whether this ceiling effect is related to physiological adaptations from non-specific traditional modes of resistance training is unknown. Furthermore, quantifying peak force provides little insight into changes in velocity performance that are kinematically more specific to shot put performance. In contrast, force-velocity profiling gives an abundance of data spanning more of the force-velocity curve relevant to shot putters. Longitudinally, Kyriazis et al. (12) observed shot put performance to improve with countermovement jump kinetics and kinematics, and maximal squat strength pre to post season. However, lower body measures were taken at the start and end of season only, which may not represent in season jump ability and performance changes noted during the season. Furthermore, no upper body or rotational measures were reported, which could be of importance to performance in athletes.

Given the interaction between biomechanical factors, neuromuscular qualities, and shot put performance, tracking both biomechanics and neuromuscular variables concurrently over longitudinal periods should provide valuable insight into the effects of these determinants on shot put performance. Thus, the purpose of this investigation was to track selected biomechanical and neuromuscular variables to understand how each changed with performance in a sub-elite to elite shot putter.

14.2 Participant description and performance history

One senior sub-elite/elite female (18 years old at the beginning of this intervention) shot putter was recruited. Senior competition level throwing performance using a standard womens shot (mass: 4.00 kg) was tracked for the duration of this investigation. After giving informed consent, full access to the periodisation of throwing and resistance training workouts was granted. The athlete had not, and was not, taking performance enhancing substances (WADA 2018) through the duration of this investigation. Average distance thrown during the 11-month period prior to the investigation was 15.10 ± 0.45 m with an improving performance trend. This performance trend was verified by a linear regression conducted on the performances from the 11 months prior to the investigation predicting that the athlete would throw 15.11 m in 12-months time.

14.3 Biomechanical testing

14.3.1 Warm-up and testing

An individual competition warm-up was performed prior to the first testing throw. The warm-up consisted of stationary bike at a self-selected pace, dynamic stretching, and two submaximal throws. Throws were performed at a competition intensity within a competition circle. Verbal encouragement was given for the recorded throws and at least 120 s of rest was given between attempts. The three ‘best’ throws based on coach and athlete feedback were taken for further analysis, and the average was presented. To avoid diurnal changes in performance, testing was performed at the same time of day [10:00 – 12:00pm] throughout the duration of this investigation. To avoid the impact of environmental conditions on performance all testing was performed indoor with ambient temperatures controlled at ~22°.

14.3.2 Three dimensional analysis

Six maximal effort throws with a competition certified shot put were performed. All throws were performed at an indoor throwing facility within a shot put throwing circle concurrent with the International Athletics Association Federation rule specifications. A 12 camera infra-red system [9 x T40, 3 x Bonita cameras (Oxford Metrics, Oxford, UK)] sampling at 240 Hz recorded three-dimensional marker co-ordinate data. Cameras were positioned at varying heights around and above the circle to ensure that all markers could always be seen during the throwing motion. The capture volume was calibrated according to the manufacture’s specifications prior to each testing occasion (Oxford Metrics, Oxford, UK). The origin was set in the centre of the circle with the y axis pointing in the direction of throw, z axes vertical and x axis perpendicular to both y and z axes. Camera positions and volume origin remained constant across the intervention via fixed attachments and markings on the floor. Marker co-ordinate data and gap filling was performed within Vicon Nexus software (Oxford Metrics, Oxford, UK). Gaps in marker data were filled individually with the fill type that best fitted the predicted marker trajectory with maximum gap fill length set at 20 frames.

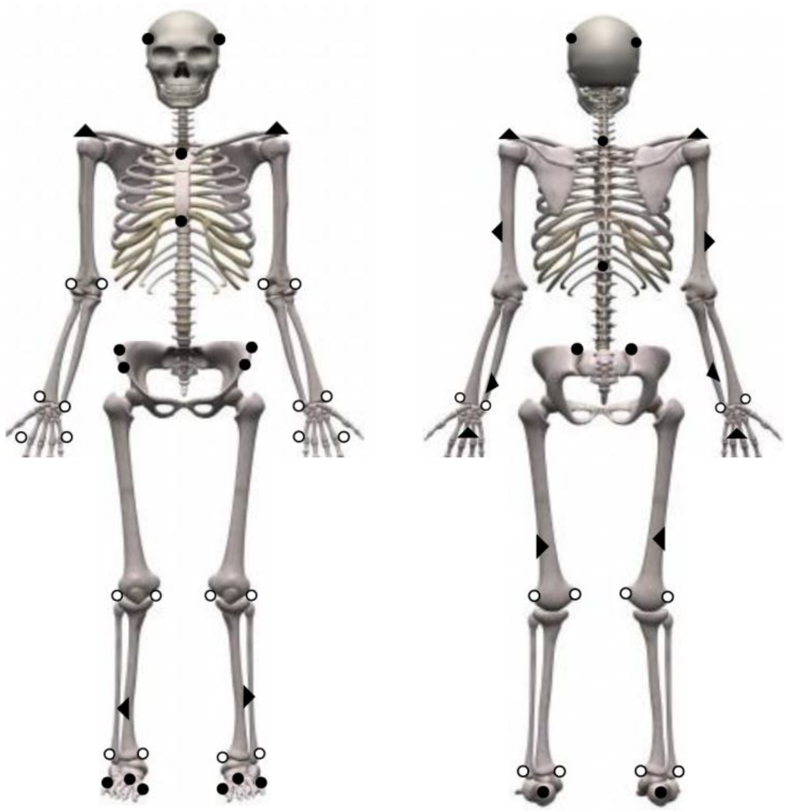

Figure 14. 1. Marker set. Dots show markers used for calibration (○) and those for both calibration and tracking (●). Clusters are represented by filled triangles (▶).

Prior to the execution of the throwing 84 retro-reflective makers were positioned on anatomical landmarks and segments to define 17 segments and 16 joints (Figure 13.1 and Appendix 4 for a detailed description of placement). The same investigator applied all markers over the duration of the investigation and was trained in palpations by experienced clinicians. Four additional markers were placed on the shot (3 marker cluster, 1 singular calibration marker) to define the implement centre. Following the collection of a static pose to define segment parameters 14 markers were removed from the body and one from the implement. A cluster based model of tracking was employed to reduce error associated with soft tissue artefact (STA) movement (90, 391). Additionally, due to the athlete's anthropometry clusters were custom designed and positioned in areas with relatively less STA movement (90, 391). All clusters were designed in accordance with the recommendations of Cappozzo et al. (392).

Marker coordinate data were exported to Visual3D to derive parameters of interest. The lower body model used a CODA pelvis segment (393), a thigh, shank and foot segment (394). The upper body model consisted of a Rab et al. (395) trunk segment and a free moving scapulae segment that was used to predict the movement of the shoulder joint centre (396). Upper arm and forearm segments similar to that of Schmidt et al. (397) were included. No joint constraints were applied as such the model used had 6 degrees of freedom. No attempt to model scapular movement was made and humorous movement was modelled relative to the thoracic segment. All data was filtered at 12 Hz as determined via residual analysis (362).

14.3.3 Parameters

Four variables of interest; shot velocity (62), hip angular velocity (68), torso angular velocity (68) and hip to shoulder separation (5) were tracked based on their relationship to performance. Shot velocity was calculated as the instantaneous velocity of the predicted COM of the shot. Hip and torso velocity were calculated as the angular velocity of the hip and torso segments about their respective z axes. Hip to shoulder separation was calculated as the relative difference between the hip and thorax about the z axis. Hip to shoulder separation values are reported as negative in sign indicating greater or increased separation. Each variable was calculated from maximum backswing until five frames post release. For simplicity, each parameter was reported at events following maximum backswing. Five events (right foot off, left foot off, right foot down, left foot down, and release) were identified. Foot contacts were determined as the instant in time when vertical separation between the feet and floor occurred or reached an instantaneous minimum. Release was determined as the instant in time when separation between the hand and shot put occurred, this was referenced against predicted shot put acceleation.

14.4 Neuromuscular testing

14.4.1 Warm-up and testing

Neuromuscular testing was performed in a separate session to the throws testing at the same time of day [10:00 to 12:00 am] within 3 days. The participant was familiarised with all tests prior to the initial testing occasion and had prior experience with all tested movements. Jumping, rotational, and explosive upper body pushing and pulling movements formed an essential part of weekly training programmes; hence, a certain level of familiarisation to testing procedures was maintained throughout the longitudinal tracking period. On arrival to the laboratory, a warm-up was performed that consisted of 5 minutes on a stationary bike and dynamic stretching. The order of testing was kept consistent for the duration of this investigation: vertical jump, inertial load bike, cable put, bench pull, bench throw, and countermovement jump. A submaximal warm-up set was performed before each assessment, after which verbal encouragement to perform each exercise with maximal intent was given. To control for the influence of environmental factors all testing was performed with ambient temperatures controlled at ~22°.

14.4.2 Vertical Jump

Six maximal effort vertical jump trials were completed with more than 120 seconds rest between trials. Data from the best trial were used for analysis as the coach wanted data to compare with historical data. Vertical jump testing was performed using a Vertec (Swift Performance, QLD, Australia) following previously reported protocols (380). Standing reach was measured initially as the highest point reached on the dominant side with the heels in contact with the ground. The athlete then performed a countermovement jump for maximal vertical height, squatting to a self-selected depth from an erect stance, immediately concentrically jumping explosively to tap the vanes on the Vertec. This assessment method has previous been shown to be reliable for quantifying vertical jump height (CV: 4.6 to 7.6%, ICC: 0.87 to 0.94) (381).

14.4.3 Inertial load bike

Three maximal effort inertial load bike trials were completed with more than 120 seconds rest between trials. The average from the three trials was used for analysis. The inertial load bike trial involved 8 maximal effort revolutions seated on a fixed-weight flywheel cycling ergometer. Flywheel weight was fixed at 30 kg with a moment of inertia of 1.08 $kg \cdot m^2$ and 165 mm crank length. Based on the results of Hautier et al. (26), optimal cadence was used as a quasi-measure of muscle fibre type. This assessment method has previously been shown to be reliable for assessing optimal cadence in power trained athletes following multiple familiarisations within our laboratory (Days 1 vs 2, CV: 3.8%, ICC: 0.69; Days 2 vs 3, CV: 2.2%, ICC: 0.92).

14.4.4 Load velocity profiling

Three continuous maximal effort trials at each load were completed across movements (i.e. cable put, bench pull, bench throw and countermovement jump) with more than 120 seconds of rest between each load. The average of the three trials was used for analysis. The cable put involved 12, 24, and 36 kg loads, and the bench pull, bench throw, and countermovement jump involved 20, 40, and 60 kg loads. An additional 80 kg load was used during the countermovement jump. More than 120 s of rest was given between each attempt to ensure recovery. All tested loads followed a lightest to heaviest progression. Absolute loads were chosen as they are more ecologically valid to throwing as implement weight is fixed regardless of strength level. Furthermore the cable rotation loads are consistent with those observed to be reliable (see Chapter 8). Bench press and bench pull loads are consistent with the loads used in Chapter 10 whereby bar velocity was related to seated putting performance.

14.4.5 Cable put

The cable height was adjusted to anterior iliac crest height when standing and was kept constant across the interventional period. Standing in a self-selected stance width the athlete rotated backwards (countermovement) into the power position. The power position is defined here as the position where the putting hand is tucked into the neck with the elbow flexed and the shoulders abducted. Slight forward rotation of the pelvis was recommended (i.e., slight relative hip to shoulder axial separation) with the trail knee flexed to approximately 100° and most of the body mass located on the ball of rear foot. Eccentric velocity and range of motion within the countermovement was self-selected. Following the eccentric backwards movement into the power position, an explosive cable put was performed. Cues were given to “lead with the hips” and “put upwards” to mimic the sequence of the shot put movement and put through a 36 to 42° arm plane (Figure 14.2) with maximal effort. This method has previously been shown to be a reliable method to quantify peak velocity across loads (ICC: 0.93 – 0.98, CV: 3.61 – 7.53)(382).

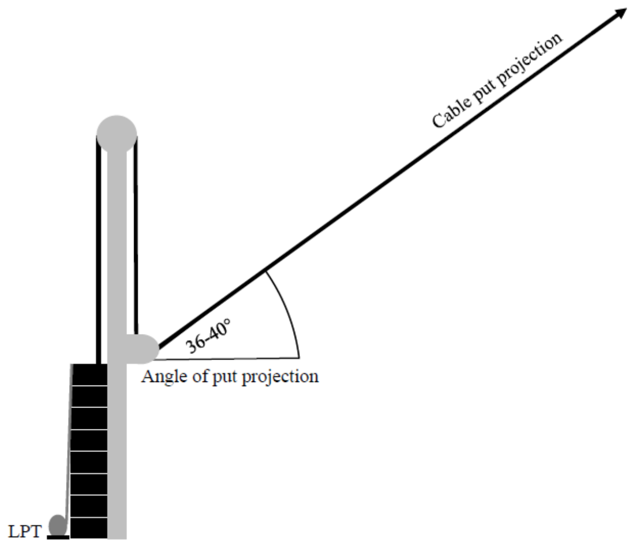

Figure 14. 2. Side view of the cable put setup showing the angle of put and LPT (linear position transducer).

14.4.6 Prone bench pull

A countermovement bench pull consistent with the methods of Sanchez-Medina et al. (307) was performed without the use of a Smith machine. Lying prone on a high-pull bench with a self-selected hand width, the athlete lowered the bar to an extended arm position and pulled the bar into the bench contacting a point coinciding with the xyphoid process. The bar was then lowered for the ensuing repetition that was immediately performed from full extension. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xyphoid process due to the steel frame. Instructions and verbal encouragement to contact the bench as forcefully as possible were given and only trials where contact was made were counted. Trials during which the chest or hips lifted off the bench were disregarded and repeated. The reliability of load velocity profiling in the bench pull has previously been documented (ICC: 0.81 to 0.90, CV: 5.19 to 6.89%) (383).

14.4.7 Bench throw

A countermovement bench throw was employed consistent with previous methods (226, 306, 384). Lying supine on a bench press, the bar was lowered to the chest at a self-selected speed, which was followed immediately by a concentric throw. The athlete was instructed that the bar should make light contact with the lower portion of the chest. Trials during which the head, shoulders, hips, or feet lost contact with their respective surfaces or bouncing of the bar off the chest was observed were disregarded and repeated. Instructions and verbal encouragement to throw the bar as high as possible were given. The reliability of peak bar velocity at similar loads during a bench throw has been previously documented (ICC: 0.86 to 0.96, CV: 1.80 to 3.55%) (384).

14.4.8 Countermovement jump

A countermovement jump consistent with previous investigations (308, 309) was used to quantify bar velocity. Starting in an erect position with an Olympic bar resting on the upper back, the athlete squatted down to a self-selected depth (310) and completed a concentric jump as explosively as possible. Instructions and verbal encouraged to jump as high as possible were given. The reliability of countermovement jump peak bar velocity has previously been demonstrated (ICC: 0.84 to 0.93, CV: 3.4%) (385).

14.4.9 Equipment and data analysis

All movements were analysed using a PT5A (Fitness Technologies, SA, Australia) LPT connected to the cable stack or bar. Displacement – time data was captured via a custom written LabVIEW programme at 1000 Hz. Manufactures recommendations for calibration were followed.

Displacement – time data from the LPT were analysed using a custom script written in MatLab (v2018a, MA, USA). Cable put LPT displacement data were multiplied by 1.8 to account for the 1.8:1 cable pulley gearing ratio and all data were filtered at 100 Hz using a 4th order Butterworth low-pass filter.

A peak detection algorithm was implemented to identify each repetition. Peaks were required to reach 80% of the maximum distance, and multiple peaks within one second were counted as a single repetition. The start of each repetition (concentric onset) was identified by finding the minimum displacement with an additional 1% added to exclude minor movements between repetitions. For each repetition across all movements peak velocity was calculated. For each repetition during the bench pull, bench throw, and countermovement jump peak velocity 100 ms pre (ECC100) and post (CON100) concentric onset was also calculated. One hundred millisecond windows pre and post concentric onset were chosen as they are consistent with contractile windows observed in elite throwing (9, 100, 386).

14.5 Resistance training and throwing periodisation

The periodised plan from November 2017 to July 2018 is shown in Figure 14.3, and the one from July 2018 to March 2019 in Figure 14.4. The periodisation model was targeted at increasing early force – time and high velocity force application (see Chapter 6).

From November 2017 to mid-January 2018, mid-March to June 2018, and August to November 2018, the model of periodisation was a “resistance-training driven” one. Accordingly, resistance training sessions were prioritised and the detrimental impact of residual fatigue on throwing performance was of lesser concern. Resistance training during this period was targeted at enhancing fibre type qualities (21), tendon stiffness (143), peak force (17), and neural output (158). Training mode was manipulated and velocity based (185), ballistic (192), slow eccentric (23), and fast eccentric (23) training modes were cycled throughout the programme. Acutely, depressed early force – time application has been shown to occur following eccentric type training (390). Therefore, during the weeks of eccentric training, throwing load was increased and throwing speed decreased to decrease the dependence of throwing performance on early force application.

From mid-January to mid-March 2018, June to mid-July 2018, and November to December 2018 the periodisation switched to a “throws driven” model and the fatigue resulting from resistance training was of greater concern. Resistance training frequency and volume were significantly reduced to elicit a detraining effect to enhance fibre type qualities (117). During this period, peak force and stiffness were expected to decrease; however, high velocity force production was expected to increase. To match and enhance the expected adaptation, throws volume was decreased, resulting in more high intensity throwing sessions from late January 2017 to mid-March 2018, June to mid-July 2018, and November to March 2019.

From early January to March 2019, velocity based training with plyometrics were used to enhance peak force and stretch shortening cycle ability while maintaining fibre type qualities (185, 193). Movement specificity was increased also to enhance the cross over between resistance training and throwing.

		6/11/2017	13/11/2017	20/11/2017	27/11/2017	4/12/2017	11/12/2017	18/12/2017	25/12/2017	1/01/2018	8/01/2018	15/01/2018	22/01/2018	29/01/2018	5/02/2018	12/02/2018	19/02/2018	26/02/2018
General	Year	2017								2018								
	Month	November				December				January					February			
	Week starts	6/11/2017	13/11/2017	20/11/2017	27/11/2017	4/12/2017	11/12/2017	18/12/2017	25/12/2017	1/01/2018	8/01/2018	15/01/2018	22/01/2018	29/01/2018	5/02/2018	12/02/2018	19/02/2018	26/02/2018
	Days training #	6	4	6	4													
	Weekly intensity (H-M-L)	M	H	M	L	M	H	H	L	M	H	H	L	M	M	M	H	M
Throwing	Throwing sessions per week	4	4	4	4	4	4	4	3	4	4	4	4	4	4	4	4	4
	Total throws	60 - 80	80-100	60 - 80	≈60	60 - 80	80-100	80-100	≈60	60 - 80	80-100	80-100	≈60	60 - 80	60 - 80	60 - 80	80-100	60 - 80
Throwing loads	3.0kg																	
	3.6kg																	
	4kg																	
	4.5kg																	
Resistance	Gym sessions per week	2	3	3	2	5	5	5	3	5	5	5	3	2	2	2	4	4
Programing specifics	Primary	Pwr				S ECC			Bal	Pwr			Bal				Pwr	
	Secondary		Plyo							Plyo			Plyo					

		5/03/2018	12/03/2018	19/03/2018	26/03/2018	2/04/2018	9/04/2018	16/04/2018	23/04/2018	30/04/2018	7/05/2018	14/05/2018	21/05/2018	28/05/2018	4/06/2018	11/06/2018	18/06/2018	25/06/2018	2/07/2018	9/07/2018
General	Year	2018																		
	Month	March				April					May				Jun				July	
	Week starts	5/03/2018	12/03/2018	19/03/2018	26/03/2018	2/04/2018	9/04/2018	16/04/2018	23/04/2018	30/04/2018	7/05/2018	14/05/2018	21/05/2018	28/05/2018	4/06/2018	11/06/2018	18/06/2018	25/06/2018	2/07/2018	9/07/2018
	Days training #			5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3
	Weekly intensity (H-M-L)	L	L	M	M	M	L	M	H	H	L	M	H	H	L	M	H	M	M	L
Throwing	Throwing sessions per week	4	4	3	4	4	3	5	5	5	3	5	5	5	3	5	5	5	4	3
	Total throws	≈60	≈60	80-100	80-100	80-100	60	80-100	100+	100+	60	80-100	100+	100+	60	80-100	100+	80-100	80-100	60
Throwing loads	3.0kg																			
	3.6kg																			
	4kg																			
	4.5kg																			
Resistance	Gym sessions per week	3	3	3	4	4	2	4	4	4	2	3	4	4	2	3	2	2	2	2
Programing specifics	Primary			S ECC			Pwr	S/M ECC			Pwr		F ECC		VBT			Pwr		
	Secondary			Strength			Plyo	Pwr			Plyo		Plyo		Plyo					

Figure 14. 3. Throwing and resistance training periodisation from November 2017 to July 2018. H – M – L, high – moderate – low; Bal, ballistic type training; Plyo, plyometric training; Pwr, power training; VBT, velocity-based training; S ECC, slow velocity eccentric training; M ECC, moderate velocity eccentric training; F ECC, fast velocity eccentric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

General	Year	2018																							2019													
	Month	July			August				September				October					November				December				January					February				March			
	Week starts	16/07/2018	23/07/2018	30/07/2018	6/08/2018	13/08/2018	20/08/2018	27/08/2018	3/09/2018	10/09/2018	17/09/2018	24/09/2018	1/10/2018	8/10/2018	15/10/2018	22/10/2018	29/10/2018	5/11/2018	12/11/2018	19/11/2018	26/11/2018	3/12/2018	10/12/2018	17/12/2018	24/12/2018	31/12/2018	7/01/2019	14/01/2019	21/01/2019	28/01/2019	4/02/2019	11/02/2019	18/02/2019	25/02/2019	4/03/2019	11/03/2019	18/03/2019	25/03/2019
	Days training #																																			4	4	5
	Weekly intensity (H-M-L)				M	M	M	L	H	H	L	M	H	H	L	M	H	H	M	M	M	M	M	M	H	H	M	L	L	M	L	H	M	L	L	L	M	M
Throwing	Throwing sessions per week				2	3	4	3	4	4	3	4	4	4	3	4	5	5	4	4	4	4	4	4	4	4	4	4	3	4	3	4	4	4	3	3	3	4
	Total throws				<80	<80	<80	100+	100+	80-100	<80	80-100	100+	100+	<80	80-100	100+	100+	<70	<70	<70	<70	<70	<70	100+	100+	80-100	<60	<60	80-100	<60	80-100	80-100	<60	<60	60-70	70-80	80 - 90
Throwing loads	3.0kg	Time off																																				
	3.6kg																																					
	4kg																																					
	4.5kg																																					
Resistance	Gym sessions per week				3	3	3	3	4	4	2	3	4	4	2	3	4	4	1	1	1	1	1	1	3	3	3	3	2	2	2	3	3	2	2	3	3	3
Programing specifics	Primary				Strength			S ECC			VBT		S ECC		VBT		F ECC		Overshoot						VBT											VBT		
	Secondary				Pwr			Plyo			Pwr		Plyo		Pwr		Plyo		VBT						Plyo											Pwr		

Figure 14. 4. Throwing and resistance training periodisation from July 2018 to March 2019. H – M – L, high – moderate – low; Plyo, plyometric training; Pwr, power training; F Iso, fast isometric training; VBT, velocity-based training; S ECC, slow velocity eccentric training; F ECC, fast velocity eccentric training. In the shaded areas, the darker colours indicate a greater percentage contribution.

14.6 Coaching directives

Within the 18-month period, there were two main periods where the coaching directives differed. From April to September 2018, the coaching directives were:

- Increase the height and width of the sweep leg.
- Straighten and increase the radius of the left arm through first double support.
- Shift the hip over the left foot through first double support.

From September 2018 to March 2019, the coaching directives were:

- Increase the spine angle (laterally to the right when viewed from the side) at right foot down.
- Drop the COM through first double and single support.
- Create a wider base in second double support.

14.7 Statistical analysis

Longitudinal change was quantified using a mixed statistical and visual analysis method (387) to allow for the quantification of large changes in the analysed variables (388). The two band SD method was used for the purpose of this investigation due to its agreement with the C statistic and split method of trend estimation (388). Within this method, numerical changes were tracked via graphs with significant change quantified by a clear set of rules. The graphs have two bands that indicate two SD above (upper band) and two SD below (lower band) the pre-test mean. Post-test data points on the graph that fall outside either bands define a significant change. Changes are considered more meaningful when consecutive or numerous data points fall outside the SD lines (Figure 14.5) (388). Visual analysis was used to identify trends in the data and was defined as two or more data points trending in the same direction (Figure 14.5). Furthermore, neuromuscular and biomechanical variables were mapped against the criterion performance variable to identify concurrent changes over prolonged periods. Additionally, to provide comparison between distinct data points where performance or release velocity showed large changes, raw (and percentage) change in variables was quantified and presented as mean ± SD. This gave the ability to compare biomechanical and neuromuscular status between data points.

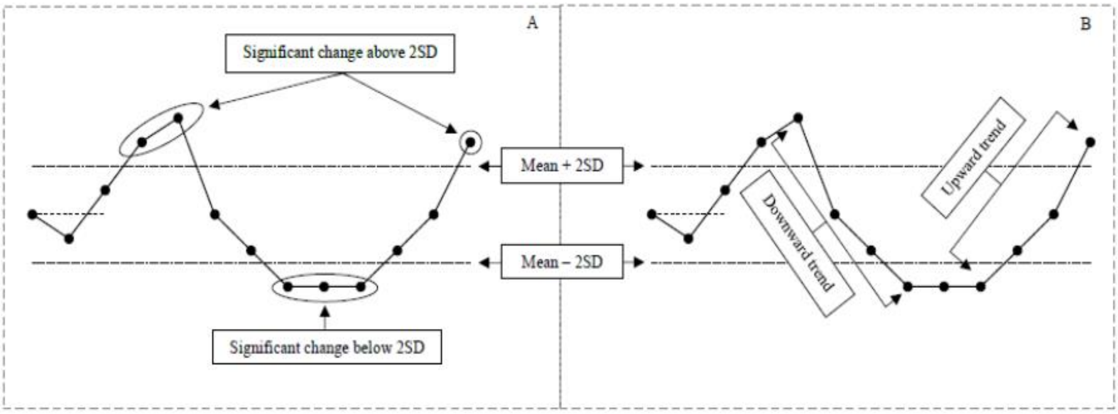

Figure 14. 5. (A) Statistical, and (B) visual analysis methods used.

14.8 Results

14.8.1 Throwing performance

Competition performance is reported in Figure 14.6. During the entire interventional period (November 2017 to February 2019) competition performance significantly increased and remained elevated during all competitions undertaken through the intervention. Between March 2018 to March 2019 seasons competition performance increased 8.2%. This period was identified as a period of significant interest. As no testing could be undertaken around competition in March 2019, March 2018 to February 2019 were the months of interest during which time biomechanical and neuromuscular changes were examined.

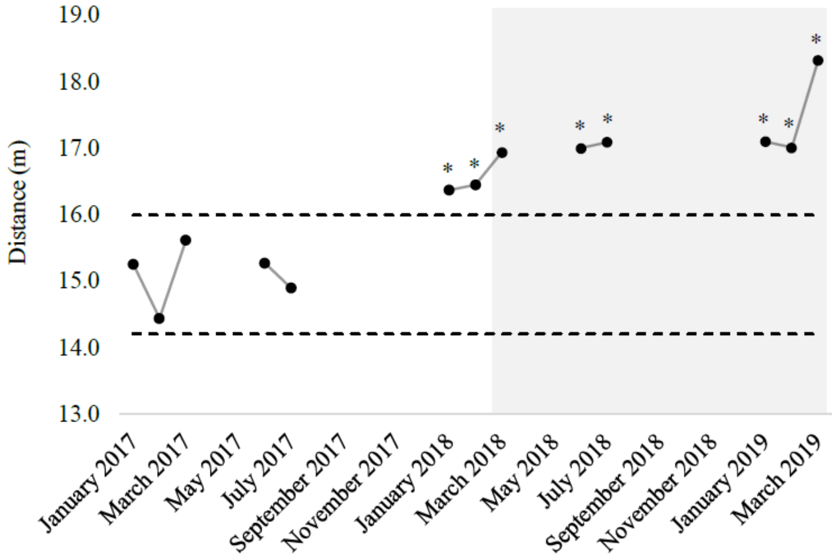

Figure 14. 6. Competition performance prior to and during (November 2017 to March 2019) the investigation period. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

14.8.2 Biomechanical variables

Release velocity over the investigation period is presented in Figure 14.7. Release velocity trended up from November 2017, reaching a level of significant increase in March 2018 and May 2018 before dropping below the ±2SD bandwidth. Again, release velocity increased to a significant level from October 2018 through to February 2019. As a large change in competition performance between years was observed, the period extending from March 2018 to February 2019 was of significant interest. An increase in release velocity of 3.0% occurred between March 2018 and February 2019.

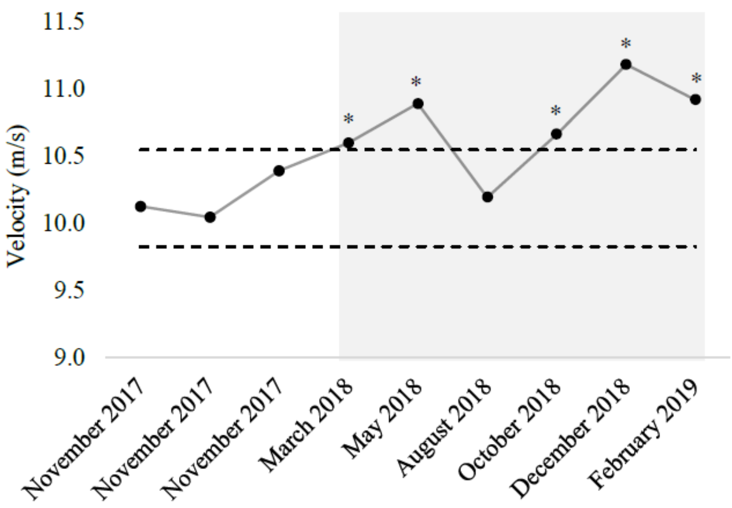

Figure 14. 7. Release velocity during the investigation period. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Shot velocity, and pelvis and trunk angular velocities at each event during the throw are reported in Table 14.1. Shot velocity at right foot off was significantly decreased from March 2018 to October 2018. At both left foot off and right foot off, shot velocity in March 2018 was significantly decreased. No other changes were observed at either events during any other months. At right foot down and left foot down, shot velocity was significantly increased during the majority of months; however, only changes in shot velocity at left foot down corresponded with changes in release velocity. Between seasons across events, shot velocity increased from 3.0 to 24.8%.

Pelvic angular velocity was significantly increased in October 2018 at right foot off and February 2018 at left foot off, and in May 2018 at left foot down and October 2018 at release. Between seasons, pelvic angular velocity increased at right foot off, left foot off, and right foot down (28.3%, 14.2%, and 4.9%, respectively) and decreased at left foot down and release (-11.3% and -9.9%, respectively).

Trunk angular velocity was significantly greater in October and December 2018 at right foot off. No significant changes were observed at either left foot off or right foot down; however, at left foot down, trunk angular velocity was significantly greater during the majority of months. At release, a significant decrease was observed in May 2018 and August 2018, but trended up to a significant increase in December 2018. Between seasons, trunk angular velocity increased at right foot off and left foot off (18.2 and 7.6%, respectively) and decreased at right foot down, left foot down, and release (-3.9%, -17.9, and -0.5%, respectively).

Table 14. 1. Shot put resultant velocity (m/s) and pelvis and trunk angular velocity (°/s) about the z axis at each event during the throw.

	Right foot off			Left foot off			Right foot down			Left foot down			Release		
	Shot	**Pelvis**	**Trunk**	**Shot**	**Pelvis**	**Trunk**	**Shot**	**Pelvis**	**Trunk**	**Shot**	**Pelvis**	**Trunk**	**Shot**	**Pelvis**	**Trunk**
November 2017	2.3	345.8	390.7	1.2	491.4	387.4	1.1	532.8	410.9	1.7	458.7	439.6	10.1	667.4	745.1
November 2017	2.4	412.1	424.7	1.3	493.6	458.2	1.0	573.2	426.6	2.1	555.8	505.0	10.0	604.2	755.6
November 2017	2.4	405.3	440.4	1.0	542.1	477.0	0.9	605.2	456.9	2.0	554.3	482.8	10.4	647.0	747.8
+2SD	2.5	460.7	469.4	1.4	566.3	535.3	1.2	643.0	478.2	2.3	634.2	542.3	10.5	704.0	760.4
-2SD	2.3	314.8	367.8	0.9	451.8	346.4	0.8	497.8	384.8	1.5	411.7	409.3	9.8	575.0	738.6
Interventional period															
March 2018	2.1$^{\#}$	356.2	383.3	0.9$^{\#}$	504.4	430.3	0.8$^{\#}$	569.5	431.7	2.3*	603.4	561.5*	10.6*	683.1	759.0
May 2018	2.5*	417.4	444.1	1.0	477.4	455.0	0.9	605.1	389.0	2.8*	634.8*	624.7*	10.9*	589.9	662.3$^{\#}$
August 2018	2.5*	408.4	446.8		478.1	452.9		570.8	437.2	2.5*	606.6	561.8*	10.2	698.0	712.8$^{\#}$
October 2018	2.3$^{\#}$	474.7*	471.0*	1.2	549.7	496.8	0.8	579.4	416.4	1.8	587.7	556.1*	10.7*	729.9*	749.0
December 2018	2.4	435.9	479.6*	1.3	507.6	512.7	0.7	626.6	432.6	2.6*	557.2	545.1*	11.2*	677.0	805.2*
February 2019	2.4	457.0	452.9	1.1	576.2*	463.1	1.0	597.5	414.8	2.6*	535.3	460.7	10.9*	615.6	755.5

* denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Changes in hip to shoulder separation are shown in Table 14.2. At right foot off, an increase in hip to shoulder separation was observed in March 2018, August 2018, December 2018, and February 2019. At left foot off significant increases were observed in August 2018, October 2018, and February 2019. At right foot down, hip to shoulder separation angle increased during all months (March 2018 to February 2019). No significant increases or decreases in hip to shoulder separations were observed at either left foot down or release. When comparing between seasons, hip to shoulder separation decreased 109.7%, 18.4%, and 254.6% at right foot off, left foot down, and release; but increased 234% and 733% at left foot off and right foot down, respectively.

Table 14. 2. Hip to shoulder separation (°) about the z axis at each event during the throw.

	Right foot off	**Left foot off**	**Right foot down**	**Left foot down**	**Release**
November 2017	5.3	12.1	10.1	-21.4	-1.1
November 2017	5.4	10.4	7.4	-17.2	4.6
November 2017	11.4	20.6	16.1	-13.0	14.1
+2SD	14.4	25.3	20.1	-8.8	21.2
-2SD	0.4	3.4	2.3	-25.6	-9.4
			Interventional period		
March 2018	-3.1*	5.0	1.8*	-23.4	1.1
May 2018	10.4	10.5	-0.3*	-17.2	20.4
August 2018	-0.9*	-3.7*	-8.9*	-19.5	4.0
October 2018	3.8	3.3*	-3.5*	-17.0	12.4
December 2018	-0.3*	5.8	-0.1*	-17.7	14.3
February 2019	0.3*	-6.7*	-11.4*	-19.1	3.9

* denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

14.8.3 Neuromuscular variables

Jump height and body mass are reported in Figure 14.8 (A and B, respectively). Jump height was not recorded in March 2018 due to injury. A significant increase in May 2018, August 2018, and February 2019 was observed. Body mass remained constant throughout the intervention, increasing from August 2018 to December 2018 before returning to baseline.

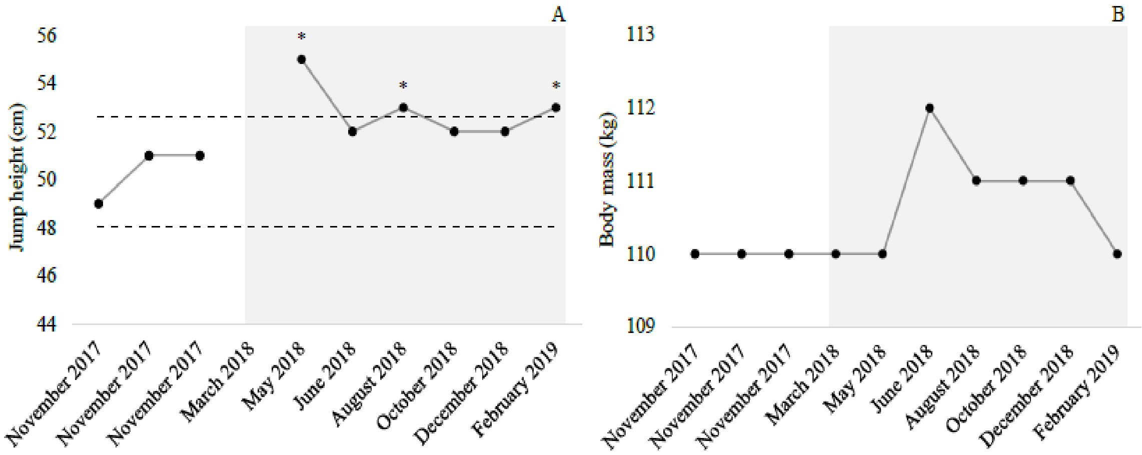

Figure 14. 8. (A) Jump height, and (B) and body mass over the intervention. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Inertial load bike optimal cadence and peak power are presented in Figure 14.9 (A and B, respectively). Optimal cadence initially fluctuated before increasing in December 2018 and February 2019; however, these changes were not significant. Peak power significantly increased in August 2018, December 2018, and February 2019. When comparing between seasons, optimal cadence increased 3.0% and peak power 6.1%.

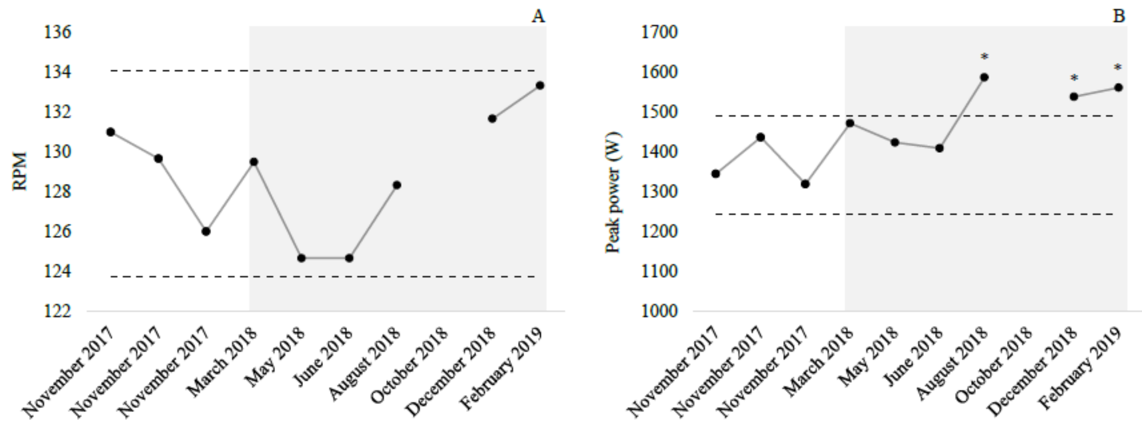

Figure 14. 9. Inertial load bike (A) optimal cadence, and (B) peak power over the intervention. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Peak bar velocities during loaded countermovement jump, bench throw, bench pull, and cable put are presented in Figure 14.10 (A to D, respectively). Significant reductions in loaded countermovement jump peak bar velocities were observed between May 2018 and October 2018 across loads (Figure 14.10A). However, between seasons peak bar velocity increased 0.2% to 5.2% across loads.

Bench throw bar velocities (Figure 14.10B) significantly increased from March 2018 to February 2019 in the heavier loads and from October 2018 to February 2019 with the 20 kg load. When comparing March 2018 with February 2019, peak velocity increased 7.8% to 19.7% across loads.

Increases in bench pull bar velocity were observed sporadically across the interventional period, the majority of which coincided with the heaviest load. When comparing between seasons, bar velocity increased 2.4% to 33.4%.

Finally, regarding the cable put, significant increases in peak cable velocity were observed across the intervention. As with the bench pull, increases predominantly coincided with the heavier loads. When comparing between seasons increases in the 12 kg (2.5%) and 36 kg (4.3%) loads were observed; however a small reduction in velocity with the 24 kg load (-0.7%) was recorded.

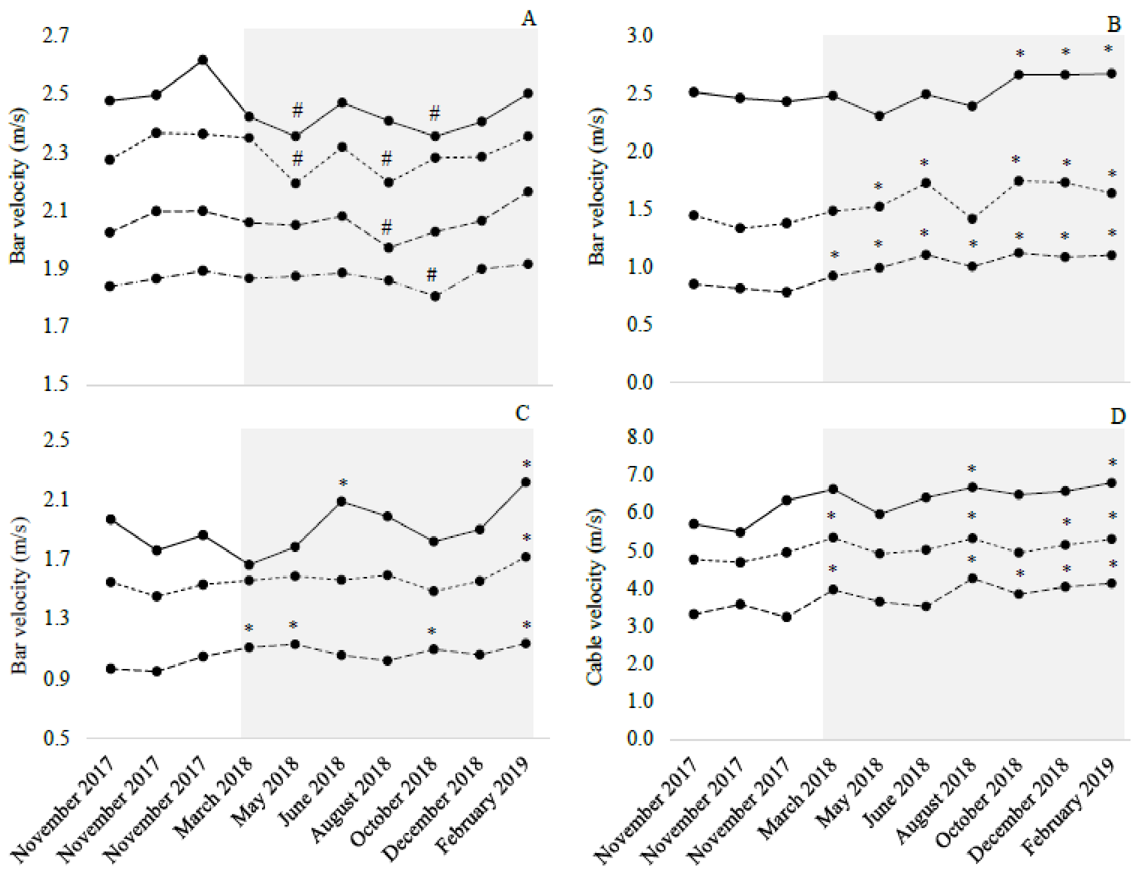

Figure 14. 10. Peak bar velocity during the (A) countermovement jump, (B) bench throw, and (C) bench pull at 20 kg (—), 40 kg (····), 60 kg (- - -) and 80 kg (·· —), and (D) cable put at loads of 12 kg (—), 24kg (····) and 36 kg (- - -). * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

ECC100 and CON100 velocities during loaded countermovement jumps are presented in Table 14.3. ECC100 at the 20 kg load significantly decreased in March 2018, May 2018, August 2018, and February 2019; while CON100 decreased from March 2018 to February 2019. With 40 kg, a significant decrease in ECC100 was observed only in August 2018. With regard to 40 kg, a significant decrease in CON100 was observed over the majority of months, with the exception of May 2018. With the 60 kg load, significant decreases in ECC100 were observed from May 2018 to October 2018. No significant changes in CON100 were observed at 60 kg; however, CON100 visually trended down from late November 2017 to June 2018. Finally, in the 80 kg condition, a significant decrease in ECC100 was observed over the majority of months, whereas significant decreases in CON100 were observed in June 2018 and August 2018. When comparing March 2018 with February 2019, ECC100 and CON100 velocities increased 1.9 to 6.8% with 20 kg and 40 kg. With the 60 kg load, an increase in ECC100 (4.5%) and a decrease in CON100 (-3.8%) velocity was observed, whereas decreases in both ECC100 and CON100 were observed in the 80 kg load (-3.0 to -7.6%).

Table 14. 3. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during countermovement jump at four loads.

	20 kg		**40 kg**		**60 kg**		**80 kg**	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-0.99	1.01	-0.88	0.80	-0.59	0.57	-0.47	0.46
November 2017	-0.88	0.97	-0.84	0.82	-0.62	0.66	-0.47	0.46
November 2017	-0.88	0.97	-0.73	0.79	-0.56	0.57	-0.43	0.41
+2SD	-1.05	1.03	-0.97	0.84	-0.65	0.70	-0.50	0.50
-2SD	-0.79	0.94	-0.66	0.77	-0.53	0.50	-0.41	0.38
Interventional period								
March 2018	-0.74#	0.81#	-0.69	0.69#	-0.54	0.57	-0.39#	0.43
May 2018	-0.78#	0.83#	-0.72	0.79	-0.52#	0.56	-0.41#	0.42
June 2018	-0.92	0.83#	-0.68	0.76#	-0.52#	0.52	-0.37#	0.37#
August 2018	-0.76#	0.81#	-0.59#	0.62#	-0.50#	0.53	-0.35#	0.36#
October 2018	-0.80	0.85#	-0.70	0.74#	-0.52#	0.52	-0.40#	0.39
December 2018	-0.83	0.88#	-0.72	0.67#	-0.60	0.54	-0.43	0.39
February 2019	-0.78#	0.83#	-0.73	0.74#	-0.56	0.55	-0.38#	0.39

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Bench throw ECC100 and CON100 are reported in Table 14.4. Both ECC100 and CON100 with the 20 kg load were significantly elevated over the majority of months from May 2018 to February 2019, with the exception of March 2018 where a significant decrease in CON100 was observed. ECC100 and CON100 with 40 kg load significantly increased over the majority of months from March 2018 to December 2018; however, a significant decrease in ECC100 was observed in February 2019. With regard to the 60 kg load, a significant increase in ECC100 was observed over the majority of months; however, significant increases in CON100 were observed from August 2018 to December 2018. Between seasons, ECC100 and CON100 increased 63.3% and 58.1% at 20 kg; decreased 44.8% and 18.5% at 40 kg; and decreased 18.6% and increased 6.3% at 60 kg, respectively.

Table 14. 4. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench throw at three loads.

	20kg		**40kg**		**60kg**	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-0.81	1.35	-0.81	0.80	-0.58	0.49
November 2017	-0.78	1.33	-0.73	0.77	-0.57	0.51
November 2017	-0.74	1.36	-0.75	0.74	-0.54	0.40
+2SD	-0.85	1.38	-0.85	0.83	-0.61	0.58
-2SD	-0.70	1.32	-0.68	0.71	-0.51	0.35
Interventional period						
March 2018	-0.80	1.03#	-0.99*	0.89*	-0.65*	0.53
May 2018	-0.97*	1.35*	-0.80	0.86*	-0.58	0.45
June 2018	-1.07*	1.46*	-0.96*	0.97*	-0.65*	0.52
August 2018	-1.35*	1.59*	-1.03*	0.96*	-0.62*	0.60*
October 2018	-1.20*	1.69*	-0.87*	1.00*	-0.67*	0.62*
December 2018	-1.15*	1.64*	-0.99*	1.08*	-0.75*	0.68*
February 2019	-1.31*	1.63*	-0.55#	0.73	-0.53	0.56

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviation below the mean.

Bench pull ECC100 and CON100 can be seen in Table 14.5. The 20 kg bench pull ECC100 significantly decreased in March 2018 and May 2018 but trended upwards to a significant increase in August 2018 before significantly decreasing in February 2019. CON100 significantly decreased initially until March 2018 before visually trending upward to August 2018. 40 kg ECC100 trended upwards from May 2018 reaching a significant increase in October 2018. Significant decreases in 40 kg CON100 were observed in March 2018 and December 2018. 60 kg bench pull ECC100 significantly decreased in March 2018 and May 2018, following which it trended upwards from May 2018 to October 2018. 60 kg CON100 was significantly decreased in March 2018 only. When comparing between seasons increases of 15.3 to 217.4% in ECC100 and CON100 were observed across loads.

Table 14. 5. Peak bar velocity (m/s) 100 ms prior to (ECC100) and post (CON100) concentric onset during a bench pull at three loads.

	20kg		40kg		60kg	
	ECC100	**CON100**	**ECC100**	**CON100**	**ECC100**	**CON100**
November 2017	-0.99	1.03	-0.73	0.74	-0.46	0.52
November 2017	-0.86	0.99	-0.60	0.73	-0.37	0.42
November 2017	-0.84	0.82	-0.50	0.65	-0.30	0.36
+2SD	-1.06	1.17	-0.84	0.80	-0.53	0.60
-2SD	-0.73	0.72	-0.38	0.61	-0.22	0.27
Interventional period						
March 2018	-0.45#	0.51#	-0.43	0.57#	-0.12#	0.18#
May 2018	-0.65#	0.84	-0.43	0.64	-0.13#	0.36
June 2018	-0.83	0.95	-0.61	0.73	-0.38	0.35
August 2018	-1.07*	1.12	-0.78	0.68	-0.45	0.50
October 2018	-1.01	1.01	-0.91*	0.78	-0.47	0.36
December 2018	-0.88	1.02	-0.70	0.59#	-0.33	0.40
February 2019	-0.77	0.96	-0.67	0.66	-0.37	0.41

Notes. * denotes change 2 standard deviations above the mean, # denotes change 2 standard deviations below the mean.

14.9 Discussion

Coaches and athletes seek to enhance biomechanical and neuromuscular qualities in the pursuit of improving performance. One method of identifying factors important to enhancing performance is to map changes in throwing performance alongside those factors to identify change in a similar manner over a given period. Using this approach, positive changes in performance and release velocity relative to baseline were noted from approximately March 2018 to February 2019. In terms of performance and biomechanical analysis, the main findings were: 1) competition performance significantly improved throughout the intervention and increased 8.2% between the 2018 and 2019 season; 2) no single biomechanical variable appeared to change in a similar fashion to release velocity; however, significant changes in the biomechanical variables of interest were observed; and 3) the release velocities in testing consistently underestimated performance.

With regard to neuromuscular changes during the period of interest, the main findings were: 1) no singular neuromuscular variable changed in parallel to release velocity; 2) significant decreases in countermovement jump peak velocity, ECC100, and CON100 were observed; however, increases in the majority of these parameters were noted between seasons; 3) increases in bench throw, bench pull and cable put peak velocity were observed concurrently with increases in bench throw and decreases in bench pull ECC100 and CON100; and 4) optimal cadence increased between seasons, but the change was not statistically significant. In contrast, significant increases in peak power were observed over the intervention and between seasons.

Coaches and athletes plan biomechanical and neuromuscular trainings to lead to adaptations over time with the intent of peak performance at pinnacle events. Our data show that the periodised planning was successful, with performance at the pinnacle 2019 event increasing by 8.2% compared to the previous year. Release velocity was significantly enhanced around periods where performance was enhanced. That said, one of the major observations was that release velocity around competition periods consistently underestimated competition performance. Release velocities of 12.24 to 12.80 m/s have been reported for 17.00 to 18.50 m throws (9), which is significantly greater than the 10.5 to 11.2 m/s release velocities (Figure 14.7) recorded in this study alongside the 17.00 to 18.50 m throws (Figure 14.6). The discrepancy between testing and competition velocities is possibly a result of: 1) the nature of a laboratory-based testing, 2) the lack of caffeine consumption and motivational atmosphere associated with testing, or 3) systematic error in the three dimensional testing methods used. To minimise systematic error the system was calibrated as per the manufactures recommendations prior to data collection and camera positioning enabled multiple cameras to view the shot markers at release (359). Furthermore, multiple markers were placed directly on the shot put to track the centre of the shot. For this particular athlete, it appears that laboratory-based testing was an inadequate measure of competition performance due to psychological and/or physiological factors. Outdoor testing in a competitive environment may provide more ecologically valid release velocities, which should be considered by future investigators in throwing events.

With regard to the relationship between kinematics and release velocity, no single biomechanical variable changed congruently with performance. That said, torso velocity at left foot down was significantly increased during the intervention and the greatest release velocity was observed with the greatest trunk angular velocity at release. This is the first investigation to report changes in angular velocities during shot put over a longitudinal period, so there are limited data available for comparisons or validation. Lipovesk et al. (62) reported absolute angular velocities of the hip and shoulder axis at release to be related to performance ($r = 0.73$, $p < 0.05$) in elite throwers. While our data suggest increases in trunk velocity occurred during times of increased release velocity, the magnitude of angular velocity change did not change in a similar manner to release velocity. Significant decreases in hip to shoulder separation also occurred during the intervention preceding right foot down, and large changes between seasons were noted but did not tend to change with performance. Byun et al. (5) reported the hip to shoulder pattern of two elite male rotational shot putters. Their results showed the shoulders (represented by a negative sign) to trail the hip from left foot off to just prior to release. Our data suggest the current athlete's hip to shoulder separation pattern through the throw trended towards that of elite throwers over the course of the investigation, as did performance. Thus, the pattern of axial separation during the throw maybe more important than the absolute magnitude. The magnitude of separation reported in the current investigation (10° to -23.4°) are at the lower end of the spectrum to those reported previously (10° to greater than -50° (5)). Elliott, Wallis, Sakurai, Lloyd, and Besier (399) observed shoulder axis position derived from video to differ significantly from infrared marker-based thorax position calculations in cricket bowling. Furthermore, the authors reported a significant overestimation of video-based assessments. Thus, although within the range of those previously calculated the two data sets are not comparable due to differences in hip to shoulder separation calculation methodologies (5, 399).

Tracking neuromuscular change against performance or key predictors of performance might unveil a causative effect of certain physical qualities on performance. Our results indicated that no singular neuromuscular variable changed congruently with release velocity. That said, between seasons, large increases in the majority of neuromuscular variables occurred with increased performance. Judge and Bellar (118) suggested that bench press, back squat, and power clean strength had a predictive role in shot put performance. Although we could not track maximum strength, our heavy load bar velocity data used as a proxy for strength do not support this contention. Across the intervention, we observed a decrease in heavy load countermovement jump velocity with increased throwing performance and release velocity, and fluctuations in heavy load bench throw velocity that did not correspond with release velocity or performance. Kyriazis et al. (12) reported maximal take-off velocity during a countermovement jump to increase 7.0 ± 8% with a concurrent increase in shot put performance of 4.7 ± 2% between seasons. We observed a similar trend in loaded countermovement jump peak bar velocity (%) between seasons. However, when looking at the pattern of velocity change across the entire investigation, a causative effect was not observed. The cable put movement was included as changes in a movement ecologically more specific to shot put was thought to potentially have a stronger causative effect. Peak cable velocity did not change congruently with release velocity, but showed a similar pattern to that of the other assessed movements. In a similar notion, early contractile ability is more temporally specific to shot put throwing. This variable also did not change in a similar manner to release velocity in the current longitudinal investigation. Our data show that increases in performance can be observed with decreases in early force – time ability during jumping and upper body ballistic type movements. Interestingly, significant changes in early force – time ability were not always observed with significant changes in peak bar velocity; thus, the two measures appear to reflect independent qualities, at least in the current athlete.

The purpose of periodisation is to plan biomechanical and neuromuscular adaptations that culminate in enhanced performance at targeted times during the competitive season. The present periodisation was targeted at enhancing peak force while maintaining or enhancing fibre type, tendon stiffness, and neural output based on the premise that these variables determine early force – time and high velocity force application (5, 66). Fibre type, peak force, early force – time and high velocity force application were measured by optimal cadence (26), high load ballistic movements, ECC100 and CON100, and inertial load bicycle peak power, respectively. Over the course of the year, both inertial load bicycle measures increased. Previous literature has suggested the velocity at which peak power occurs corresponds to fibre type in vivo (130) and in vitro (26). Thus, the changes in optimal cadence are likely explained by a shift towards a faster muscle fibre type. High load peak velocity was also enhanced over the interventional period, suggesting peak force was enhanced. That said, differing magnitudes of changes were observed between movements suggesting differential adaptive responses between muscle groups. A similar response was observed in early force – time application whereby decreases in countermovement jump and bench pull ECC100 and CON100 were observed, while bench throw ECC100 and CON100 increased. The coach employed the same theme of training mode across movements, which indicates that the different muscle groups responded differentially to the same training mode. The eccentrically biased periodisation plan with detraining is a possible explanation to our findings. Prior investigations have suggested selective recruitment of fast fibre types with eccentric training (23, 400) and during detraining a conversion of IIa to IIx, but not Ia to IIa, occurs (401). Johnson, Polgar, Weightman, and Appleton (402) reported the predominance of fast fibre types in pressing musculature; conversely, pulling musculature is dominated by slow fibre types. Thus, the discrepancy between upper body responses to the current periodisation might be related to fibre type. Future investigators should look to understand the divergent neuromuscular responses to the present periodisation scheme between muscle groups and the possible underpinning mechanisms.

14.10 Conclusion

Coaches seek to enhance competition performance over longitudinal periods by optimising biomechanical and neuromuscular adaptations. This case study tracked biomechanical and neuromuscular variables of a sub-elite female shot putter over a longitudinal period. Competition performance and release velocity significantly increased over the longitudinal period and significant changes in biomechanical and neuromuscular variables were observed. However, no variable, biomechanical or neuromuscular, changed in a manner that corresponded with release velocity. Furthermore, release velocities reached in testing underestimated competition performance. Overall, this case study highlights that no singular variable was able to predict performance. It is likely that many variables interact together to enhance performance. Additionally, caution should be taken in interpreting biomechanical data captured in a laboratory setting as it may not be indicative of competition performance. Given the single subject design of this investigation, inferences should also be made with caution as the results presented here may not be applicable to other subject groups. Future research should look to recreate the methodologies presented with larger cohorts of athletes. Such studies would enhance our understanding of the interaction between biomechanical and neuromuscular qualities, and the effects of biomechanical and neuromuscular changes on throwing performance.

Chapter 15

Summary, practical recommendations, limitations, and future research

15.1 Summary

The overall purpose of this thesis was to understand which biomechanical and neuromuscular variables relate to discus, shot put, and hammer throw performance. In addition to addressing the identified gaps in the literature, this thesis was directed at providing practical recommendations to practitioners working within track and field throwing. An advanced and integrated understanding of biomechanical and neuromuscular training is required to perform at a high level within rotational throwing, and these two aspects in practice are interrelated (e.g., the neuromuscular system allows throwing performance, and throwing performance leads to neuromuscular adaptations). However, following a comprehensive review of the biomechanical literature across throws, it was found that few kinematic variables had been related to performance acutely, with no investigation tracking any variable longitudinally. Tracking key variables over time was thought to provide an understanding of the causal effect of adaptation and targeted training of these qualities on performance. Furthermore, a comprehensive review of resistance training literature found a paucity of literature across throwing events, the main finding being that training maximal strength/peak force was the dominant training mode used by throws athletes. More specifically, measurements of peak force during pressing and squatting type movements were used in most of the literature, whereas more specific movements (i.e., rotational and putting movements) were not examined. As a result, it was concluded that the existing body of research provided little direction for strength coaches and that further research on neuromuscular, biomechanical, and practical aspects in throws was required. Basing resistance training on a comprehensive understanding of neuromuscular traits that theoretically drive elite throwing biomechanics was thought to be an appropriate model to use to direct resistance training practices in elite throwers. Hence a theoretical model of resistance training was developed that could be practically implemented by practitioners working within rotational throws.

From the reviewed literature, it was difficult to assess and justify the inclusion of select neuromuscular and biomechanical variables in rotational throws athletes given their general lack of existing methodologies, association with performance, and practical relevance. The second section of this thesis therefore investigated: 1) the reliability of musculoarticular stiffness in compound movements; 2) the reliability of the cable put and cable rotation assessments; 3) the reliability of manual digitization in a throwing motion; and, 4) the relationship between velocity of a bench pull and bench press and kinematics in a throwing motion. The first protocol, the reliability of musculoarticular stiffness, used force – time and position – time data to quantify force and bar movement of a perturbation applied to the bar in a bench, bench pull, and squat hold. It was proposed that the natural oscillatory frequency of the bar represented musculoarticular stiffness. This method was unreliable across loads and positions at quantifying stiffness. Musculoarticular stiffness during the bench press (CV: 16.1 to 111%; ICC: -0.58 to 0.75) and bench pull (CV: 7.07 to 40.6%; ICC: -0.15 to 0.89) exhibited poor absolute and relative reliability. During the squat, no discernable wave form at the time of perturbation could be seen from force plate measures. Therefore, this method of measuring musculoarticular stiffness was considered unreliable and required major methodological changes before being integrated into a practical or research setting.

The second protocol sought to investigate the inter – day reliability of the cable rotation and cable put motion across multiple loads as these two movements are ecologically specific to rotational throwing. Kinematic (displacement and velocity) measures were found to have acceptable reliability across movements and loads (cable put CV: 3.1 to 8.6%, ICC: 0.92 to 0.99; cable rotation CV: -1.73 to 16.1%, ICC 0.76 to 0.99). However, kinetic (force and impulse) variables were less reliable across movements and loads likely due to the indirect measurement of kinetic measures using a LPT. Cable put and cable rotation kinematic outputs were therefore deemed reliable and identified as a suitable method to quantify putting and rotational neuromuscular ability.

The third protocol sought to understand the inter–day reliability of a seated medicine ball put protocol, intra–assessor reliability of manual digitization, and comparability between two and three camera configurations. Understanding the intra–assessor reliability was proposed to give insight into error associated with assessor contrast identification; and examining the comparability of outcome measures between camera numbers gives insight into the comparability of findings from prior throwing biomechanical research using different camera numbers. Between days, peak (CV: 2.7 to 8.4%; ICC: 0.82 to 0.90) kinematic measures were more reliable than mean (CV: 10.2 to 13.5%; ICC: 0.51 to 0.71) measures. Intra–assessor reliability of temporal variables, peak kinematic variables, and mean kinematic variables was acceptable (CV: -0.12 to 5.15%; ICC: 0.87 to 1.00). Comparing kinematic measures calculated using two versus three cameras revealed that peak kinematics were comparable, but mean and temporal variables significantly differed ($p < 0.05$). The differences between mean and temporal data were likely a function of the inability to identify the start time that confounded both mean kinematics and temporal variables. Therefore, manual digitization was concluded to be a reliable method of tracking peak kinematic variables and comparable between two and three camera data collection methods; however, the generalisation of mean variables derived from two versus three cameras was questioned.

The fourth protocol sought to investigate the relationship between pressing and pulling kinematics and seated medicine ball kinematics. Understanding the relationship between bench press and bench pull kinematics was proposed to provide insight into the role of pulling musculature within a rotational throwing motion. Both bench press (20 kg – 1RM bar velocities, $r = 0.70$ to 0.82, $p < 0.05$) and bench pull (20 to 60 kg bar velocities, $r = 0.75$ to 0.89, $p < 0.05$) bar velocities were strongly associated with medicine ball peak velocity. Interestingly, bench pull at lighter loads (peak acceleration, $r = 0.69$ to 0.82, $p < 0.05$; $accel_{50\text{-}100\%PV}$, $r = 0.67$ to 0.81, $p < 0.05$) and 1RM bench press (peak acceleration: $r = 0.76$, $p < 0.05$; $accel_{50–100\%PV}$, $r = 0.76$, $p < 0.05$) bar velocities correlated with medicine ball put acceleration variables. It was proposed that pulling and pressing movements have separate functional roles within rotational throwing. Therefore, both movements should be trained and tracked concurrently over longitudinal periods to understand their causal effect on performance.

The final section comprised of four case studies investigating the effects of changes in neuromuscular and biomechanical variables on performance. These studies involved four variations of the theoretical model presented in Chapter 6 over a 14 to 18-month training period. Throughout the 14 to 18-month period, neuromuscular and biomechanical variables were measured periodically. The four participants were at a sub-elite to elite level, highly trained, and full-time athletes. Testing and training variations were determined by the head coach in consultation with the researcher. As such, testing was integrated within the performance development pathway. Performance was recorded as the furthest distance achieved at recognized athletics meets (IAAF, 2019). Neuromuscular variables tracked included inertial load bicycle variables and vertical jump, cable rotation, cable put, and eccentric and concentric variables during bench pull, bench press, and countermovement jump. Implement velocity throughout the throw and release velocity, as it is the strongest determinant of performance, were tracked across throws in a laboratory environment. Other biomechanical variables were included based on the throwing discipline as derived from the literature searches.

When comparing the results across case studies, significant variations in adaptive responses to training were observed and few neuromuscular or biomechanical variables adapted concurrently with performance. When looking specifically at each case study, the first case study (male hammer thrower) showed that ECC100 ability trended closely with hammer ball velocity. However, the same trend was not observed in case study two (female hammer thrower), and no single neuromuscular variable changed in a similar fashion to performance. Similarly, in case studies three and four, no single neuromuscular variable changed in a congruent manner with performance or release velocity. That said, several variables increased at times when performance was elevated. To summarise, from a resistance training perspective, few variables trended concurrently with performance and those that did were highly individualized. Enhanced performance was observed with the inclusion of the theoretical periodisation model. Therefore, the inclusion of this periodisation model in throwing was effective, but the effectiveness above other periodisation schemes remains unknown. Interestingly, a common observation across all case studies was the divergent adaptations between movements to training modes. For example, countermovement jump could be increased, bench pull depressed, and vice versa. In all case studies, the theoretical model of resistance training appeared effective at enhancing inertial load optimal cadence and peak power, which were used as a proxy of fibre type composition and high velocity power ability.

Regarding biomechanical variables, significant changes in biomechanical determinants were observed across the investigations, but few changes matched performance changes. Of note was that the changes in biomechanical variables often reflected coaching directives. During the second case study (female hammer thrower), increased release velocity was observed with increased ball velocity during the preceding turns; however, this pattern was not seen in case study one (male hammer thrower). Although biomechanical changes were observed in case studies three and four, no single variable changed in a consistent manner with performance. These studies demonstrated that no single variable, neuromuscular or biomechanical, determines throwing performance across individuals. Each individual likely requires adaptations of multiple variables, neuromuscular and biomechanical, to enhance performance. Finally, the findings of these studies exemplify the individuality that exists within performance predictors and adaptive responses to resistance training. This information provides substantial insight into the totality of performance enhancement and the ability of a theoretical model of periodisation to enhance early force – time and high velocity force application.

This thesis has comprehensively reviewed rotational throwing biomechanical and resistance training literature and provided a strong rationale as to the need to understand how biomechanical and neuromuscular variables adapt with performance at an individual level. It provided a theoretical model of resistance training to enhance neuromuscular predictors linked with biomechanical variables important to throwing performance. It has shown the flaws of perturbation-based stiffness methods and developed two novel methods of assessing rotational performance abilities in a practical setting. Furthermore, we established the reliability of kinematic measures from manually digitized videos and provided data to support the inclusion of both bench pull and bench press within a thrower's testing battery. Finally, it was observed that no singular neuromuscular or biomechanical variable trended concurrently with performance and each individual adapted differentially to the theoretical model of resistance training.

15.2 Practical recommendations

This thesis was intended to have direct applications to coaches and sport scientists working with track and field rotational throwers. More specifically, the research design was such that it had practical relevance and ecological validity for Athletics New Zealand athletes, coaches, and support staff. Several practical recommendations were generated:

1. Practitioners working in high velocity, high power sports can implement the theoretical model of resistance training and or variations of it. Given the correspondence between throwing biomechanics and neuromuscular adaptations that are promoted by this model, it is recommended above more traditional modes to improve proxy measures of fibre type.

2. Practitioners seeking to quantify musculoarticular stiffness of compound movements via the perturbation stiffness protocol that has previously been implemented should do so with caution (311). Practitioners should use alternative means that are more reliable to assess lower body stiffness such as single joint perturbation (403) and ultrasound based protocols (176, 222). Future researchers should investigate alternative means to quantify upper body musculoarticular stiffness.

3. Practitioners seeking to quantify an ecologically specific shot put motion in a gym setting can reliably use the cable put motion and LPT outputs. Kinematic outputs from these assessments should be used over kinetic ones as the former exhibit superior reliability.

4. Rotational performance can be reliably assessed using a seated cable rotation and LPT in terms of kinematic, but not kinetic, measures. Peak kinematic variables exhibit greater reliability, and are recommended for use over mean measures to test and track athletes over time.

5. Practitioners looking to quantify a quasi-rotational upper body putting motion can do so via the seated medicine ball put peak velocity. Furthermore, peak acceleration and acceleration from 50% of peak velocity to peak velocity can be reliably calculated from manually digitized videos.

6. Although reliable, repeated testing occasions using the same number of cameras is required to enhance reliability. Reducing the camera number for digitization from three to two produces significantly different temporal results. Sports scientists may also consider this limitation when comparing biomechanical data derived from video as temporal and acceleration data are camera-number dependent. Comparisons between methods may therefore not be appropriate.

7. As identified in Chapter 10, greater peak medicine ball put velocities appear to be underpinned by the ability to press and pull fast across multiple loads. However, accelerating the medicine ball once moving is underpinned by the ability to pull light loads and press maximal loads rapidly. Thus, it is likely that pulling and pressing musculature have differing functional roles within a medicine ball put. Both motions should therefore be included in a testing and training programme for rotational throwing.

8. As Chapters 11 to 14 demonstrated, throwing performance is not determined by any one biomechanical or neuromuscular measure. Moreover, biomechanical and neuromuscular performance correlates are highly specific to the event and individual. Thus, it is

recommended that practitioners consider multiple biomechanical and neuromuscular variables to track over time for each individual. The ones most important to performance may change over time, so these need to be reassessed on a regular basis to identify strengths and weaknesses.

9. As shown in Chapter 14, laboratory-based testing may not be representative of competition performance. Coaches and athletes may try to replicate competition environments; however, these settings may not simulate competition performance. Thus, sport scientists should seek ways to derive biomechanical outputs from competitions and integrate modes of testing that can be used in a performance setting.

10. Chapters 11 to 14 used variations of the theoretical model of resistance training presented in Chapter 6. From a performance perspective, this theoretical model was deemed effective, although differences in neuromuscular responses were observed between the assessed movements and individuals. In other words, responses between athletes and within athletes between neuromuscular and biomechanical measures differed. Practitioners using this approach to resistance training should continually monitor between and within athlete responses over multiple movements patterns and loads to ensure sought adaptions. Appropriate changes to the training model are recommended on an athlete-by-athlete and neuromuscular/biomechanical measure basis.

15.3 Limitations

A strength of this thesis was that it is directly applicable to biomechanists, strength coaches, and throws coaches as it was undertaken in an applied setting. At present, literature has identified cross-sectional relationships between biomechanical and neuromuscular variables and rotational throwing performance. Longitudinal data exist largely within a resistance training context; but biomechanically-driven or integrated biomechanics and resistance training literature is sparse. Often, longitudinal resistance training data are in reference to strength and power measures, with other neuromuscular variables thought valid to throwing performance not investigated. Furthermore, longitudinal biomechanical data are limited to projectile motion variables and temporal analysis that allow for few definitive conclusions. Thus, a comprehensive understanding of which biomechanical and neuromuscular variables are important to throwing performance still does not exist.

Subsequently, a conceptual model of resistance training directed at enhancing neuromuscular qualities that considers event-specific biomechanical concepts was developed, the limitations of which are acknowledged:

1. The conceptual model presented in Chapter 6 is as stated: *conceptual*. This conceptual approach was necessary as the existing literature had no training model that was ecologically valid for throwing. Furthermore, sequencing training modes as presented in Chapter 6 assume that physiological adaptation can be layered on top of one another, which may not be the case. Finally, it is assumed that throwers can easily integrate neuromuscular adaptations in the throw to enhance performance, whereas transference of adaptations to a throwing-specific context is not ensured .

The limitations with the reliability investigations included:

2. First the perturbation protocol employed in Chapter 7 did not include a standardized perturbation magnitude. However, elastic tissue functions at a constant resonant frequency, regardless of perturbation magnitude (403).

3. The number of participants recruited for Chapters 7, 8, 9, and 10 is a limitation and restricts the statistical power of the results. The number of resistance trained participants that met the inclusion criteria within New Zealand is limited. Most participants competed at a national level within their respective sports and all participants were well trained in power based events. Thus, the quality of participants was given priority in investigating questions applicable to elite rotational throwing events.

4. The cable shot put and cable rotation assessments investigated in Chapter 8 had two limitations that likely confounded mean data. First, the starting position was not rigorously controlled; similarly, the end position was controlled by an elastic stopper. Given the lack of reliability in mean data, small changes in starting and end positions likely occurred. However, the methodology did not allow us to determine whether error in mean data was a function of changing start or finish positions.

5. Digitization error was apparent in Chapter 9 that affected the majority of measured variables. However, it was not possible to understand the direction of change as the gold standard system (i.e., infrared cameras) could not be run with the video-based system simultaneously due to lack of space.

Although a cohort-study approach would have been preferred, this thesis was limited to four case studies with the following key limitations:

6. Chapters 11, 12, 13, and 14 were comprised of longitudinal case studies of four sub-elite to elite throwers. Case studies have some inherent limitations, primarily that the results are only applicable to the tracked individual. Statistical power is low due to small participant numbers. Repeated testing to establish baseline data and multiple testing

occasions were undertaken over the course of the tracking period to examine the emergence of patterns at an individual level.

7. Throughout the tracking period (Chapters 11, 12, 13, and 14), the researcher was part of the performance team, therefore strict control of the programme was not possible. This aspect is acknowledged as a weakness when trying to establish academic rigor and could also lead to confounding due to involvement of the researcher in testing; however, as this thesis was directed to enhance practice in the Athletics New Zealand system, it can be seen to provide practical validity to findings. Athletics New Zealand promotes a coach led structure. Therefore, to have impact, research needs to be relevant to coaching practices.

8. Testing over the course of the tracking period was largely dictated by the coach based on competition and training schedules. Thus, the week of testing was directed by athlete availability.

15.4 Future research

This thesis addressed several gaps in the athletic throwing literature; however, there remains scope for further research. A paucity of literature pertaining to rotational throwing in both biomechanical and resistance training fields was identified. Cross-sectional and longitudinal documentation of biomechanical and neuromuscular variables are required to understand causation and identify the variables associated with performance enhancement. As a result of the paucity of resistance training literature, a theoretical model of resistance training to enhance neuromuscular abilities that underpin throwing biomechanics was presented. This model is highly theoretical and requires further investigation using larger sample sizes and testing modalities relevant to targeted adaptation. The four case studies provide preliminary evidence of the model’s effectiveness, although the efficacy of the model was not compared to other models.

One variable of specific interest in sport is multi-joint musculoarticular stiffness. An assessment of multi-joint musculoarticular stiffness that uses accelerometry technology and is practically accessible to strength coaches would be of substantial value. Such assessments and objectivisation of musculoarticular stiffness could provide insight into the natural resonant frequency of a movements; which, if matched to sports frequency, could yield performance benefits. However, to match the natural frequency of the tissue to the sports frequency, further biomechanical research is required to identify valid and reliable assessment methods.

Finally, there would be substantial interest in attempting to replicate the final case study Chapters methodological approach with larger sample sizes. It is argued that the present case studies combine ecological validity and scientific rigor within the constraints of a high-performance sport setting. Nonetheless, the case study design limits inferences to other groups. Further research is warranted to understand which biomechanical and neuromuscular variables are important to discus, shot put, and hammer throwing performance.

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15.6 Appendices

Appendix 1.A. Ethical Approval Form Stages 1 to 5 (applicable to Chapters 7, 8, 9 and 10).

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

13 December 2016

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **16/438 Understanding which kinematics and kinetic variables are important in improving shotput and discus performance**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 12 December 2019.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 12 December 2019;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 12 December 2019 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

K O'Connor

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: mtschofield@yahoo.com; Adam Storey; Angus Ross

Appendix 1.B: Ethical Approval Form Stages 4 and 5 (applicable to Chapters 11, 12, 13 and 14).

AUT

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www.aut.ac.nz/researchethics

10 April 2017

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **17/66 Understanding which kinematics and kinetic variables are important in improving shotput and discus performance - Stages 4 and 5**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Subcommittee (AUTEC).

Your ethics application has been approved for three years until 10 April 2020.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 10 April 2020;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 10 April 2020 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

K O'Connor

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: mtschofield@yahoo.com; Adam Storey; Angus Ross

Appendix 2.A. Consent form 1 (applicable to Chapters 7, 8, 9 and 10).

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: "Understanding which kinematics and kinetic variables are important in improving shotput and discus performance."

Project Supervisor: *Prof. John Cronin*

Researcher: *Michael Schofield*

○ I have read and understood the information provided about this research project in the Information Sheet dated / / .

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I understand that any data/details collected through my inclusion in this research will be held in an unidentifiable encoded state on the AUT university, SPRINZ data base and may be used in future research projects.

○ I am not suffering from any acute or chronic injuries.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form

Appendix 2.B. Consent form 2. (applicable to Chapters 11, 12, 13 and 14).

AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Consent Form

Project title: "Understanding which kinematics and kinetic variables are important in improving shotput and discus performance."

Project Supervisor: *Prof. John Cronin*

Researcher: *Michael Schofield*

○ I have read and understood the information provided about this research project in the Information Sheet dated dd mmmm yyyy.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I understand that any data/details collected through my inclusion in this research will be held indefinitely in an unidentifiable encoded state on the AUT university, SPRINZ data base and may be used in future research projects.

○ I am not suffering from any acute or chronic injuries.

○ I agree to take part in this research.

○ I wish to include my coach and/or support team in the reporting process: Yes○ No○

If yes, please provide coach/support team name and contact details;

....

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form

Appendix 3. Embargo (applicable to Chapters 6, 11, 12, 13 and 14).

POSTGRADUATE

AUT

Graduate Research School
Private Bag 92006 Auckland 1020
+64-9-921-9907
postgraduate.centre@aut.ac.nz

Ref: 0947305

06 March 2017

Michael Schofield
10 Arirang Rise
Pinehill
Auckland
New Zealand 0632

Dear Michael,

RE: Embargo Request

The University Postgraduate Board has approved your application for an Embargo at their meeting held on 21 Feb 2017. At that point in time the University should contact you to confirm the expiry of the embargo and give you the opportunity to extend if required.

Faculty Contacts

Your primary supervisor is John Cronin
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Yours sincerely,

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Appendix 4. Marker placement (Applicable to Chapters 13 and 14).

Segments and marker locations

Segment	Marker location
Head segments	Two markers placed laterally either side on the anterior aspect of the head
	Two markers placed laterally either side on the posterior aspect of the head
Thorax segments	Single marker placed over the sterno-jugular notch
	Single marker placed over the xiphoidal process
	Single marker placed over the seventh cervical spinal process
	Single marker placed over the twelfth thoracic spinal process
Shoulder joint centre	T shaped cluster placed over the acromion
Upper arm segments	Cluster placed on the distal and lateral aspects of the upper arm
	Single marker placed over humeral medial epicondyles**
	Single marker placed over humeral lateral epicondyles**
Distal arm segments	Cluster placed posteriorly and distally
	Single marker placed over the radial styloid process
	Single marker placed over the ulnar styloid process
Hand segments	Cluster place on the dorsum of the hand
	Single marker placed laterally over the fifth metacarpophalangeal joint**
	Single marker placed laterally over the first metacarpophalangeal joint**
Pelvis segments	Single marker placed over the posterior superior iliac spines
	Single marker placed over the anterior superior iliac spines
	Single marker placed over the iliac crests
Thigh segments	Cluster placed distally and laterally on the thigh
	Single marker placed on the lateral femoral epicondyle**
	Single marker placed on the medial femoral epicondyle**
Shank segments	Cluster placed distally on the anterior shank
	Single marker placed over the lateral malleoli**
	Single marker placed over the medial malleoli**
Foot segments	Single marker placed over the first metatarsal
	Single marker placed over the lateral portion of the second metatarsal joint
	Single marker placed over the lateral portion of the fifth metatarsal joint
	Single marker placed posteriorly over the calcaneus

Note. All orientations in reference to the ** Calibration markers only, removed for dynamic trials.