AUT SPORTS PERFORMANCE
RESEARCH INSTITUTE NEW ZEALAND

Plyometric dosing strategies and manipulation for improving sprint performance in rugby union players.

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M.S.

A thesis submitted in fulfillment of the degree of

Doctor of Philosophy (PhD)

March 2021

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Abstract

Speed and acceleration are integral athletic qualities in rugby union, impacting line breaks, activity rate, metres advanced and tries scored. While there are many methods of training speed, plyometric training utilises similar force-generating mechanisms as sprinting during limited ground contact times, making it ideal to transfer gym-based improvements to the sports field. However, at present a lack of information exists regarding the optimal dose and manipulation of plyometric programme parameters, thereby limiting our understanding of best practice in the context of physical preparation. Thus, the primary purpose of this thesis was to investigate functional and mechanistic characteristics of plyometric training to better inform speed and acceleration training in professional and semi-professional rugby players. Accordingly, the main questions this thesis sought to answer were: 1) What is the lowest necessary plyometric dose for improving sprint performance? 2) What is the best training manipulation of key variables for improving sprint performance? 3) What are the resulting force-velocity sprint profile adaptations from plyometric training and how best do we implement them for position-specific demands?

To better understand these questions, extensive literature searches were conducted surrounding plyometric loading mechanisms and adaptations relating to rugby union (narrative literature review) and plyometric variable manipulation (systematic literature review). The former provided evidence for the use of plyometric training for all positions, despite unique positional demands, while the latter critically analysed plyometric variable manipulation and volume loads for improving sprint performance. From an acute perspective, the second section of this thesis provided a more comprehensive understanding of these ideas and their relevance to current practice. Results from a cross-sectional investigation into competition-level and position-specific speed demands reiterated the importance for all players to train speed and acceleration (Chapter

4). Specifically, international, and professional rugby players across all positions ($n = 152$) showed faster split times (-0.01 to -0.06 s), greater maximal velocity (V_{max}: +0.10 to +0.26 m.s^{-1}) and a more force-dominant force-velocity sprint profile (F_0: +92.2 to +233.2 N) than academy players ($p < 0.01$; ES: 0.22 – 1.42). Irrespective of competition level, split times (30 m: 4.402 – 4.046 s) and maximal velocity characteristics (V_{max}: 8.02 – 8.97 m.s^{-1}) demonstrated a linear trend across positions, wherein outside backs were the fastest and tight-5 players were the slowest (ES: 0.38 – 2.22; Chapter 4). Notably, loose forwards shared similar force attributes to tight forwards (F_0: 955.7 N vs. 918.6 N), but similar maximal velocity characteristics (V_{max}: 8.51 m.s^{-1} vs. 8.64 m.s^{-1}) to inside backs, providing insight to individualised programme needs.

For Chapter 5, an international survey of 61 elite strength and conditioning practitioners' current plyometric practice revealed a large gap between published recommendations and reported practical applications. In particular, 68.4% of international practitioners reported frequently using very low plyometric volumes (≤20 ground contacts (GC)) during off-season periods compared to professional practitioners (30.8%) and semi-professional practitioners (16.7%). Collectively, these real-world findings contrast the current high-volume literary recommendations (120 – 400 GC) (Chapter 5). Additionally, competition-level and sport analysis revealed differences in several plyometric variables including weeks of plyometric training during competition (Chi-Square = 50.65; $p < 0.03$), sessional volume loads across competition phases ($Q = 15.74 – 36.66$; $p < 0.05$), and exercise choice (Chi-Square = 8.83 – 12.62; $p < 0.02$) (Chapter 5). Results herein provided numerous considerations for practically relevant interventions, attempting to bridge the gap between practice and theory.

A unique characteristic of plyometric training, unlike many other forms of training, is using the athlete's own bodyweight as a primary stimulus, rather than an external load. However, absence of an external load has previously created difficulties in monitoring plyometric quality and volume loads, resulting in scarce information surrounding dose response. This thesis has provided novel insight to the effects of progressively increased horizontal vs. vertical plyometric session volumes on direction-specific kinetic performance (Chapter 6). While rugby players were typically able to maintain or improve performance during plyometric training induced fatigued states, several kinetic characteristics were altered during high-volume sessions (Chapter 6). For example, both training directions resulted in increased eccentric impulse following 40 horizontal GC (+12.9%) and 80 vertical GC (+4.9%) which was generally maintained for the remainder of the session. Moreover, these kinetic fluctuations corresponded with a shift in vertical force producing strategies in the horizontal condition only ($p < 0.05$). Results therein provided evidence for the use of minimally effective dosing strategies. Accordingly, short-term low-volume plyometric training was found to improve (Δ30 m time: -0.020 s; ES = -0.23) or maintain sprint performance (Δ30 m time: + 0.049 s; ES = 0.17) better than rugby specific training and resistance training only (Δ30 m time: +0.071 s; ES = 0.36), and that the magnitude of adaptation may be in part related to fitness levels (R = 0.434 to -0.568). Moreover, vertical plyometric training was found to improve secondary acceleration (Vertical Δ10 – 20 m split: -0.01 s; ES = -0.28 vs. Horizontal Δ10-20 m split: 0.00 s; ES = -0.10) and force-centric variables (Vertical ES = 0.43 – 0.78 vs. Horizontal ES = 0.13 – 0.35) more so than horizontally applied training (Chapter 7). Further investigation into horizontal dose response showed low-volumes (40 – 60 GC), but not ultra-low volumes (50% reduction) of single-leg horizontal drop jump were sufficient for improving 10-, 20- and 30- m time (-0.03 s to -0.05 s; ES = 0.32 – 0.54) in semi-professional players (Chapter 8). However, both protocols were similarly effective at improving vertical jump performance (19.2 – 22.6%; ES = 1.34 – 1.42).

Overall, this thesis adds to the existing literature on plyometric manipulation and minimally effective dose strategies for improving sprint performance, particularly relevant for trained rugby players. Specifically, this thesis provides substantial support for the use of low volume (40 – 60

GC), but not ultra-low volume (<35 GC), moderate-high intensity plyometric training strategies. In particular, practitioners may want to implement exercises facilitating a sizeable and fast eccentric component for adaptations pertinent to maximal speed. Whereas, longer duration exercises enabling greater concentric impulse may be more suited to improving accelerative performance. Additionally, rugby athletes may benefit from greater use of horizontal plyometrics in their programming. However, when introducing a new stimulus practitioners are advised to consider an athlete's individual characteristics, positional demands, and adaptation periods for optimal programming. Importantly, while acute performance can be maintained in trained individuals during high-volume (i.e., 200 GC) sessions, even moderate volumes may impose kinetic decrements in movement speed and power. These decrements raise questions about the purpose of additional plyometric volumes, and whether high-volume sessions are beneficial or just added stress in trained rugby players.

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Attestation of Authorship

"I hereby declare that this submission is wholeheartedly 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 another university or other institution of higher learning."

Casey Watkins

PhD Candidate, March 2021

Acknowledgments

"Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less."

-Marie Curie

I am very grateful for the opportunity to pursue this PhD, as well as the support and assistance I have received throughout the process, so that I may understand more about this topic as well as myself.

First, I would like to thank my supervisors. Dr. Adam Storey, you have driven me to become a better writer, scientist, and have greater expectations for myself. I am truly thankful for your insight, detailed critique, and guidance throughout this programme. Associate Professor Nic Gill, thank you for encouraging me to pursue new ideas, believing in me and providing me with the opportunity to come to New Zealand. Professor Michael McGuigan, your wise council and cheery demeanor I will always cherish. Not to mention, your ability to quickly return meaningful feedback in a matter of hours ceases to amaze me.

I would also like to acknowledge Paul Downes and the entire team at Auckland Rugby for allowing me to work with you and to the athletes for participating in my studies. Paul, I am forever grateful for the time and knowledge you have given me, through consultation, observation, and experimentation.

Additionally, I would like to thank all the people that contributed to the final document, either through data collection, editing and proof reading, or my own personal wellness during this period. Colonel Douglas Knighton and Mrs. Maja Knighton, I very much appreciate your attention to detail and the comfort of having family know your journey. Dr. Ed Maunder, I am grateful to you for loving me, believing in me, and supporting me every step of the way. To my collaborators and New Zealand colleagues, Alyssa-Joy Spence, James Young, Dr. Jono Neville, Anja Zoellner, Josh McGeown, Benjamin Taylor, and Kim SantaBarbara, I am very thankful to share this journey with you.

I would be remiss if I did not acknowledge my friends and family who have encouraged me to grow and follow my dreams. Dr. Lee Brown, Saldiam Barillas, Arjan Dougan, and Kathy Morales, I will always cherish you all and my time in Fullerton. Samantha Smith, Katie Miller and Josh Buchanan for providing years of friendship and always being there for me. Lastly, I am deeply grateful for my family and my parents for all the love and support they have given me. Kelly, you have always guided me, inspired me, and loved me though all my faults. CJ, you have always been on my team and wanted me to succeed. To my parents, I have never doubted your love for me or your belief in my ability, even when I doubted myself. Denise, my mother, you have been one of the best examples of female strength and I am constantly encouraged because of you. To my father, I can have unwavering optimism because of the love I have received from you. There is a comfort in knowing you can try to fly, because you will be loved even when you fall.

List of Co-Authored Works

Watkins, CM, Storey, AG, McGuigan, MR, and Gill, ND. Horizontal force velocity power profiling of rugby players: A cross-sectional analysis of competition-level and position-specific movement demands. *J Strength Cond Res* 35(6): 1576–1585, 2021.

(Watkins, 85%, Storey, 5% McGuigan, 5%, Gill, 5%)

Watkins, CM, Storey, AG, McGuigan, MR, and Gill, ND. Implementation and efficacy of plyometric training: Bridging the gap between practice and research. *J Strength Cond Res* 35(5): 1244–1255, 2021.

(Watkins, 85%, Storey, 5%, McGuigan, 5%, Gill, 5%)

Watkins, CM, Gill, ND, Maunder, E, Downes, P, Young, JD, McGuigan, MR, and Storey, AG. The effect of low-volume preseason plyometric training on force-velocity profiles in semi professional rugby union players. *J Strength Cond Res 35(3):* 604–615, 2021.

(Watkins, 80%, Gill, 4%, Maunder, 4%, Downes, 2%, Young, 2%, McGuigan, 4%, Storey, 4%)

We, the undersigned, hereby agree to the percentages of participation to the chapters identified above.

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Primary Supervisor: Dr Adam Storey ______________________

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Ethical Approvals

Ethical approval was initially granted by the Auckland University of Technology Ethics Committee (AUTEC) on the 6^{h} of December 2017.

- ❖ Ethics application 17/422: Methods of improving speed and power in semi-professional and professional rugby players.
    - Chapter four, six, and seven

Amendments to this ethics application were subsequently approved by AUTEC on the 11^{th} of October 2018 to add additional testing procedures and the inclusion of a survey.

- ❖ Ethics application 17/422: Methods of improving speed and power in semi-professional and professional rugby players.
    - Chapter five – eight

A second application for amendments to this application was approved by AUTEC on the 15^{th} of July 2019 to include international athletes.

- ❖ Ethics application 17/422: Methods of improving speed and power in semi-professional and professional rugby players.
    - Chapter four

List of Common Abbreviations

1RM	One-repetition max	GC	Ground contacts
CI	Confidence intervals	GCT	Ground contact time
CE	Contractile element	GRF	Ground reaction forces
CMJ	Countermovement jump	GPS	Global positioning software
CNS	Central nervous system	HSRD	High-speed running distance
CV	Coefficient of variance	HRmax	Maximal heart rate
DJ	Drop jump	ICC	Intraclass correlation coefficient
EMG	Electromyographic signals	MHC-I	Myosin heavy chain type 1 fibres
F_0	Theoretical maximal force	MHC-II	Myosin heavy chain type 2 fibres
FV	Force-velocity	MTU	Muscle-tendon unit

PEC	Parallel elastic component
PEC_1	PEC component in muscle
PEC_2	PEC component in tendon
RFD	Rate of force development
RSI	Reactive strength index
SEC	Series elastic component
SEC_1	SEC component in muscle
SEC_2	SEC component in tendon
SF	Skinfold
SJ	Squat jump
SL	Single-leg
SSC	Stretch-shortening cycle
Vmax	Maximal velocity
V_0	Theoretical maximal velocity

Force-Velocity Profile Definitions

Table 0.1. Definition and practical interpretation of biomechanical variables of interest during power-force-velocity sprint profiling

Variable	Definition	Practical interpretation
F_0 (N)	Theoretical maximal horizontal force production extrapolated from the linear sprint F-V relationship.	Maximal force output in the horizontal direction. Initial "push" of the athlete into the ground during sprint acceleration.
F_{rel} ($N \cdot kg^{-1}$)	Theoretical maximal horizontal force relative to body mass.	Maximal horizontal force output per kilogram of body mass.
V_0 ($m \cdot s^{-1}$)	Theoretical maximal running velocity, extrapolated from the linear sprint F-V relationship.	Maximal sprint-running velocity capability of the athlete with negligible mechanical resistance. Ability to produce horizontal force at high velocities.
V_{max} ($m \cdot s^{-1}$)	Highest actual achieved velocity during the sprint test.	Functional maximal linear velocity.
P_0 (W)	Theoretical maximal mechanical power output in the horizontal direction. Computed as $[(0.5*F_0) * (0.5*V_0)]$ or $(F_0*V_0)/4$.	Maximal power-output capability of the athlete in the horizontal direction during sprint acceleration.
P_{rel} ($W \cdot kg^{-1}$)	Maximal mechanical power output in the horizontal direction relative to body mass.	Maximal horizontal power output per kilogram of body mass.
S_{fv}	Rate of decrease in horizontal force with increasing running speed. Computed as $(-F_0/V_0)$	The balance of force production and velocity with increasing running speed. The more negative, the steeper the linear FV slope and the more force-dominant that athlete is.
S_{rel}	The FV slope represented relative to body mass in Kilogram.	The balance of force production per kilogram of body mass and velocity with increasing running speed.
RFpeak (%)	Maximal theoretical ratio of forces (RF), computed as a ratio of the step-averaged horizontal component of the ground reaction force to the corresponding resultant force.	Theoretical maximal effectiveness of force application. Proportion of total force production that is directed in the forward direction of motion at the start of the sprint.
RF2-RF20 (%)	RF with increasing running speed during sprint acceleration, RF2, RF5, ...RF20, corresponding to maximal RF at 2-m, 5-m, …20-m.	Describes the athlete's capability to limit the inevitable decrease in mechanical effectiveness at specific distances.
DRF (%)	Rate of decline in RFpeak as running speed increases to maximal velocity.	Representative of the athlete's ability to maintain mechanical effectiveness across the entire maximal sprint.

F= force; V= velocity; P= power; S_{fv} = slope, RF = ratio of forces, DRF = decline in RF. Adapted from Delaney et al. (2017).

Chapter 1 – Introduction

1.1. Background

1.1.1. Rugby union

Originating in rural England during the 1800's, present-day rugby has evolved tactically and in popularity since its infamous backyard school days. Largely, the professionalisation of rugby union in 1995 led to increased commercial attention and increased participation and in 2018, World Rugby reported up to 9.6 million players worldwide (223). This global expansion contributed to changes in match laws, match activities, athlete profiles, technological advancements, and improved training strategies. Most prominently, the introduction of professionalism prompted a faster-pace, ruck-dominated game than previous years (95,308). In fact, historical analysis of Bledisloe Cup matches between 1995 and 2004 revealed dramatic changes in match activities including a greater number of tries (72%), tackles (160 vs. 270), rucks (72 vs. 178), passes (204 vs. 247), and an increase in the average size of players (+9-12 kg) (308). In support of the latter point, anthropomorphic data in rugby players from 1905-1999 depicts a progressive increase for all players in body mass (+2.6 kg), body size (+1.1 units more mesomorphic), and decreased skinfold measurements (10 – 20%) with each passing decade (290). Similar playing trends were reported from data collected during the 1988 – 2002 Five and Six Nations rugby tournament, the 2007 – 2013 South African Currie Cup and the 2000 – 2009 Super 14 rugby tournament (290,308,378). In addition to a more physically-dominant game, match analysis has reported an increased number of sprints for all positional groups, faster ball recycling, and longer continuous phase play in more recent times (95,378). Altogether, these results highlight the increasing importance of rapid play and physicality in the evolution of rugby union (95,308,378).

Rugby union is a unique, physically demanding team sport requiring all athletes to maintain sufficient aerobic endurance, explosive strength and maximal speed (18,76,86,323). Characterised by continuous phases of play, professional rugby players typically cover 4,100 – 6,500 m within a game, with repeated physical contests for the ball (50,87,323). Sprinting is a fundamental aspect of rugby, impacting line breaks, activity rate, tackle breaks, metres advanced and tries scored (144,357). Rapid acceleration is essential across shorter distance sprints (5 – 20 m), while striding and sprinting contributes to ~30% of distance covered (500 – 920 m) regardless of positional group (18). Interestingly, both forwards and backs reach speeds >90% of their maximal velocity during half of their sprints performed, emphasizing the importance of acceleration and maximal velocity for all players (18,307).

1.1.2. Force and velocity characteristics

Many factors affect a rugby player's on-field sprint performance most notably concerning their contraction- and velocity-based loading strategies. During any movement, each player's individual force-velocity (FV) relationship governs their capacity for force expression at a given speed (263). Typically, for that movement or positional demand, an imbalance exists between an athlete's optimal FV relationship with their actual working FV expression (73,74,177,279,280,337,338). These imbalances can cause up to a 30% performance decrement even when maximal power is equivocal (177,280,337). Therefore, inclusion of FV profiling, in addition to single parameters like split times or jump height, can provide valuable information in understanding the whole FV spectrum of an athlete's capability (280,338). Multiple methods have previously been used to determine FV profiles including loaded jump protocols, cycle ergometers, treadmill sprinting, inverse dynamics, multiple force plate set-up, and more recently radar or photoelectric cell monitoring over ground sprinting (74). These technological advancements have made it easier for strength and conditioning practitioners to compare between athletes of different ability (81,133,135,176), different sports (121,133,134), different positions within the same sport (81,135), in a fatigued state (175,276) and following a training cycle to determine training priorities and effectiveness (177). Unfortunately, scarce literature surrounds horizontal FV profiles between specific positional roles in rugby union players which prevent such comparisons.

While increasing peak force garners many athletic benefits, game situations swiftly regulate the available time to produce force, with ballistic actions materialising long before players can exert maximal force. An investigation of international rugby union players reported mean accelerative durations of approximately 0.76 – 0.85 s, which is ~16 – 25% of the time required to generate peak force during favourable static conditions (82,211,386). This is where exercise durations can be useful in directing training; short ground contact times (GCT) reinforce a player's ability to generate force rapidly which is paramount during competitive efforts. Yet, the relative importance of speed will differ accordingly by positional- and movement-specific demands (82,309). Thus, strength and conditioning coaches need a thorough understanding of speed and acceleration profiles across each positional group to help prescribe individualised training throughout the competitive season.

However, without regular stimuli, physiological adaptations readily decline. This is particularly relevant for semi-professional, professional, and international teams who experience periods of compromised training due to conflicting schedules or hefty travel requirements (267). While strength adaptations can be maintained for up to 30 ± 5 days, maximal speed rapidly declines in as little as 5 ± 3 days (166). Although further research is needed to identify the specific FV adaptation rates, the limited existing research suggests high velocity characteristics tend to decrease more rapidly than strength qualities (166,258). Therefore, special attention is needed to determine the most effective training dose and periodisation strategies for professional and semi-professional rugby athletes to achieve optimal speed and acceleration during the competitive season.

1.1.3. Stretch-shortening cycle and sprint performance

Stretch shortening cycle (SSC) mechanisms are the primary force generators in jumping motions, acceleration and sprinting alike (261). As rugby players are frequently required to perform these tasks during a match, there is an insufficient understanding on the best protocols to positively impact SSC function and sprint profiles in rugby players. During these movements, an effective SSC system creates favourable muscle length-tension relationships, facilitating muscle contraction, elastic properties, proprioceptive feedback and central nervous system (CNS) stimulation for optimal power production (141,164). Using a stretch-recoil muscle action, the body can optimally store and reuse a greater proportion of kinetic energy (237,240). During the initial stretch, or eccentric action, energy is primarily stored in the tendon creating an active "steady state" in the targeted muscle-tendon unit (MTU) (188,240). Simultaneously, stretch-induced myotatic reflexes and CNS initiated motor programmes prompt increased muscular activity, resulting in a greater potentiated neuromuscular response during the isometric and concentric phases (163,165,252). Greater tendon elongation increases the SSC mechanical efficiency by maximizing the inherent elastic properties; the energy stored being proportional to the magnitude of deformation (42,240). These changes in MTU length, recoil and energy storage during eccentric motions augment the muscle's ability to stretch at velocities unfavourable to muscle contraction alone, while also optimising energy storage (239,240). Ultimately, SSC-mechanisms create greater concentric power production for less metabolic cost (164,167,209).

Effective SSC function is a critical consideration for rugby players who perform repeated high-intensity sprinting efforts, fatiguing contact-related actions, and still require adequate aerobic fitness to last the entire match. While there is substantial evidence on SSC function and fatigue in endurance athletes (19,120,353) and track and field sprinters (353,361), there is a lack of understanding on their importance in the context of a rugby union match. Thus, these mechanisms prompt a specific research emphasis in rugby union players as the degree of transferability relies on the available time allocated for force production, and associated loading parameters (231). Analysis of SSC performance relative to sprint speed reveals countermovement jump (CMJ) and drop jump (DJ) exercises share significant correlations with sprint performance over 30-, and 100- m distances, accounting for 50% and 63% of the variance in 5 – 10 m velocity and 30 m time, respectively (138,225). For many of the same reasons, chronic SSC training in isolation or in conjunction with strength training has been shown to optimise neuromuscular activity during jumping, sprinting, and long-distance running (141,340,350). Therefore, these same methods may also prove beneficial for improving position-specific sprinting demands in rugby players.

1.2. Plyometric Training

1.2.1. Plyometric volume and intensity

Plyometric training is one form of ballistic training that primarily targets the SSC, integrating the MTU and neural structures to optimise athletic performance through velocity-based loading strategies (141). Previous literature gives ample support for plyometric training's benefit (39,157,236,266), yet the majority of which has been conducted in prepubescent soccer athletes or untrained populations (103,380). Athlete characteristics including training experience, strength levels, maturation status and tissue capacity will affect their tolerance for stress, thus these reported findings may have little relevance for semi-professional rugby players.

In contrast, the current published plyometric recommendations for adults advise against any athletes weighing more than 100 kg performing any form of DJ, regardless of training experience, and propose session volumes up to 200 – 400 high-intensity ground contacts (GC) for advanced athletes (78,96). Anecdotally, many rugby practitioners utilise DJ varieties for assessment and training, while session volumes are reportedly very low (0 – 20 GC). As a result, there seems to be a disconnect between literary recommendations and practically applied plyometric programmes. Considering anthropomorphic profiles of many rugby players, and high weekly sport and resistance training loads, these recommendations discourage the effective implementation of a plyometric programme and more clarity is needed surrounding programme variables.

Authors have demonstrated that acute plyometric ability during a high-intensity DJ exhibits a significant relationship to both strength and speed parameters in rugby players (24,92). Still further research should investigate these relationships in the context of training to determine optimal plyometric dosing strategies. Sessional volumes >100 GC frequently cause excessive soreness, decreased neuromuscular ability, and jump performance post-session in untrained subjects (354). However, some authors suggest post-session deficits from a high-volume session (i.e., 212 GC) were mostly due to peripheral fatigue and all but recovered following two hours of rest in recreational rugby players (85). On the other hand, different session volumes (i.e., 100, 200, and 300 GC) seem to end in similar hormonal, neural and metabolic stress for at least 24 hours post-session in collegiate rugby players, suggesting additional volumes may not be acutely beneficial (49).

In regards to training programmes, there has been a recent increase in literary evidence investigating elite athlete populations (157,184,236). However, what is deemed to be best practice for the proper manipulation of dose and volume load is still up for debate (9,315). For example, elite sprinters have demonstrated superior sprint performance from short periods (2 weeks) of high-volume (>200 $GC\cdot session^{-1}$) moderate-intensity plyometric training (236). In contrast, professional handball athletes have reported substantial improvements in sprinting profiles and jump kinetics following 12-weeks low-volume (40 – 60 GC·session^{-1}) single-leg DJ training (157). Furthermore, the need for high volume sessions is brought into question as burgeoning evidence suggests doubling programme volume is not necessarily effective for increasing adaptation in adolescent soccer (380) and recently in collegiate rugby players (173). This disparity in peer-reviewed literature and real-world application warrants further investigation to bridge the gap and determine the most effective stimulus without overtraining.

As such, strength and conditioning practitioners need a comprehensive understanding of loading properties, adaptations, and critical variables to better understand the optimal dose and manipulation strategies of plyometric training for improving sprint performance in rugby players. Using jumping and throwing motions, plyometric training primarily depends on the athlete's body mass as a stimulus rather than external weight used in traditional resistance training. As a result, movement velocity, peak tensile force, and energy absorption depend on the magnitude and rate of MTU stretch determined by the exercise and training direction (231,361,367). Thus, an athlete's body mass is a consideration, which may also affect their MTU stress tolerance, the volume warranted, and/or the pliability of adaptation. Moreover, categorically slow SSC exercises with long ground contact times (GCT) like the CMJ will provoke significantly different adaptations than fast SSC exercises with short GCT like the DJ (195,332). Currently, there is insufficient information regarding plyometric intensity specific adaptations in semi-professional and professional rugby players and the most effective dose response for trained athletes which warrants further elucidation.

1.2.2. Training direction

The direction in which force is applied may affect sprint profile adaptations differently (282). During the initial acceleration phase, there is a much greater reliance on forward body lean and propulsive force production in order to overcome inertial resistance, while there is very little influence from braking forces (201,282). However, the influences of braking and mean vertical force become much more prevalent as the body position becomes more vertical and running speed increases toward maximal velocity (282,390). As a result, Nagahara et al. (2018) suggests that athletes who are hoping to be successful during an entire maximal sprint should produce large propulsive forces at the start, suppress braking forces with increasing speed, and work to generate large vertical forces near maximal velocity (282).

However, further elucidation is warranted on the specific stress imposed on the MTU and the associated adaptations. Vertical ground reaction forces are significantly greater with vertically oriented plyometrics (262), whereas increased lumbar-pelvic stabilisation is reported during horizontal and lateral varieties (180) to counteract shear landing forces. Such direction-specific kinematics play an important role in identifying specific adaptation and MTU stress responses following a plyometric session. There is some evidence to suggest horizontally-oriented plyometrics may preferentially benefit starting acceleration and change of direction speed, while vertically-oriented plyometrics are superior at improving secondary acceleration, and maximal sprinting speed (157,315). However, programmes void of any horizontal stimuli may be more likely to report no change or insignificant benefits (185). This may be due to a greater hip drive required for forward movement (283). Although, the manipulation of such variables is unclear in trained athletes. Considering the varied position-specific sprinting demands within a rugby team, tight-5 players may benefit from different plyometric dosing strategies when compared to outside backs. Thus, more research is necessary to determine the effect of training direction on sprint profiles, with respect to positional demands in rugby union players.

1.3. Purpose and Significance

1.3.1. Purpose of the thesis

The primary purpose of this thesis was to investigate the functional and mechanistic characteristics of plyometric training to better inform speed and acceleration training in professional and semi-professional rugby players. Specifically, this thesis aimed to answer the following questions:

1) What is an effective plyometric dosing strategy (i.e., volume and intensity) for speed improvement and maintenance in semi-professional and professional rugby union players?
2) What are the critical plyometric training components for improving speed profiles in rugby union players and how best do we manipulate those variables to accommodate position-specific demands?
3) What are the resulting FV profile adaptations resulting from plyometric training?
4) What influence does plyometric training axis have on sprint and acceleration adaptations?
5) How much volume is necessary to elicit adaptation pertinent to sprint and acceleration performance?
6) What is the acute effect of increasing session volume?

1.3.2. Significance of the research

There is ample literature to support plyometric training's beneficial effect on sprinting. However, the current literature is unclear on the optimal volume loads and periodisation strategies to maintain speed throughout the season for elite rugby players. Professional environments lend themselves to heightened competition states, increased fatigue, and extensive team commitments that can compromise the time available to develop specific strength and speed. Therefore, proper periodisation, proactive fatigue management and maximal training efficiency are of the utmost importance to improve and maintain speed without incurring extraneous stress. Plyometric training modalities are a popular method due to their easily modifiable nature, and intrinsic ability to enhance specific areas under the FV curve whilst simultaneously generating significant neurophysiological adaptations. However, most of the research regarding plyometric dosage thus far has focused on prepubescent and amateur athletes. Sport characteristics, biological age, tissue integrity, muscular strength levels, and training experience all correspondingly affect the level of stress an athlete can positively tolerate. Thus, several questions arise around proper dosage, variable manipulation, physiological pliability and optimal periodisation strategies for both plyometric and eccentric loading protocols.

1.3.3. Structure of the thesis

This thesis was designed in accordance with Auckland University of Technology's format two, such that there are three sections and six chapters appropriate for peer-reviewed journals. This thesis is designed to be practical and immediately applicable to strength and conditioning professionals working to improve speed in professional and semi-professional rugby players. The first section (Chapter 2 and 3) critically reviews the relevant literature surrounding plyometric training, via a narrative and systematic analysis. Specifically, the narrative review (Chapter 2) focuses on the physiological loading mechanisms and adaptations arising from plyometric training and how these relate to rugby performance. Furthermore, the narrative attempts to provide a comprehensive understanding of the SSC, with a specific emphasis on the structural and neural considerations for improving speed profiles. The systematic review (Chapter 3) is targeted for coaches and practitioners as it focuses on the dose response and the manipulation of critical variables that have been identified to improve speed in rugby players. The second section (Chapter 4, 5 and 6) identifies critical training components for improving speed profiles and focuses on the acute adaptive responses. Chapter 4 comprises of a cross-sectional analysis of FV characteristics of international, professional and semi-professional rugby players. Chapter 5 globally surveys the current plyometric training practices of a variety of athletes to determine perceived efficacy, programming and periodisation. Chapter 6 acutely investigates multiplanar volume load manipulation, force characteristics, and acute MTU stress. Finally, the third section (Chapter 7 and 8) implements aforementioned components into training programmes. Chapter 7 investigates both vertical and horizontal low-volume mesocycles, while Chapter 8 investigates the dose response in horizontal only plyometrics. Lastly, Chapter 9 summarizes the important findings compared to previous literature, discusses practical applications of training interventions and load manipulation, and will outline the thesis limitations, and areas of future research.

The appendices provide supporting information for the individual chapters as well as the whole thesis. Below is a brief overview of thesis structure (Figure 1.1).

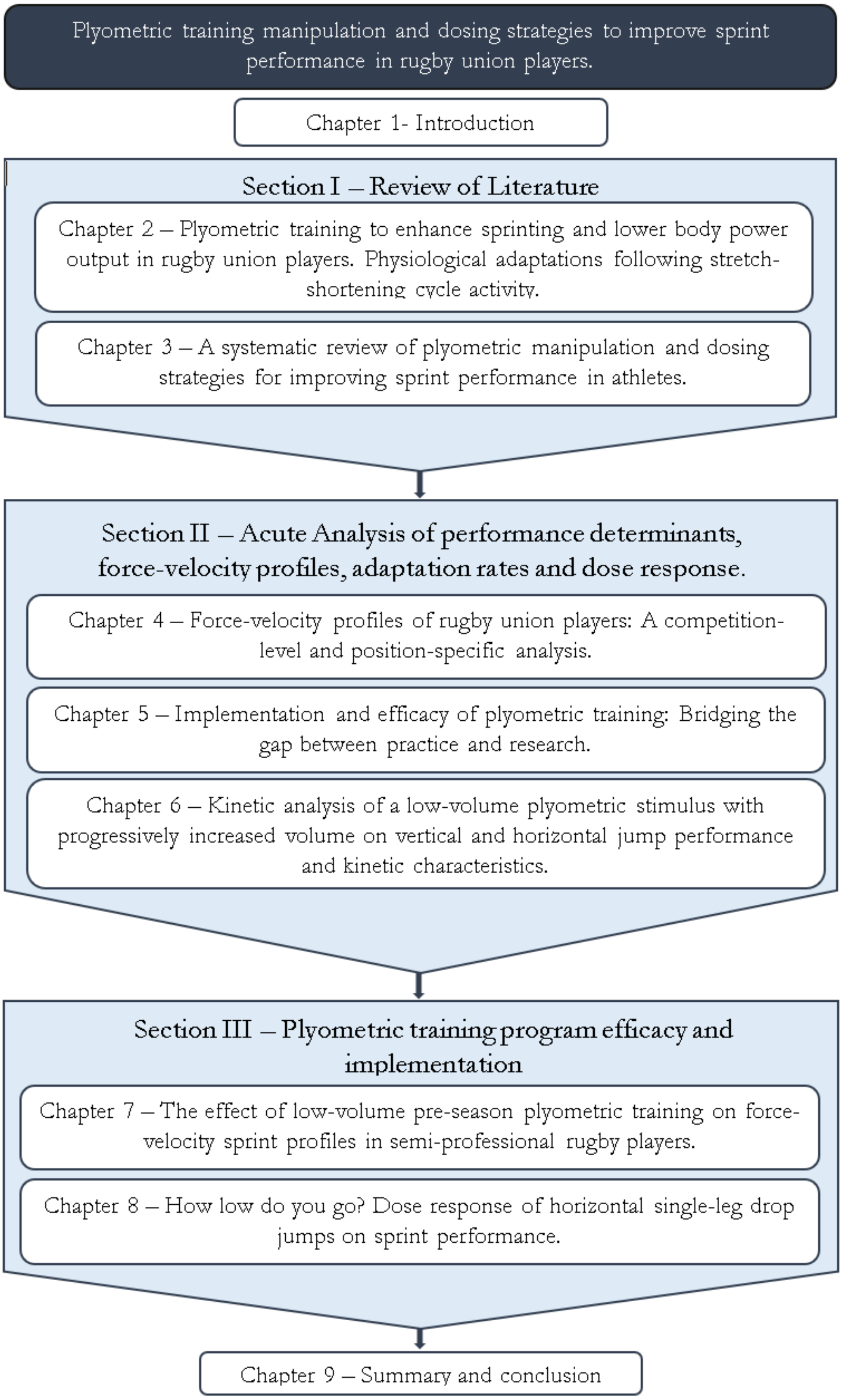


Figure 1.1. Thesis structure schematic.

Section I – Review of the Literature

Chapter 2 – Plyometric training to enhance sprinting and lower body power output in rugby union players. Physiological adaptations following stretch-shortening cycle activity.

2.1. Introduction

Rugby union is characterised by considerable aerobic activity interspersed with various high-intensity actions including sprinting, tackling and scrummaging (18,76,86,323). Competitive success requires the attacking team to be physically dominant at the breakdowns, and effectively manoeuvre through the opposition's defence to gain territory and score tries. As such, sprinting and acceleration are fundamental aspects of rugby union, impacting line breaks, activity rate, metres advanced and tries scored (144,357). Global positioning software (GPS) analysis indicates that rugby union players travel 4,00 – 6,500 m during a match, 300 – 540 m considered running at or above high-speed running distance (HSRD; >14.4 $km \cdot hr^{-1}$) (86,323). While large discrepancies between backs and forwards for maximal sprint speed, HSRD, work to rest ratios, and static exertions, temporal analysis reveals no difference in number of accelerations, decelerations, time spent in high-intensity efforts (>85% Maximal heart rate; HR_{max}) or percentage of sprints performed at near-maximal velocity (>90% V_{max}) (86,90). These activity profiles suggest all players require sufficient mechanical capabilities to effectively accelerate, maximally sprint and perform high-intensity actions (86,90). Furthermore, the speed and contact demands of professional, national and international rugby union are increasing, with a greater number of sprints per match in recent years resulting in a faster pace, more ruck-dominated game than previous seasons (18,82,86,89). Therefore, speed and acceleration are essential in rugby union, yet the relative importance of these qualities will differ accordingly by positional- and movement-specific requirements (178).

Underpinning sprinting, acceleration and dynamic performance on-pitch is a rugby union player's mechanical loading capacity, or their ability to load their MTU structures and produce concentric force within movement, velocity, and time-based constraints (263,278). In this respect, athletes are regulated by their SSC effectiveness and their ability to integrate muscular, tendinous, and neural structures for rapid force transmission (164,188,209,259). However, movement is not uniform and the interaction of these structures will differ based on task-specific characteristics (366). Typically, as movement speed increases, the duration and capacity for force production decreases, a relationship graphically represented as an athlete's FV profile (338,352). For example, maximal voluntary muscular contraction can require lengthy durations to generate peak force, yet rugby union players perform movements with wide ranging GCTs (~0.15 – 5.2 s) (323,386). Thus, faster running velocities and more ballistic movements (~0.15 – 0.75 s) rely heavily on the SSC to produce force during limited GCTs (164,188,209,259). Therefore, practitioners need to comprehensively understand MTU loading mechanisms and physiological adaptations in order to specifically target SSC adaptations pertinent to expressing FV across a range of movements and GCTs.

While there are many methods for improving rugby sprint performance, plyometric training is one viable option that can easily be implemented in rugby teams within the many training constraints including group size, time, equipment and space (10). Plyometrics target the SSC during eccentric-concentric muscle actions, maximizing neuromuscular performance and the elastic recoil of the MTU(374). Multiple studies have demonstrated plyometric training's effectiveness on sprinting and jumping performance during acute exercise bouts (24,49,138,162) and chronic training programmes in isolation (156,186,231,232,236) or combined with other exercise modalities (10,38,185). Locomotive patterns inherent to athletic performance (i.e., sprinting, jumping and bounding) involve the same SSC mechanisms to generate force as seen in plyometrics (163,202). Thus, these similarities make plyometric training an ideal method to transfer training improvements to the rugby field (231,365). However, research thus far has focused primarily on prepubescent and amateur athletes (55,185,231,313). Biological age, tissue integrity, muscular strength, body composition, sport demands and training experience all directly affect the physical stress an athlete can positively tolerate (221). As such, effective plyometric training manipulation for improving sprinting and SSC-related performance in rugby union players remains unknown. Therefore, the purpose of this article is to review relevant literature on plyometric training, summarize the loading mechanisms, and discuss the neurophysiological adaptations relating to rugby union.

2.2. Methods

2.2.1. Literature search

A literature search was performed using US National Library of Medicine (PubMed), MEDLINE, SportDiscus®, and Google Scholar Databases to identify literature relevant to this review. Search terms included: 'plyometrics,' 'plyometric training,' 'jump training,' 'power training,' 'ballistic training,' 'speed training,' 'acceleration,' 'stretch-shortening cycle,' 'dose response,' 'load manipulation,' 'low dose plyometric training,' and 'complex training.' Literature was additionally sourced from reference lists, and related articles originally obtained via database searches. Inclusion criteria limited studies to *in vivo* investigations involving healthy humans as well as *in vitro* human and animal muscle fibres for mechanistic analysis. Only articles with full-text availability printed in English were included in this review.

2.3. Stretch-Shortening Cycle Loading Mechanisms

Mechanical and neurological components work in conjunction to explain the multifaceted SSC energy storage and utilisation processes during explosive athletic movements (245,248,335). Using a quick eccentric-concentric coupling muscle action, the MTU is able to produce greater force and power than either isolated muscle action alone (188). The functional benefit of the SSC is demonstrated most clearly when comparing a SJ, CMJ, and DJ; each variation involves a greater pre-stretch and elastic potentiation, typically resulting in a concomitant increase in jump height (104,253). For example, prior to any specific training, untrained men exhibited jump height values of 28.5 cm, 33.5 cm, and 36.5 cm for a SJ, CMJ, and DJ of 40 cm (214).

2.4. Mechanical Loading of the Stretch-Shortening Cycle

2.4.1. Series and parallel elastic components

Connective tissues (i.e., sarcolemma, endomysium, perimysium, and epimysium) encasing muscle components are called aponeuroses and collectively form the parallel elastic component (PEC) (Figure 2.1). Together, tendons (alongside cross-bridge elasticity referred to jointly as the series elastic component [SEC]) and the aponeuroses are largely responsible for passive force production, elastic energy storage and resulting MTU length changes (Figure 2.1) (136,324,367). Tendons have a greater capacity for stress than muscle fibres which not only serves to store and re-distribute energy, but also amplify muscular force production (116). During high-intensity actions tendons will undergo greater lengthening, followed by rapid shortening, thus allowing muscle fibres to operate within optimal length and number of cross-bridges (6,165,361). This catapult-like action during early-onset contraction means tendons can augment the extent and speed at which voluntary muscle contraction alone can produce force (117,198). Concentric force enhancement is vital for rugby union players considering that athletes with a top speed of 11.1 $m.s^{-1}$ are typically producing ~1.26 times greater mean force than that of an athlete with top speed of 6.2 $m.s^{-1}$ during short (~0.11 – 0.18 s) GCT (264,390). As such, rapid force production and neuromuscular ability are often limiting factors in achieving high speeds and should be considered carefully for improving ballistic performance in rugby players (264,390).

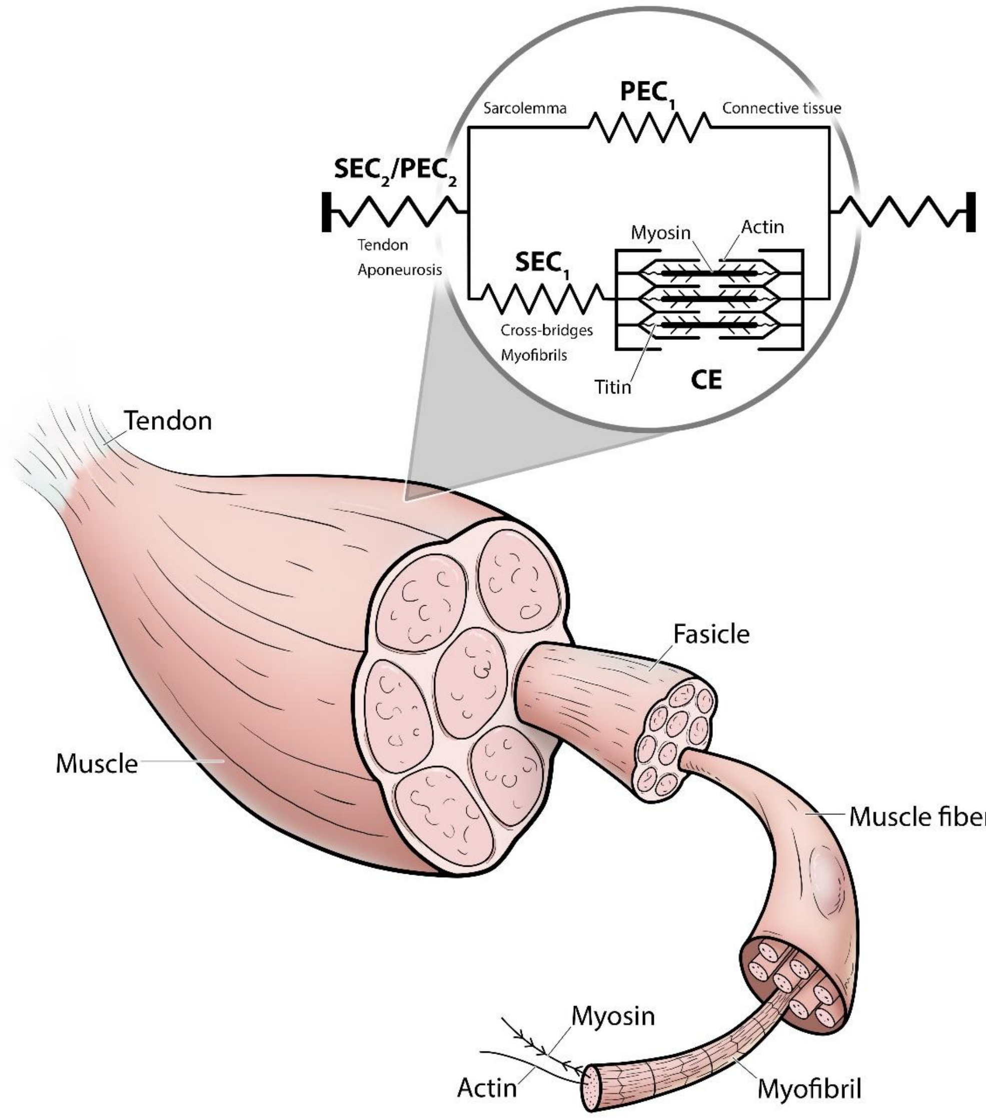


Figure 2.1. Muscle-tendon unit and stretch-shortening cycle structures.
SEC_1= series elastic component in muscle; SEC_2= series elastic component in tendon; PEC_1=parallel elastic component in muscle; PEC_2= parallel elastic component in tendon; CE= contractile element.

During ballistic exercises, the interaction of SSC passive contractile and elastic components creates a mechanical advantage, with specific emphasis on their inherent recoil properties (188,287). Specifically, potential energy that is absorbed in the tendon during lengthening (i.e., negative work) movements is then primarily recycled during the subsequent concentric phase to produce power (i.e., positive work) (15,124,233). During dynamic movements, ~72% of the elastic energy that is reutilised during the concentric action comes from tendons, while only 28% results from contractile elements (35). This energy exchange underpins ballistic performance; greater energy storage by tensile tissue during this process enables an athlete to sprint faster, jump higher, be more explosive on the pitch, and plays a critical role in regulating fatigue (188,287). However during this paired muscle action, a small portion of absorbed energy is lost, generally dissipated as heat (35,197,199,237,240,306). This discrepancy in energy transfer is referred to as hysteresis and differs between athletes based on the tendon's viscous properties (197,238). However, previous literature has reported hysteresis values of 18 – 19% in both the gastrocnemius and tibialis anterior tendons, in some cases as high as 36% of energy stored being lost due to large individual differences in SSC utilisation (216,240,385). More clarity is needed to understand how best to manipulate and monitor hysteresis and energy absorption for performance. At present, strength and conditioning professionals may want to consider SSC training using immediate transitions (i.e., small amortisation time) between eccentric-concentric actions to maximise tensile energy potentiation.

2.4.1. Time-dependent strain characteristics

Time-dependent strain characteristics, or the magnitude and rate of loading, will determine the extent of tensile deformation, represented graphically in a curvilinear tendon-load relationship (Figure 2.2)(17,358). For example, a long slow static stretching bout (i.e. 12 – 90 s) will cause tendons to relax up to ~30% which contributes to decreased force capacity and dampened athletic performance (97,135,144). For dynamic actions with slow stretch rates, the PEC inside the muscle are able to undergo the majority of lengthening (239). Tendinous fibres become taught and the slack is reduced, but little tensile length change occurs at this stage (392). As stretch velocity and loading increase with increasing movement intensity, the MTU response depends primarily on tendon elongation for maximal energy storage and recuperation (**Figure 2.2**) (392). Accordingly, tendons may benefit most from SSC training with rapid MTU loading. *In vivo* studies demonstrate MTU length changes beyond ~4% strain, or tension, cause tendinous tissue to stretch in proportion to load until mechanical or volitional failure (33,47,300).

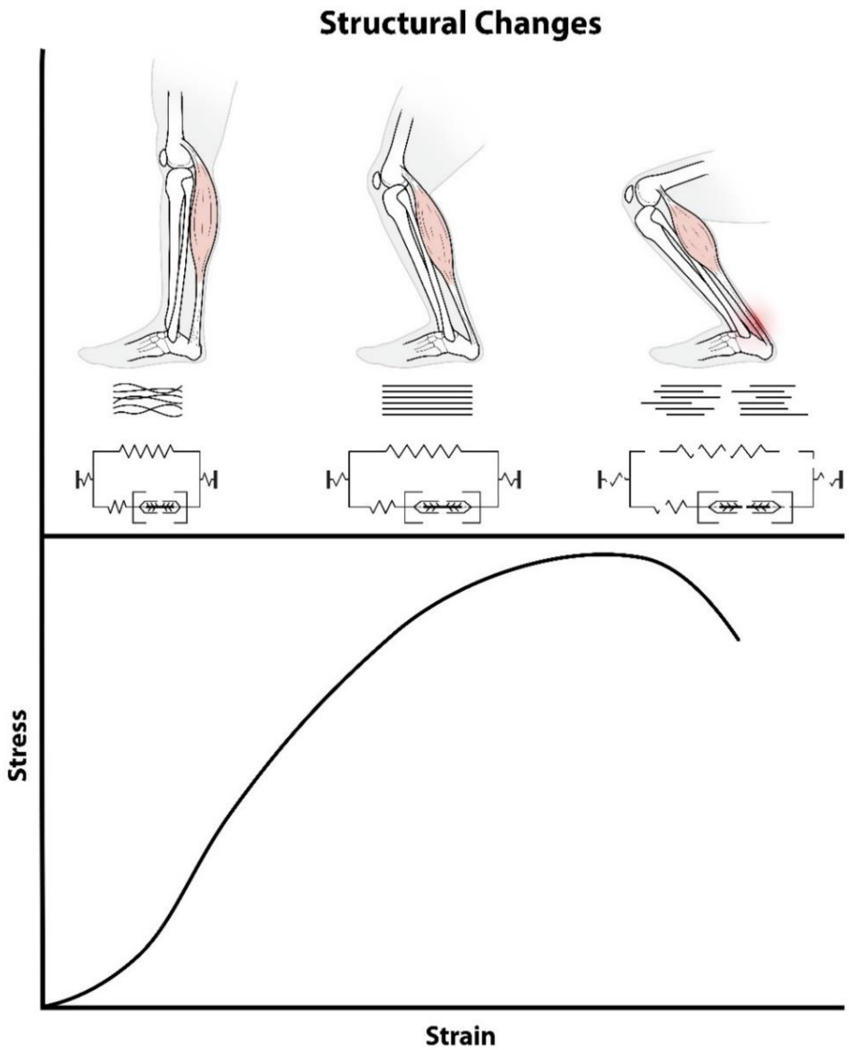


Figure 2.2. Tendon stress-strain load graph with structural change illustrations.

This overall ratio of muscular effort to energy output is known as mechanical efficiency, and characterizes net energy utilisation during all muscle actions (17). Previous literature reports the mechanical efficiency of positive work, or the added contribution of elasticity during the concentric portion of SSC actions, to be ~23 – 44% and ~38 – 55% during walking and running based on pre-stretch intensity (15,17,54,124,167). At speeds of 33 km.h^{-1}, the mechanical efficiency of positive work may be upwards of 80% (54), primarily due to a greater contribution of tendon stretch-recoil to effectively absorb and redirect large impact forces (~1 – 5 x body weight) (17,54,282,310). As such, insufficient MTU capabilities can often be a limiting factor in achieving maximal sprinting velocities (264). This is crucial for professional rugby union players across all positions reaching top match speeds of 33 – 40 km.h^{-1} (368).

For rugby players, this elastic storage and recuperation works in conjunction with an enhanced neuromuscular response to drastically affect one's speed during acceleration, linear sprinting, and change of direction tasks (129). Similar to sprinting, change-of-direction tasks require rugby players to absorb large amounts of force during the deceleration phase, then effectively redirect that force to accelerate in the opposite direction (129). Thus, lapses in energy absorption rates will drive rugby players to elongate the time required for both deceleration and reacceleration tasks. However, with longer transition times, players are less likely to manoeuvre around the field, or the opposition effectively. As a result of large eccentric stress, inside backs expend greater energy during these utility movements (i.e., lateral or backwards repositioning) than other positions using primarily forward-oriented low-speed temporal movements (309). Thus these positions would benefit from efficient SSC energy storage and recoiling from the tendon, improving force transmission rates during change-of-direction tasks, and subsequently decreasing movement time and required attacking space (129). In contrast, individuals with insufficient MTU capabilities may have to work harder for the same power, take more time to change direction or conversely not be able to tolerate as much load.

2.5. Neurophysiological Loading of the Stretch-Shortening Cycle

CNS pre-planned motor programmes and involuntary stretch reflexes work in conjunction with passive and active elements to favourably shift FV characteristics and create a potentiating effect, such that an athlete can produce more force in the same timeframe (42,43,72,125,202,209,285,287). This potentiated neuromuscular activity is crucial for rapidly generating power during fast accelerations and quick change-of-direction tasks.

2.5.1. Musculotendinous stiffness

The CNS moderates stiffness on a local (i.e., muscle membranes, and tendon stiffness) and global (i.e., vertical, joint, and leg stiffness) scale independently to optimize task-specific performance (137). Stiffness is quantified by the change in tension divided by the change in MTU length, characterizing the time over which force is applied (153). Contrary to tendons, muscle stores minimal energy via cross-bridge attachments, known as 'short-range stiffness' (302,312). Cross-bridge energy utilisation contributes ~3 – 4% of MTU length changes (312), after which short-range stiffness ceases because of increased compliancy (16,312). Short-range stiffness utilisation varies tremendously based on range of motion, stretch velocity, fibre elasticity and energy absorption demands (381). However, CNS motor programmes, reflex loops, and rapid MTU stretch rates can contribute significantly to continued crossbridge engagement (17,312). For example, greater tendon lengthening fosters favourable muscle length-tension relationships by allowing muscle fibres to operate within optimal myofilament overlap, facilitating even greater cross-bridge attachment for the same contractile work (202). Particularly, the role of pre-planned motor programmes and stretch reflexes are determined by stretch velocity (42,162,163,358), stretch magnitude (108,162,163), energy absorption needs (91,397), amortisation time (42,71,167,233,358), and muscle fibre characteristics (43,91,197,369).

2.5.2. Proprioceptive initiation

Muscle spindles, located in the muscle belly, send afferent signals regarding the magnitude and rate of induced stretch; the lower-level CNS then immediately returns an involuntary stretch reflex to increase muscle activation and protect the muscle from over-stretching (189). This involuntary response, paired with pre-planned motor programmes, prompts increased muscle electromyographic (EMG) signals, prior to GC. This muscular "pre-activity" increases localised stiffness, absolute force, RFD, facilitates energy transfer and creates a potentiated neuromuscular response at the MTU for the same operating cost (42,43,91,148,150,162,202,208,281). Essentially, by maintaining a quasi-isometric state and greater muscular stiffness, a greater percentage of stored elastic energy can be reutilised without dissipation, resulting in less hysteresis (116). Additionally, these high EMG ratios facilitate an optimal number and elasticity level of cross bridges, essentially making voluntary muscle contraction more effective (16). Aura and Komi (16) postulated the functional elastic threshold to be ~40 – 50% of the muscle's contractile capacity, drastically increasing elastic return of energy for force production. Alternatively, when length changes become too great, Golgi tendon organs positioned at the muscle-tendon junction inhibit muscle activity to avoid injury (285,365). Both proprioceptive organs work with the CNS to balance localized stiffness and optimal task performance with respect to structural protection (285).

2.5.3. Stretch reflex involvement

Historically, there has been some debate as to the contribution of stretch reflexes during lower body locomotion (e.g. hopping, jumping, and running) because of the limited force-generating windows (160,189). For example, some authors argue the CMJ does not meet the conditions for optimal SSC efficiency, and the stretch reflex response is therefore inhibited (107,146,189). The SSC contributes most to power production with timely pre-activation of musculature, a short, fast, eccentric phase (<250 ms), and a minimal amortisation time (189,341). For an action to be considered eccentric, active muscle lengthening must occur (146). Interestingly, new EMG analysis suggests the contractile element may actively shorten or act isometrically during the downward portion of CMJ, with most if any lengthening occurring passively (107,146,181,190,191,205). If no active muscular stretch is initiated, the contribution of the stretch reflexes is questionable (146,205). As a result, categorically slow-SSC exercises such as the CMJ depend on the reorientation of MTU fibres and uptake of slack, the build-up of tension, tendon elasticity and longer force-generating windows for greater performance (106,108,145,181,189,341). Accordingly, MTU stretch velocity in combination with maximum strength is found to be the best two-part predictor of power absorption during slow, large-amplitude movements such as the bench press (71).

In any case, substantial support exists for varying levels of stretch reflex involvement during a wide range of GCT durations seen in jogging (~2 $m \cdot s^{-1}$; 250 – 264 ms), running (3.5 –5.0 $m \cdot s^{-1}$; 168 – 215 ms), and sprinting (≥6.5 $m \cdot s^{-1}$; 80 – 149 ms)(72,153,163,260,285). Previous literature clearly demonstrates stretch reflex potentiation 13 – 15 ms following elevated EMG response, which has been shown to increase Achilles tendon force by 200 – 500% compared to slow stretch non-reflex conditions (285,288). Given the response time of the short-latency stretch reflex is ~35 – 45 ms, force potentiation occurs ~50 – 55 ms after the initial stretch, well within ground contact durations for sprinting (285). Interestingly, the stretch reflex system is most critical during moderate running speeds (approximately 7 – 15 $km \cdot h^{-1}$), where pre-activity EMG levels prior to ground contact are lower and reflexes are initiated earlier on in the braking phase (72,108,163,260). This stretch-induced EMG response is thought to be essential in linearising muscular stiffness and maximizing force by preventing cross-bridge yielding during MTU lengthening (72,163,358). Speeds ≥15 $km \cdot h^{-1}$ involve greater pre-activation levels, reducing their susceptibility to yielding, but subsequently cause a greater delay in the stretch-induced response

(72,163). Considering international rugby union athletes cover approximately 35 – 45% of their total match distance at moderate speeds (6 – 14.4 km·h^{-1}), maximising the stretch reflex response is critical for force enhancement and maintaining speed throughout later stages of play (82,189). This adaptation is particularly relevant for scrum-halves and flankers who proportionally spend the greatest amount of active time at moderate speeds (309). Future research should investigate the intricacies of fascicle-tendon interaction, the most appropriate training prescription to enable cross-bridge interaction and how to promote task-specific neurological movement strategies (91,108,124,125,382).

2.5.4. Task-specific neurological responses

When comparing dynamic neurological properties of landing and hopping sequences, differing EMG responses, reflex excitation, and MTU stiffness have been observed, indicating unique neural activation strategies are highly dependent on task characteristics (91,300,382). On one hand, sprinting and hopping movements stretch extensor muscles rapidly over small distances, thereby storing energy during the decent which is readily available during the subsequent take-off movement (91,312,382). Conversely, landing sequences prompt MTU dampening, a protective mechanism making the system more compliant to handle large eccentric forces (216,312). As a result, excessive DJ exercises from heights above an athlete's mechanical threshold may even impose cross-bridge separation, and altered CNS motor programmes as a response to protective inhibitory mechanisms (162,366). For example, rugby union matches often expose athletes to substantial eccentric stress during scrummaging as teams contest for the ball. Athletes with poor MTU capabilities have reduced capacity to resist opposing forces and may opt for a more compliant or protective strategy, which in turn, may reduce the force exerted onto the opposing team resulting in a lost or collapsed scrum. Similarly, sprinting requires athletes to absorb large amounts of force (~5 – 10 x body mass) eccentrically during short ground contact times (390).

As a result, these athletes may not be capable of reaching near-maximal velocities without risk of injury (390). Alternatively, trained athletes have previously increased range of motion during CMJs as a means of increasing the build-up time to effectively transmitting forces during fatigued states (151).

2.5.5. Importance of mechanical efficiency in rugby union

For many of the same reasons, improving SSC mechanical efficiency additionally benefits rugby union players looking to maximize power output while minimizing fatigue (277). Just five repeated efforts of either sprints, mauls, or scrums has been shown to provoke moderate (7–23%) decrements in muscle activation, increased subjective effort scores, and greater blood lactate concentrations in professional rugby union players (277). In the same context, associations have been made between greater pre-programmed CNS activity, stiffness regulation, DJ performance and less associated metabolic fatigue following plyometric sessions with 100 GC (149,151). Force production from voluntary muscle actions becomes less effective as a player sustains more impacts and travels more distance (255,357,396), making the need for enhanced mechanical efficiency throughout a match increasingly important. This is particularly important for mitigating the negative effects of fatigue in professional rugby union players who have to repeat ~91 static and ~61 dynamic high-intensity actions during a full match (110,323). Considering competition schedules can include short transitions between games, even marginally improving a player's running economy could reduce the metabolic cost associated with a match and reduce the fatigue for subsequent weekly practices or matches (64,298).

The relevant fallout of accumulated fatigue is demonstrated most clearly through GPS analysis of English premiership rugby, revealing significant decreases in distance travelled after 50 minutes of play (0 – 10 min: 832 m vs. 50 – 60 min: 704 m & 70 – 80 min: 734 m), primarily in low-speed temporal movements (i.e., cruising/striding) (110,323). Specifically, no differences were observed in distance sprinting, high-intensity running, or number of high-intensity static exertions across any 10 min window of a match indicating differences would have occurred during slower phase play, likely characterising an inability to recover from rucks, maintain defensive position, or run support lines (323). Essentially players were typically able to maintain high-speed demands only by sacrificing low-speed distances as a pacing strategy to deal with transient fatigue (67,110,323). However, this strategy could prove detrimental if fatigue-related alterations in temporal positioning create more opportunities for the opposing team to gain an advantage and/or score. At present, rugby strength and conditioning professionals should emphasize immediate transition phases during SSC movements to maximize elastic recoil of MTU structures during ballistic movements, thereby preserving energy for later periods of play. For example, GCT during DJ (~0.18 – 0.39) or hurdle hops (~0.10 – 0.25 s) are similar to those seen in sprinting and acceleration (~0.11 – 0.25 s) and can be used as a monitoring tool for performance (24,52,53). Alternatively, an athlete's reactive strength index (RSI) measured during a drop jump (jump height ÷ GCT) has been proposed as a useful indicator of SSC behaviour and their ability to transition from a lengthening or eccentric action to a shortening or concentric action (28). However, substantial changes in one metric may cause adverse effects in the other metric, causes changes in RSI to be falsely interpreted.

2.6. Training Adaptations

Prescribing appropriate training regimes for different movement profiles and speed/acceleration demands requires knowledge of FV expression, and the appropriate training stimulus to achieve desired adaptations, without which effective periodisation at the elite level is near impossible.

Simply put, the ability to accelerate, achieve high velocities, and repeat this performance in a fatigued state hinges in part on an athlete's mechanical ability to efficiently recycle energy, rapidly activate muscle, and produce large amounts of force during short time frames (188). Plyometric training naturally offers unique neural, mechanical, morphological, and geometrical contributions to address these adaptations and effectively improve ballistic performance in rugby union players (10).

2.6.1. Neural adaptations

Plyometric training enhances speed and acceleration profiles primarily through neuromuscular integration (6,17,138,189,361,393). Specifically, plyometric training has been observed to increase maximal voluntary contraction and improve neural drive early on in training programmes (29,113–115,200,265). Six to eight weeks of plyometric training increased jump performance and enhanced EMG activity during the eccentric portion of the CMJ (9.6 – 13.9%) due to increases in efferent motor neuron output (265,359). These CNS stimulated adaptations are crucial for improving maximal kicking velocity, allowing players to kick for greater distances and influence attacking opportunities (51,316). Indeed, game data from the men's 2015 Rugby World Cup suggests winning teams preferentially kicked away possession into the opposition 22 – 50 m compared with losing teams (155). Winning teams opted to kick long in attempt to gain territory by playing pressure defence and forcing turnovers. However, these tactical strategies are not without cost. Rugby strength and conditioning coaches may want to consider these adaptations, particularly for scrum-halves, fly-halves, and full-backs who sustain a substantially greater kicking load than other positions (309).

2.6.2. Rate of force development

Plyometric training can also lead to improved RFD (14.6 – 107.0%) and rate of torque development (+10.8%) due to favourable cross-bridge attachment and motor unit synchronization strategies (29,38,46,130,208). Kryöläinen et al. (208) found maximal RFD increased substantially for the knee extensors (18,836 ± 4,282 N^{-1}·s to 25,443 ± 8897 N^{-1}·s) during 10 weeks of plyometric training. Similarly, Bogdanis et al. (38) recently established six weeks of combined low-volume, high-intensity eccentric half-squats and plyometric training (30%1RM loaded SJ, unloaded SJ and CMJ) increased RFD (40 – 107%) across all time windows (0 – 50, 0 – 100, 0 – 150, 0 – 200 ms). These results suggest high intensity training is more beneficial for increasing RFD across a wide range of desired traits. Typically, early phase (<100 ms) force production and (30 – 50 ms) RFD during isometric tests have been shown to preferentially affect acceleration (5 m) and sprint (20 m) performance, while jump height or scrum success may be more affected by later-phase (>100 ms) force-time characteristics (371,386). These results are somewhat contrasted by Kubo et al. (200), who determined unilateral jump performance improvements were a result of improved MTU mechanical properties, rather than activation patterns. Following a 12-week unilateral plyometric intervention, EMG activity and RFD exhibited similar patterns in both legs despite the fact the contralateral limb underwent traditional weight training. However, only the plyometrically-trained leg improved unilateral CMJ and DJ performance and time to peak torque, alongside better tendinous energy storage. These results suggest SSC-targeted training is multifaceted, and plyometric training affects both the mechanical and neurological loading aspects.

2.6.3. Mechanical and morphological adaptations

As previously outlined, greater tendon elongation during eccentric motions augment the ability of the MTU to stretch at velocities that would be unfavourable to muscle tissue alone (361,382).

Evidently, plyometric training has previously demonstrated enhanced elastic energy storage, maximal tendon elongation and jump performance in physical education students (200,393). In contrast, low-intensity plyometric training does not seem to elicit any change in elastic energy transfer (152). However, participants displayed decreased strain values, thus extending the tendon's safety margin until the maximal stretch threshold, preventing tensile failure. Such adaptation is likely to be useful during repeated sprints rucks, scrummaging and blocking incoming tackles where players are required to sustain large impact forces. Accordingly, forwards are more likely to sustain joint, ligament, and upper limb injuries than backs, in part due to front-row forwards performing 25% greater contact-related actions than all other positions and encountering far greater impact stress (22). If a player can create stiffness and effectively absorb forces quickly, they have a better chance to maintain their position, and avoid injury.

Much the same as tendons, longer fascicle lengths positively affect sprint performance by allowing for greater shortening velocities and a larger area over which crossbridge attachment can occur (271). A paucity of research currently exists concerning morphological adaptations from plyometric training. Recently, Secomb et al. (344) demonstrated a combined plyometric training and gymnastics programme produced significant decreases in vastus lateralis pennation angle, with increases in associated fascicle length and lateral gastrocnemius thickness for adolescent athletes. While the resistance was limited to body weight, fast eccentric landings provided sufficient stimulus to cause structural changes in the MTU (344).

2.6.4. Muscle fibre proportion

Similar to sprinting, there is evidence plyometric training may preferentially damage MHC-IIx (85%) and MHC-IIa fibres (84%), compared to MHC-I fibres (27%) due to their superior FV characteristics (235,245,246). Moreover, plyometric training has previously demonstrated shifts in myosin heavy chain (MHC) isoform IIa and IIb/IIx distribution (245,246,398) and intrinsic muscle fibre characteristics (38,245,246,305), while one author reported no change (38,305). However, in both cases, improvements in vertical jump height (~4.6 – 36.0%), peak power (~2.5 – 22.0%) and unloaded shortening velocity (18 – 29%) were observed, along with muscle fibre cross-sectional area increases across all studies in all isoforms 4.4 – 7.8% (305), 8.3 – 11.6% (38) and 22 – 30% (245). Increases in cross-sectional area contribute to maximal strength and RFD by facilitating cross-bridge attachment and cycling (38,391). Notably, SSC-induced plyometric training improves power production by affecting both aspects of the FV relationship, particularly influencing velocity-oriented attributes (245,246). In comparison, traditional strength training primarily increases MHC-IIa content by transitioning the faster MHC-IIa/x and MHC-IIx fibres to the more glycolytic phenotype, thereby increasing the force qualities of a muscle, but decreasing the capacity for velocity (391). Strength and conditioning professionals should consider this adaptive discrepancy between methods when targeting muscle architecture for velocity-focused athletes. Additional research should aim to determine optimal plyometric programming to elicit positive fibre type shifts and intrinsic FV adaptations pertinent to speed and acceleration.

Research on South African club rugby players suggests forwards' (54%) and backs' (57%) MHC-II proportions fall somewhere between trained sprinters (59%), and middle-distance runners (49%), well above that of true endurance cross-country runners (24%)(169,192). Furthermore, generalized MHC-II:MHC-I ratios from semi-professional footballers indicate greater peak and total sprint volumes are related to overall MHC-II distribution (269). Greater concentrations of MHC-II fibres are beneficial for sprinting because of their superior force-generating characteristics and faster contraction speed, but large aerobic demands would still require the improved oxidative capacity of MHC-I isoforms (169,194).

2.6.5. Musculotendinous stiffness

Furthermore, properly applied plyometric training can stimulate changes in stiffness, although research on MTU structural adaptations has been fairly convoluted until recently (Table 2.1). The majority of previous research reports lower-body plyometric training significantly increases Achilles tendon stiffness (24.1 – 42.0%)(46,113,115,393), overall leg (222) and ankle joint stiffness (115,196,200,222). Only a few studies have reported decreases (115,130), or no change (112,114,152,196,200) in tendon stiffness. Differing programme variables, conflicting terminology, challenging measurement techniques, and grouped analysis of specific components may lead to these contrasting results.

Recent technological improvements may have provided a more comprehensive analysis of MTU stiffness, isolating series and parallel elastic components (Figure 2.1)(115). Fouré et al. (2011) were able to provide some clarity on the topic by using a mathematical model to determine the stiffness of both the torque dependent and independent active (muscle) and passive (tendon) components of the plantar flexors SEC (111,194). Following 14 weeks of plyometric training, participants significantly decreased their active SEC_1 stiffness (-10.4%), while they simultaneously increased their passive SEC_2 stiffness (+13.2%), and jump performance (+12.7%, +7.4%, +27.7% for SJ, CMJ, and reactive jumps, respectively). Considering a lack of change in either muscle architecture or tendon CSA, the authors noted that changes to both active and passive SEC delineated intrinsic structural changes (Table 2.1). Decreases in muscular stiffness indicated an upregulation of MHC-II fibres and better energy storage during SSC eccentric phases. On the other hand, increases in tendon stiffness suggested changes in collagen cross link patterns allowing for enhanced tension transmission and energy recoiling (16,115,200).

Table 2.1. Muscle-tendon adaptations resulting from plyometric training.

*Note: SJ= squat jump; CMJ= countermovement jump; DJ= drop jump; RJ= reactive jump; ps= per session; SL= single leg; DL= double leg; MD= multidirectional; Mixed= SL, DL, and alternating exercises; P#= post number of weeks from pre-assessment; PV= peak velocity; Pmax= Maximal power, Prel= relative maximal power; Vs= velocity of initial step during sprint test; V5= peak velocity of the first 5 metres; Vmax= maximal velocity between 35 and 40 m of sprint test; MVT= maximal voluntary torque; MVC= maximal voluntary contraction; RMS-EMG= root mean square of electromyographic signal; RTD= rate of torque development; RFD= rate of force development; IMP= impulse; Con= concentric; Iso= isometric; ROM= range of motion; Penn <= pennation angle; FL= fascicle length; YM= Young's modulus; TL= tendon length; EE= elastic energy; TLmax= maximum tendon length; EMD= electromechanical delay; rel= relative; Tc= contraction time; Dm= maximum displacement/amplitude of muscle contraction; MCH= myosin heavy chain; MTU= muscle-tendon unit; GC= gastrocnemius muscle; VM= vastus medialis; RF= rectus femorus; AT= Achilles tendon; GCT= Gastrocnemius tendon; TA= tibialis anterior; PF= plantar flexor muscles; DF= dorsiflexion muscles; CSA= cross-sectional area; K= stiffness; Kindex= changes in stiffness irrespective of changes in tendon force; DC= dissipation coefficient; sec1= series elastic component in muscle; sec2= series elastic component in tendon; pec1= parallel elastic component in muscle; pec2=parallel elastic component in tendon; "trend"= non-significant improvement as identified by author; n/a= not applicable; jump height reported as absolute values, unless only reported as percentages

Author	Population	Frequency	Exercises	Intensity & Volume	Muscular	Tendon	Performance
Behrens et al. (2013)	Recreational volleyball players (n = 23)	2x week 8 weeks 16 sessions total	SJ, CMJ, DJ (40 cm)	Moderate 54 – 63 GC·session^{-1} 972 total	80° Knee Flexion- MVT: +23.1 N.m-1 MVC: +4.6% RMS-EMG: +0.021 RTD: +308.7 Nm.s-1 IMP0-50ms: +0.55 Nm.s-1	n/a	SJ: +4.5 cm CMJ: +4.6 cm
Borzuchek et al. (2019)	Collegiate male volleyball players (n = 16)	2x week 6 weeks 12 sessions total	MD Mixed PT	Low-High 136 – 304 GC·session^{-1} 2,608 total	TA Muscle K: +80.35 N.m^{-1} Quadriceps, Hamstrings, & PF muscle K: no change	n/a	SJ: +2.2 cm CMJ: +3.2 cm CMJ 2-step: No change
Burgess et al. (2007)	Physically active males (n = 13)	2-3x week 6 weeks 15 sessions total	SLDJ	High 80 – 480 GC·session^{-1} 1,890 total	Con RFD: +18.9% "trend" (p>0.05) Iso RFD: +14.6% "trend"(p>0.05)	Medial GCT K: +29.4%	SL Straight-leg Con jump: +58.6%

Chelly et al. (2010)	Junior (18 – 20) soccer (n = 23)	2x week 8 weeks 16 sessions total	Hurdle + DJ	Moderate 400 – 100 $GC{\cdot}session^{-1}$ 860 total	Thigh CSA: +3.3% "trend" (p>0.05) Thigh muscle volume: +2.5% Leg volume: +3.45% "trend" (p>0.05)	n/a	SJ: +3 cm; SJ PV: .1 $m.s^{-1}$ CMJ: +1 cm; CMJ Pmax: +80 W CMJ Prel: +1.3 $W.kg^{-1}$ 40 m Sprint- Vs: +0.4 m.s-1; V5: +0.4 m.s-1; Vmax: +0.8 m.s-1 FV cycle test- PP: +32 W; Prel: +0.8 W.kg-1; peak force: -1.1 N
Fouré et al. (2009)	Explosive recreational sport males (n = 17)	2x week 8 weeks 16 sessions total	SJ, CMJ, DJ, SL +DL Hurdles	Moderate 150 – 280 $GC{\cdot}session^{-1}$ 3,200 total	PF max Torque, passive ankle joint K & DF ROM: no change Passive GC Kmax: +33%	AT K: "trend" to increase at 80 N, 160 N, 240 N & 320 N (P>0.5)	SJ: +4.6 cm 8 RJ: +7 cm
Fouré et al. (2010)	Recreational sport males (n = 19)	2-3x week 14 weeks 34 sessions	SJ, CMJ, DJ, SL +DL Hurdles	Moderate - High 200 – 600 $GC{\cdot}session^{-1}$ 6,800 total	MVC: +5.2%; RTD: +12.7% "trend" (p=0.10)	AT K: +24.1%; Kindex: +65.2% AT K/CSA: +21%; DC: -35% AT CSA, TL, TLmax: No change	SJ: +4 cm CMJ: +3 cm 8 RJ: +8.3 cm
Fouré et al. (2011)	Recreational sport males (n = 19)	2-3x week 14 weeks 34 sessions	SJ, CMJ, DJ, SL +DL Hurdles	Moderate - High 200 – 600 $GC{\cdot}session^{-1}$ 6,800 total	SEC1 K: -10.4% Penn < & FL: No change	SEC2 K: +13.2% Ankle joint K: +~8% AT CSA: no change	SJ: +4 cm CMJ: +3 cm 8 RJ: +8.3 cm
Fouré et al. (2012)	Recreational sport males (n = 19)	2-3x week 14 weeks 34 sessions	SJ, CMJ, DJ, SL +DL Hurdles	Moderate - High 200 – 600 $GC{\cdot}session^{-1}$ 6,800 total	GC PEC1 K: +26.1% GC CSA: No change Passive Ankle joint ROM: +7.6%	GC PEC2 K and AT CSA: NC GC MTU K: +7% "trend" (p=0.09)	n/a

Houghton et al. (2013)	Cricket players (n = 15)	2x week 8 weeks 15 sessions	MD Mixed PT	Low-Moderate 71 – 158 GC·session^{-1} 1,785 total	n/a	AT CSA: +12.86% AT K0-40% & AT K50-90%: NC Tendon resting length, EE, MTU displacement, strain, YM: NC Max MTU displacement, strain, K50-90%, and Young's modulus correlated with 5-0-5 m turn time (r= 0.548, 0.577, -0.535, -0.522) (p=0.024-0.046) AT peak force: -4.9% "trend" (p=0.08) AT Peak stress: -15.3 "trend" (p=0.09) Submaximal AT Stress at all points "trend" down ES:1.21-1.24 (p =0.05-0.07)	5 m time: NC 5-0-5 m performance: NC SJ: +9% CMJ: +11%
Kubo et al. (2007)	Healthy males (n = 10)	4x week 12 weeks 36 sessions	SL hop + SLDJ (20 cm)	High 100 GC·session^{-1} 800 total	PF muscle thickness: +4.9% MVC: +17% Activation level: 5.6% Time to peak torque: -9.15%	AT K: no change AT CSA: no change Ankle joint K: +63% AT elongation: +9.5% EE: +19.6%	SJ: +5.9 cm CMJ: +8.2 cm DJ: +10 cm
Kubo et al. (2017)	Healthy males (n = 11)	4x week 12 weeks 36 sessions	SL hop + SLDJ (20 cm)	High 100 GC·session^{-1} 800 total	PF muscle thickness: +5.7% MVC: +4.4% Active PF K: 30%MVC=+38%; 50%MVC= +60%; 70%MVC= +70% Passive PF K: NC	AT K, CSA and Hysteresis: NC Ankle joint K: +31% TL above 100 N: +~2 mm EE: +19.6%	SJ: +8.6 cm CMJ: +9.2 cm DJ: +7.7 cm
Mirzaei et al. (2013)	Healthy males (n = 27)	2x week 6 weeks 12 sessions	CMJ or DJ (45 cm) on sand	Moderate-High 100 GC·session^{-1} 1200 total	CMJ- EMG VM: +45% RF: +48% DJ- EMG VM: +26% RF: +46%	TLmax: +2.3 mm "trend" (p=0.06)	CMJ Group- CMJ: +13.04% DJ Group- CMJ: +17.04%

Sozbir et al. (2016)	Highly physically active physical education & sport students (n = 24)	2x week 6 weeks 12 sessions	MD Mixed PT	Low- High 90-140 GC·session^{-1} 1,460 total	EMG- VL: +13% VM: +10% GC: +14%	n/a	CMJ: NC
Wu et al. (2009)	Male university students (n = 21)	2x week 8 weeks 16 sessions	Vertical DL	Low-Moderate 60-120 GC·session^{-1} 1,440 total	P4 & P8- Soleus RMS-EMG: +51% P8- EMD: -12%	P8- AT K: +42% EE input: +35% EE Release: +34% AT K, EMD (r=-0.77); AT K, JH (r=0.54)	P4- CMJ: +3.9 cm P8- CMJ: +5.9 cm
Zubac et al. (2016)	Kinesiology students (n=20)	3x week 8 weeks 24 sessions total	hurdle + DJ	Moderate-High 50-80 GC·session^{-1} 1,560 total	Tc- VL:-9%; BF:-27% TA:-33%; GL:-26%; GM: -8% "trend" (p=0.158) Dm: BF:-27%; GM:-15%; GL:-32%; VL:-6% "trend" (p=0.654); TA:-17% "trend" (P=0.113) MCH-I proportion: -8% VL MCH-I CSA: +4.4%; VL MCH-II CSA: +7.8%	n/a	CMJ: +12.2% CMJ Prel: NC

These results are somewhat contrasted by Kubo et al. (196) who reported plyometric training similarly caused no significant change in tendon stiffness, but largely increased active muscle stiffness of the plantar flexor muscle group (Table 2.1). The authors speculated that changes in myofilament mechanical properties or tensile extensibility may have been the cause but did not compartmentally investigate those components individually. Interestingly, both authors reported similar increases in joint stiffness, and jump performances suggesting the underlying mechanisms may not be mutually exclusive. After compartmental analysis of stiffness-related measures, there is sufficient support that plyometric training positively affects muscle, tendon, and joint stiffness for superior rapid force-transmission. Future research should continue to clarify stiffness terminology in relation to global and localized stiffness contribution for ease of comprehension.

2.7. Practical Applications

Previous literature supports plyometric training as an effective tool for improving speed profiles in a range of athletes through integration of force-generating mechanisms, MTU stretch velocity and the efficient use of the SSC. Specifically, plyometrics target intrinsic muscle fibre FV characteristics, CNS stimulation, and MTU energy transmission during SSC exercises (Figure 2.3) (265,393). As such, the rate and magnitude of loading will affect mechanical efficiency and determine the ensuing adaptation (165,358). In that respect, performing plyometrics in a fresh state is likely to be more beneficial than performing them at the end of a training session or under fatigue, as movement velocity will be a key regulator of tendon loading rate (185). Thus, practitioners may want to consider having 48 – 72 hours between plyometric sessions or once-weekly sessions (11,394).

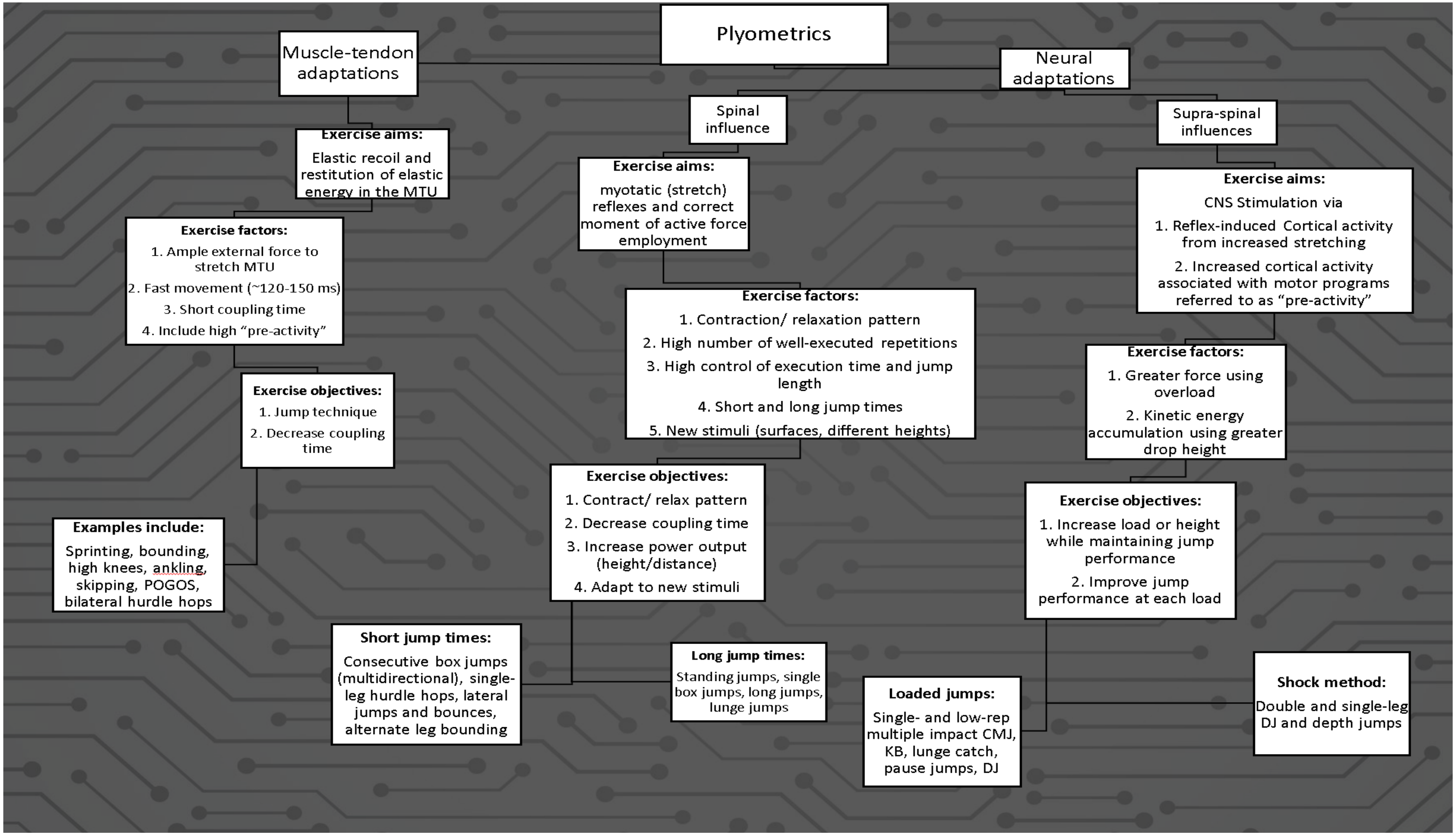


Figure 2.3. Exercise aims, objectives and practical applications of plyometric training.

While current recommendations span wide ranges (60 – 400 GC)(78), recent literature is becoming increasingly supportive of using low-volume high-intensity sessions (20 – 60 GC) with professional athletes (157,230,231). Some caution is advised for both the prescription and progression of training, as plyometric exercise intensity that is too great for the athlete's force absorption capacity can overly stress an athlete. Loading demands above an athlete's mechanical threshold are likely to prompt protective strategies, in turn hindering performance (162).

2.7.1. Elastic energy adaptations

When specifically targeting elastic recoil and restitution, practitioners may choose activities with a rapid GCT (120 – 150 ms), a large external force which induces a large pre-stretch and a short coupling time (Figure 2.3) (91). These excises facilitate high EMG ratios and short-range stiffness elasticity contribution during repeated muscle stretch, while short coupling times maximise energy reutilisation with "spring"-like movement (91). This is where exercise durations can act as a good indicator of movement-specific force production demands, particularly for high-intensity exercises. These activities can be easily tailored and progressed such that they may benefit all positions on the field, improving movement economy and mitigate fatigue related neuromuscular decrements. These exercises may be best executed as continuous repetitions to gain the most benefit. Examples may include sprinting, hopping, bounding, skipping, low hurdles or double-under jump-rope exercises.

2.7.2. Neural adaptations

Spinal and stretch reflex adaptations

For neural adaptations, these may be broken up into spinal influences including stretch reflexes and muscle proprioceptors and supra spinal influences targeting CNS motor programming. The short latency component of the stretch reflex is mediated primarily by group IA muscle spindle afferents and excitation thereof has been shown to vary with jump technique and task-specific demands (91). For instance, stretch reflex has been shown to increase with falling height during the DJ exercise (342), however, excessive heights (76 cm) have also demonstrated diminished values compared to low heights (31 cm) due to CNS modulated protection strategies (91,215). Hopping exercises emphasise the contraction-relaxation pattern by the large amount of proprioceptive feedback and muscle stretch, thus practitioners may want to target reflex stimulation using a high number (10 – 30+) of well-executed repetitions (91). The inclusion of different surfaces, box heights, or stimuli in one drill may additionally target corticospinal excitability of stretch reflexes in order to modulate ankle stiffness accordingly (249). In contrast, longer duration exercises like SJ, CMJ and DJ are not likely to elicit changes in stretch reflex activity (30). The intensity of these exercises can range from low-high intensity, with the aim here being to execute quality repetitions, focusing on decreasing coupling time, and increasing power output.

These can be broken down into short- and long-coupling time exercises. Examples of short coupling time exercises may include alternate leg bounding, single-leg hurdle or forward hops, consecutive low-height box jumps, consecutive lateral jumps and bounces. These may be particularly beneficial for athletes required to perform large amounts of sprinting. However, set-up and execution will strongly dictate coupling time, meaning the height of box or hurdle should not be too high as to encourage longer transition times if targeting myotatic reflexes and rapid force transmission. Long coupling exercises will still include multiple repetitions focus on creating greater power via height or distance. These may include standing long jumps, repeated broad jumps, vertical jumps, and box jumps. These may be preferable for improving acceleration, heavier athletes or those that cannot tolerate high forces during low coupling times.

Supra-spinal adaptations

Exercises targeting supra-spinal or CNS stimulation require a more severe force overload from eccentric or complex actions (101,128). The goal with these exercises is to accumulate large quantities of kinetic energy and stimulate "pre-activity" with higher drop heights, or greater load and larger MTU stretch magnitudes. In particular, maximal strength will largely affect the drop height which is considered high-intensity, with stronger athletes requiring larger drop heights to maximise power output (250). Practitioners should be cautioned, these high-intensity varieties are suited only for trained athletes that possess sufficient mechanical capabilities and demonstrate sufficient mastery of lower-intensity plyometrics. These exercises should be built up slowly to avoid CNS activation of protective, performance dampening mechanisms, or injury (91). Examples of these may include single impact exercises like the DJ or multiple high-impact exercises including loaded and unloaded (i.e., weighted or band-assisted and resisted) varieties designed to accentuate the eccentric motion, kettlebell loaded jumps, pause loaded or drop pause jumps. However, while additional load will increase the external force's impact, it is also likely to increase the coupling time of exercises, which may have adverse effects on energy transfer if used in isolation. Alternatively, the DJ will be beneficial for improving eccentric muscle activation patterns, stretch reflex stimulation and energy absorption, subsequently improving running economy (162,339). As such, this exercise may be a viable option for both forwards and backs looking to last a whole match. Notably, the taller the drop height, the larger the MTU stretch and loading requirements placed on the athletes, meaning a 30 cm DJ may feel differently for tight forwards and inside backs due to differences in body mass, adipose tissue, and SSC effectiveness. As a general rule, drop heights equal to or above 90% maximal SJ height may start to induce significantly greater MTU stretch requirements and should be progressed carefully (162).

Rugby union envelopes a wide range of movement profiles requiring differing quantities of FV expression for optimal team performance. Therefore, strength and conditioning professionals programming positional-specific training must consider the underlying physiological mechanisms when aiming to direct programme design and manipulate FV characteristics for unique movement demands. Importantly, practitioners should consider exercise durations and drop-height specific adaptions: repeated hopping exercises with short coupling times for elastic restitution or short-contact DJ with for neural firing sequences and spinal reflexes, whereas long contact (>400 ms) exercises with sharp external forces like very high intensity DJ may preferentially improve supra-spinal stimulation and motor programmes, so long as the athlete has sufficient tissue resilience.

Chapter 3 – A systematic review of plyometric manipulation and dosing strategies for improving sprint performance in athletes.

Reference

Manuscript in preparation for journal submission.

Author Contribution

Watkins, CM, 80%; Gill, NG, 5%; McGuigan, MR, 5%, Storey AG, 10%

3.0. Prelude

Having reviewed important physiological factors relevant to rugby positions, and athletic traits necessary for optimal rugby performance (Chapter 2), the literature positively supports the proposed benefits of plyometric training for rugby union players of all positions. Whether traveling large distances at moderate speeds, or performing maximal sprint efforts, the SSC functions to integrate neural, muscular and elastic structures for greater ballistic performance (287). Plyometric training has been shown to improve contraction dynamics, stretch reflex and proprioceptive modulation, CNS activation, muscle morphological characteristics, eccentric force absorption, and energy recoil (1,29,91,266,365,393). These physiological adaptations help rugby players efficiently perform in contact-related actions, change-of-direction tasks, high speed running and sprinting, with greater energy efficiency, power production and less metabolic fatigue (148,150,376,393). However, task-specific characteristics will innately influence these adaptative processes. For example, the CNS will modulate proprioceptive activity during the DJ based on drop height, while stretch reflex activity is maximised during hopping exercises (91).

Certain exercise characteristics were identified through a more comprehensive mechanistic understanding of loading parameters. However, a literary gap surrounds the proper dosing strategies for improving sprint performance including volume loads and manipulation of plyometric training in trained athletes. Moreover, the majority of research has been performed in non-athlete and adolescent populations. As appropriate volume loads will depend on an athlete's maximal strength and capacity for load (251), specific volume load recommendations are required for trained populations. Therefore, a systematic review was subsequently conducted to meticulously analyse and provide recommendations on plyometric training characteristics relating to speed and acceleration performance in trained adult athletes.

3.1. Introduction

Plyometric training is a form of ballistic training targeting the SSC which, integrate neural, mechanical and elastic structures to maximize athletic performance (374). However, the available information on how best to manipulate plyometric variables to achieve specific adaptations relevant to sprinting in well-trained athletes is scarce. Previous literature is overwhelmingly supportive of plyometrics for enhancing neuromuscular coordination and associated jump performance in as little as two weeks (236), with significant increases (2.4-58.6%) in both vertical (14,29,38,46,59,115,200,236,245,246) and horizontal directions (13,156,236,314,395), as well as sprint (27,44,56,58,157,184,236,284,377), agility (66,377), and aerobic (40,41) performance. Very few studies have reported no change (274,359,373,395) or slight decreases (232), mostly due to inadequate prescribed training volume, intensity and/or recovery. Many of the previous literature reviews surrounding plyometrics have investigated their effect on jump performance (379), strength (334), agility (12), youth (273) and/or amateur athletes (335), thus their transferability to improving sprint performance in trained adult athletes may be limited.

Such predominant results are not surprising considering shared kinematic properties between plyometric training and natural ballistic movements (i.e., running, jumping) (24,163,264,271,390). Extensive research has long recognised the favourable MTU adaptations resulting from plyometric training (30,196,393). In particular, previous literature emphasises improved SSC elastic response (196,200,393), superior muscle morphology (38,196,200,246), enhanced neural efficiency (29,30,265,359), and CNS and reflex stimulation (5), leading to greater movement economy (298,373). As a result, faster athletes can typically generate greater ground reaction forces in less time than slower athletes, thereby maximizing ground contact efficiency (224,390). In particular, sprint athletes (whom readily utilize plyometric methods) have shown very high levels of muscular pre-activation, increased concentration of MHC-II fibres, and efficient energy utilization strategies (142). Essentially, these adaptations can be broken down into myogenic (i.e., muscular), spinal-level neurogenic (i.e., proprioceptive feedback) and supra-spinal neurogenic factors (i.e., CNS stimulation) leading to superior running performance (229,390).

However, while plyometrics' beneficial effect on neuromuscular, sprinting and jumping performance is well studied, further investigation surrounding the optimal dose and manipulation of critical factors to stimulate such adaptations is necessary. Current literary recommendations span low to very high sessional volumes (40 – 400 GC), with vague information surrounding training direction, intensity or exercise choice (78,96). In particular, these recommendations report that, "any single leg exercise is more intense than the same exercise performed on both legs," without any further analysis (96). In fact, intensity based solely on limb support is an over-simplification of exercise demands without considering the concomitant characteristics associated with unilateral and bilateral variations. For example, it is true that proprioceptive demand, lumbar-pelvic stabilisation, and load distribution is usually greater during single-limb exercises (143,180). However, these factors subsequently affect movement velocity, and MTU loading strategies, often resulting in longer GCT and lower peak GRF (170). For these same reasons (i.e., a decreased stabilisation requirement), athletes typically are faster and jump higher on two feet, leading to greater peak GRF, faster GCT, greater MTU stretch velocities, and greater rebound jump heights from which they land from (143,170). All these factors directly affect the MTU stress and exercise intensity.

Moreover, much of the previous analysis is centred on sub-elite or adolescent populations (96,103,335). Thus, their relevance to dosing strategies in semi-professional and professional athletes is inconclusive due to factors including maturation, strength, athletic experience, and tissue resilience (168). Therefore, this review will collectively analyse plyometric training literature to provide a more comprehensive assessment of critical variable manipulation for improving sprint profiles in semi-professional and professional athletes.

3.2. Methods

3.2.1. Experimental approach to the problem

Search of scientific literature

A comprehensive literary search was performed electronically through databases: Scopus, Pubmed/Medline, Science Direct, Web of Science and SPORTdiscus. Articles were included from inception to October of 2019, only from peer-reviewed journal articles published in full-text, using English-language. Additionally, articles were sourced from reference lists and a final search was completed prior to publication. Boolean search terms used included Plyometric training* (i.e., plyometrics, plyometric, plyo), alone or in conjunction with stretch-shortening cycle training*, or jump training*, or ballistic training*, or power*, and speed*, or sprinting*, or sprint performance*, or running*, and dosage*, or volume*, or frequency*, or time-course*.

Inclusion criteria

The study criteria were designed to provide practical recommendations on plyometric training variable manipulation and dosing strategies for improving speed and acceleration in semi-professional and professional athletes. Therefore, study selection was limited to training interventions implementing land-based lower-body plyometric training and assessments in adult (> 18 years) athletes. Additionally, studies were required to include a linear timed or velocity-based sprint assessment and no additional ergogenic aids or non-training modalities (i.e., electrical stimulation, whole body vibration) that would interfere. A total of 93 studies were identified. Further steps were taken to incorporate previous recommendations concerning internal validity (334,355) and identified studies were required to meet the following criteria: i.) experimental study design; ii.) sufficient sample sizes (n > 5) and minimal experimental mortality; iii.) exercise intervention and results clearly stated; iv.) research using instruments with high validity and reliability; v.) sprint assessments conducted pre- and post- plyometric intervention. Considering the typical absence of elite populations in published literature, concessions were made to include studies with no control group and single-group designs.

All studies were subsequently read and coded for modifiable variables that may have affected programme effectiveness. Variables were grouped according to subject characteristics, programme elements, volume load, and output measure. Athlete characteristics included age, sport, competition level, training, plyometric and sport experience. Programme elements included alternate training regime, training duration, frequency, inter- and intra-session rest, repetition ranges, loading schemes, number, and types of exercises (i.e., depth, non-depth, single, continuous) training directions and target distance. Volume load included programme volumes, sessional volumes, exercise choice, and drop height. Output measures included linear maximal sprint from a static start (4, 5, 10, 15, 20, 30, 40, 50 m), from a flying build up (20mFly, 30mFly, 60mFly), a treadmill-based sprint test to obtain Vmax, or linear sprint with change of direction (T-test, repeated sprint assessment). Effect sizes (ES) were calculated according to Cohen's D for all studies using pooled standard deviations, whereby thresholds of 0.2, 0.5, 0.8, 1.2 were categorized as small, moderate, large, and very large (109). Web Plot Digitizer was used to estimate pre- and post-assessment scores from graphically represented results.

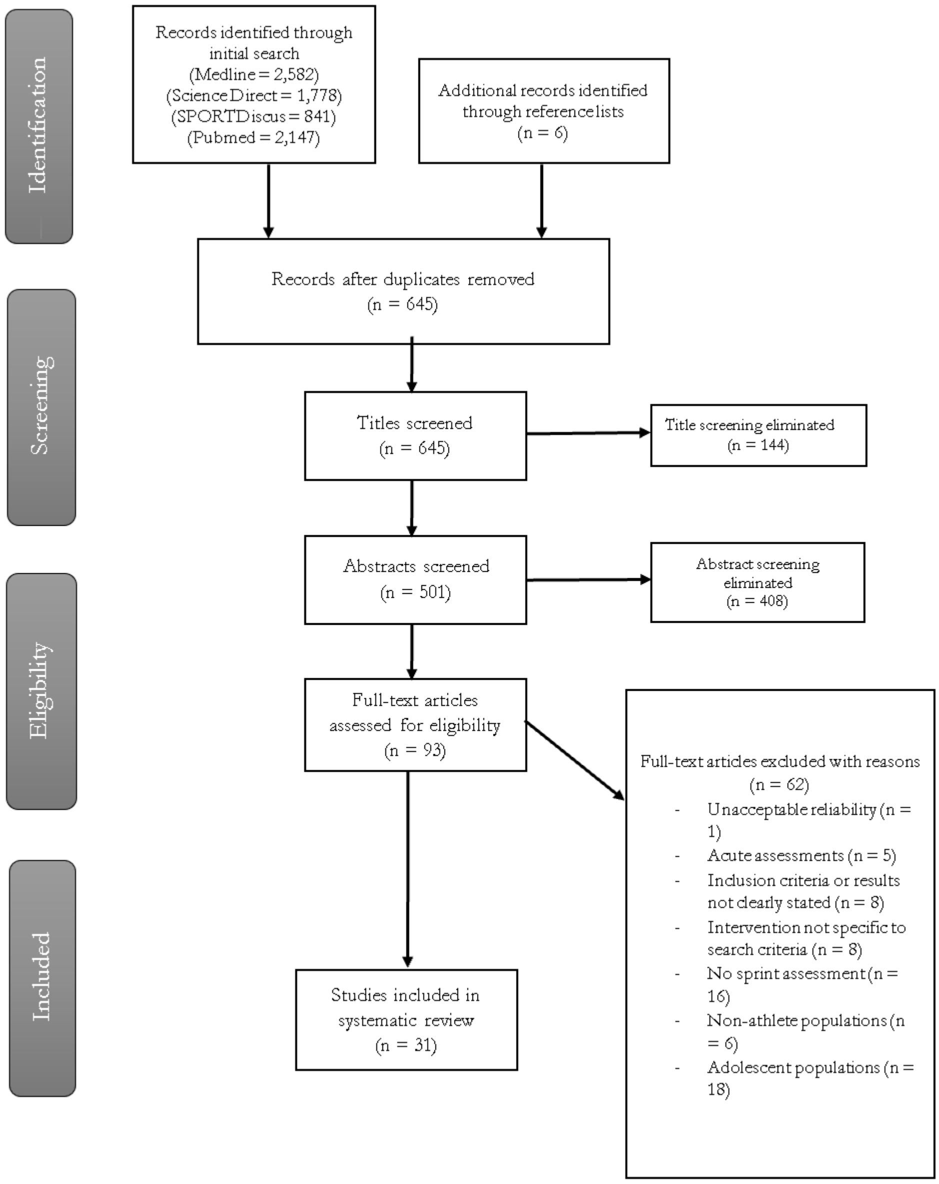


Figure 3.1. Systematic study selection flow chart.

3.2.2. Intensity definitions

Plyometric intensity has been historically difficult to define and categorise primarily as it is dependent on the physical capacity of the athlete. However, in order to systematically analyse programme elements, appropriate intensity characteristics need to be defined. Unlike resistance training, plyometric intensity domains have often been left to subjective perceptions of effort and intensity. However, recent research reveals that such subjective measures are not typically accurate when compared to joint powers and induced GRF (219). However, plyometric exercise intensity can be broken down into three considerations: i.) impact velocity; ii.) collision forces and time (GCT); iii.) distribution of load (170,206,243).

Impact velocity is determined by the height an athlete's centre of mass falls relative to the position of impact. When the landing surface is below that of the take-off surface (e.g., DJ or down-hill jumps), the vertical velocity at ground contact will be high (170). Conversely, when the landing surface is above that of the take-off surface (e.g., box jumps), the vertical velocity will be much lower (170). The magnitude and rate of loading are primary considerations in determining plyometric exercise intensity and are dependent on the drop height and time over which the forces are absorbed (243). Athletes can assume stiff landings where they attempt to absorb forces more quickly and are more effective in transferring energy. Alternatively, athletes can soften landings to lengthen the duration of force absorption thereby reducing physiological load (174). Both the impact velocity and forces need to be characterised in the context of direction as well. For example, horizontal exercises have shown to have significantly greater landing forces in all three planes compared to vertical exercises, and should be considered higher intensity (193).

The distribution of load at impact is another factor determining exercise intensity, whereby the greater the surface area at impact, the less load incurred. On this basis, the following classifications for load distribution are proposed: i.) bilateral exercises with a temporal offset (i.e., skips, step-ups); ii.) bilateral exercises with an asymmetrical load (i.e., split jumps); iii.) bilateral with symmetrical load (i.e., CMJ, tuck jump, BJ); iv.) unilateral loading where there is single-leg support during landing (i.e., single-leg jumps or alternating bounds). Temporal offset exercises are deemed to be the lowest intensity because they innately cannot generate high velocities and a short time between alternate foot contacts results in low impact. While these exercises contain components of single-limb support, disjointed movement sequencing during a single contact means neither limb assumes full responsibility of dissipating landing forces. Asymmetrical load requires force absorption to occur more quickly, split evenly between limbs, and lower velocities are generated when compared to symmetrical loading condition due to a decrease in instability. Unilateral loading includes those exercises which are truly single-leg from start to finish as well as two-legged exercises which require single-leg support during landing, SSC transitory, and take-off phases each contact. For example, lateral leaps, alternating bounds and sprinting involve two legs, however, during each contact one limb is entirely responsible for absorbing and redirecting forces in isolation (206).

These loading factors can be exemplified during cyclic or multiple-repetition exercises, compared to acyclic single-repetition exercises (242). Variable loading will alter load, but subsequently impact velocity simultaneously and needs to considered separate to bodyweight variations(243,244). High-intensity plyometric exercises therefore are those which involve multiple repetitions of high impact velocities, large external forces, quick rebound times, and unilateral loading as in alternating or single-leg bounds, sprinting, hurdles (> 100% CMJ height) (52,193). In contrast, single-repetition or acyclic exercises with long GCT and no-drop (non-depth) like SJ and CMJ will be less intensive, and slow exercise with low impact loads like submaximal skips and jump rope will be the lowest intensity (170,268).

3.3. Results

The initial search procured 645 articles. Title screening eliminated 144 articles as presented in Figure 3.1. Further screening of selection criteria resulted in 93 abstracts being accepted. Closer examination of full-text versions for study methods and internal validity revealed a total of 31 studies which met the criteria outlined.

3.3.1. Participant overview

A total of 1004 participants were included in this review, of which 547 underwent plyometric training. Overall programme characteristics are presented in Table 3.1. The current studies investigated plyometric training most commonly against an active control that maintained activity in their sport (n = 20) or against additional conventional sport training (n = 3). Other studies included two or more experimental conditions (n = 15), while very few included either a no training control (n = 1), or no comparison group (n = 2). Additionally, while all studies included regular sport training, the majority did not include alternative resistance training (n = 17). Some authors additionally included combined plyometric with only resistance training methods (n = 2), with resistance and sprint training (n = 3), only upper-body resistance training (n = 2), compared resistance training and non-resistance training methods (n = 2), additional endurance training (n = 3), or sprint training only (n = 2). All studies investigated adult athletes (≥ 18 years), 12 of which investigated regional, semi-professional or national cohorts, whereas nine of the cohort studies involved collegiate or club athletes. A variety of authors (n = 8) investigated very-trained, professional, and elite cohorts, and a small number of studies (n = 6) investigated novice or recreational athletes. The majority of studies investigated soccer athletes (n = 20), while some authors investigated other field sports (n = 8), court or rink sports (n = 7), track and field (n = 2), or endurance athletes (n=2).

Table 3.1. Systematic article programme characteristics.

Author	Y	Gr	N	G	A	Sport	Exp	F	W	S_{Vol}	P_{Vol}	Rep	Int	Prog	Ex	Ld	H_{dep}	Tp	No. Ex	Dist	Sig	ES
Arazi	2011	Active	6	M	20	BB	SP	-	8	-	-	-	-	-	-	-	-	-	-	>35	NC	0.0
Arazi	2011	Aqua PT	6	M	18	BB	SP	3	8	117-183	1188	8-25	Low	Step	Comb	DL+Alt	ND	Cont	4	>35	S	1.3-1.4
Arazi	2011	PT	6	M	18	BB	SP	3	8	117-183	1188	8-25	Low	Step	Comb	DL+Alt	ND	Cont	4	>35	S	1.2- 1.4
Blazevich	2003	PT+ST +BS	8	B	22	Multi	WT	4	5	36	360	4	Mod	Cons	CMJ	SL+DL	ND	SE	1	10/20	S/NC	-0.1
Blazevich	2003	PT+ST +HS	7	B	22	Multi	WT	4	5	36	360	4	Mod	Cons	CMJ	SL+DL	ND	SE	1	10/20	S/+NS	0.3/0.2
Blazevich	2003	2xPT+ ST	8	B	22	Multi	WT	4	5	36	720	4	Mod	Cons	CMJ	SL+DL	ND	SE	1	10/20	S/+NS	0.4
Brito	2014	Active	21	M	21	Soccer	Uni	-	9	-	-	-	-	-	-	-	-	-	-	5/20	+NS	1.5/0.3
Brito	2014	RT	12	M	20	Soccer	Uni	2	9	-	-	-	-	-	-	-	-	-	-	5/20	+NS/ S	1.2/1.0
Brito	2014	PT	12	M	20	Soccer	Uni	2	9	25	450	3-11	Low	Cons	SJ+CMJ+DJ	DL	ND+60			5/20	+NS/ S	2.9/1.5
Brito	2014	RT+P T	12	M	20	Soccer	Uni	2	9	25	450	3-11	Low	Cons	SJ+CMJ+DJ	DL	ND+60			5/20	S	5.3/2.4
Chelly	2010	Active	11	M	19	Soccer	Reg	2	8	-	-	-	-	-	-	-	-		-	0-V_{max}	+NS	0.8/0.3
Chelly	2010	PT	12	M	19	Soccer	Reg	2	8	50-100	860	10	High	L+C	Hur+DJ	DL+Alt	40-60	SE+ C	2	0-V_{max}	S	1.3/3.9
Cherif	2012	Active	11	M	20	HB	Pro	-	12	-	-	-	-	-	-	-	-		-	RSA	S	0.1
Cherif	2012	PT+ST	11	M	20	HB	Pro	1-2	12	40-60	640	10	High	Step	DJ +LHur	DL+Alt	10-45	SE	2	RSA	S	0.7
Cook	2013	RT	20	M	20	Rugby	SP	3	2	-	-	-	-	-	-	-	-		-	40	NC	0.0
Cook	2013	ECC	20	M	20	Rugby	SP	3	2	-	-	-	-	-	-	-	-		-	40	S	0.0
Cook	2013	RT+O S+PT	20	M	20	Rugby	SP	3	2	8	48	8	Mod	Cons	20% ACMJ	DL	ND	SE	1	40	S	0.1
Cook	2013	ECC+ OS+P T	20	M	20	Rugby	SP	3	2	8	48	8	Mod	Cons	20% ACMJ	DL	ND	SE	1	40	S	0.1
Coratella	2018	No train	16	M	21	Soccer	Rec	2	8	-	-	-	-	-	-	-	-		-	10/30	NC	-1.0/0.0
Coratella	2018	PT	16	M	21	Soccer	Rec	2	8	50	800	10	Low	Cons	SJ	DL	ND	SE	1	10/30	NC	0.0/0.0
Coratella	2018	PT	16	M	21	Soccer	Rec	2	8	40-42	656	10-11	Mod	Cons	30% RSJ	DL	ND	SE	1	10/30	S	1.0
Dello Iacono	2016	PT+U BRT	9	M	23	HB	Pro	2	10	30-80	1028	6-10	High	L+S	SLDJ	SL	25	SE	1	10/25t	S	1.0/3.3

Dello Iacono	2016	PT+UBRT	9	M	23	HB	Pro	2	10	30-80	1028	6-10	High	L+S	SLDJ	SL	25	SE	1	10/25t	S	2.2/7.9
Faude	2013	Active	8	M	23	Soccer	Club	2	7	-	-	-	-	-	-	-	-		-	10/30	- NS	-0.7/-0.6
Faude	2013	PT+RT+ST	8	M	23	Soccer	Club	2	7	20/63	581	3-8	Mod	Cons	Comb	DL+SL+Alt	ND+35/NR	SE+C	6	10/30	NC	-0.1/0.0
Gjinovci	2017	Cond	20	F	22	VB	Pro	2	12	-	-	-	-	-	-	-	-		-	20	NC	0.17
Gjinovci	2017	PT	21	F	22	VB	Pro	2	12	46-48	1096	1-3	L-H	Step	Comb	DL+SL	ND+NR	SE+C	6	20	S	1.0
Harris	2008	PT+RT+ST	9	M	22	Rugby L	Pro	2	6	60-72	800	10-12	Mod	Lin	20-45% RSJ	DL	ND	SE	1	10/30	S	0.4/0.3
Harris	2008	PT+RT+ST	9	M	22	Rugby L	Pro	2	6	25	300	5	MH	Lin	80% RSJ	DL	ND	SE	1	10/30	S	1.0/0.6
Houghton	2013	Active	8	M	21	Cricket	Reg	2	8	-	-	-	-	-	-	-	-		-	5	NC	0.0
Houghton	2013	PT	7	M	21	Cricket	Reg	2	8	71-158	1785	2-10	Mod	Und	Comb	DL	ND+ 20-60	SE+C	>10	5	+NS	0.5
Impellizzeri	2008	Sand PT	19	M	25	Soccer	Rec	3	4	78-156	1500	5-15	Mod	Lin	CMJ+B+BJ+DJ	DL+Alt	ND+NR	SE+C	4	10/20	S	0.8/0.6
Impellizzeri	2008	Grass PT	18	M	25	Soccer	Rec	3	4	78-156	1500	5-15	Mod	Lin	CMJ+B+BJ+DJ	DL+Alt	ND+NR	SE+C	4	10/20	S	0.9/1.0
Kobal	2017	PT>RT	9	M	19	Soccer	Pro	2	8	36-50	656	10-12	High	Step	DJ	DL	30-45	SE	1	10/20	- S	-1.4/-1.4
Kobal	2017	RT>PT	9	M	19	Soccer	Pro	2	8	36-50	656	10-12	High	Step	DJ	DL	30-45	SE	1	10/20	- NS	-1.4/-1.8
Kobal	2017	RT/PT	9	M	19	Soccer	Pro	2	8	36-50	656	10-12	High	Step	DJ	DL	30-45	SE	1	10/20	NC	0/-0.6
Lockie	2012	RT	6	M	22	Field	Rec	2	6	-	-	-	-	-	-	-	-		-	5/10	S	2.2/1.5/2.3
Lockie	2012	ST	9	M	22	Field	Rec	2	6	-	-	-	-	-	-	-	-		-	5/10	S/+NS/S	1.3/0.4/0.9
Lockie	2012	RST	9	M	22	Field	Rec	2	6	-	-	-	-	-	-	-	-		-	5/10	S/NS/S	0.9/0.0/0.9
Lockie	2012	PT	9	M	22	Field	Rec	2	6	100-181	1668	6-10	Mod	Lin	Box+B+HH+DJ	DL	ND+NR/40	SE+C	4	5/10	S	0.9/0.4/0.8
Lockie	2014	ST+RT	8	M	23	Field	Rec	2	6	-	-	-	-	-	-	-	-		-	5/10	S	1.2/0/1.1
Lockie	2014	PT+RT	8	M	23	Field	Rec	2	6	100-181	1668	6-10	Mod	Lin	Box+B+HH+DJ	DL	ND+NR/40	SE+C	4	5/10	S	0.8/0.2/1.2
Loturco[a]	2015	PT	12	M	19	Soccer	Reg	3	6	36	432	6	Mod	Cons	20% ASJ	DL	ND	SE	1	5/10/20	S	2.1/1.6/2.6
Loturco[a]	2015	PT	12	M	19	Soccer	Reg	3	6	36	432	6	Mod	Cons	20% RSJ	DL	ND	SE	1	5/10/20	NC/NC/S	0.4/0.5/0.8
Loturco[b]	2015	PT	12	M	19	Soccer	Reg	2-5	3	40-60	512	10	Mod	Pyr	CMJ	DL	ND	SE	1	10/10-20/20	NC/S	0.1/1.2/0.8
Loturco[b]	2015	PT	12	M	19	Soccer	Reg	2-5	3	40-60	512	10	Mod	Pyr	BJ	DL	ND	SE	1	10/10-20/20	S	0.6/0.6/0.2

Loturco	2017	PT	7	M	22	Soccer	Pro	2-3	5	84-52	848	4-6	Mod	Cons	SJ+CMJ+BJ	DL	ND	SE	3	5/10/20/30	S	5.3/2.9/0.9/0.6
Loturco	2017	PT+RST	11	M	22	Soccer	Pro	2-3	5	36-16	344	4-6	Mod	Cons	SJ	DL	ND	SE	1	5/10/20/30	S	4.2/3.0/1.2/1.0
Maćkala	2015	PT+RT+ST	14	M	18	Sprint	WT	3	2	180-250	1311	5 or 10	High	Lin	Comb	DL+SL+Alt	ND+NR	SE+C	8	20F/60F	S	0.4/0.5
Manouras	2016	Active	10	M	19	Soccer	Rec	-	8	-	-	-	-	-	-	-	-		-	10/30	NC	0.1/0.0
Manouras	2016	PT	10	M	19	Soccer	Rec	1	8	60-110	680	4-10	MH	Step	VPG+CMJ+Hur+DJ	DL	ND+NR/40	SE+C	4	10/30	+NS/S	0.7/0.6
Manouras	2016	PT	10	M	19	Soccer	Rec	1	8	60-110	680	4-10	MH	Step	HPG+BJ+DHur+C.BJ	DL	ND+NR	SE+C	4	10/30	+NS/S	1.3/0.6
Moore	2012	WL+RT	8	B	20	Soccer	Uni	3	12	-	-	-	-	-	-	-	-	-	-	25	S	1.8
Moore	2012	PT+RT	7	B	20	Soccer	Uni	3	12	368-162	7968^	10-30	LM	Step	Comb	DL+Alt	ND	SE+C	5-8	25	S	1.8
Ozbar	2014	Active	9	F	19	Soccer	Uni	1	8	-	-	-	-	-	-	-	-	-	-	20	+NC	0.6
Ozbar	2014	PT	9	F	19	Soccer	Uni	1	8	90-220	1210	5-15	High	Lin	Hur	DL+SL	40-60	Con	2	20	S	1.5
Ozbar	2015	Active	10	F	20	Soccer	Uni	2	10	-	-	-	-	-	-	-	-	-	-	10/20/30	NC	0.0/0.0/0.2
Ozbar	2015	PT	10	F	20	Soccer	Uni	2	10	120-250	3460^	5-8	L-H	Step	Comb	DL+S+Alt	ND+40-60	Cont	6	10/20/30	S	0.6/1.8/1.5
Ramirez-Campillo	2014	LDR	18	B	22	End	Nat	2	6	-	-	-	-	-	-	-	-	-	-	20	+NS	0.3
Ramirez-Campillo	2014	PT+LDR	18	B	22	End	Nat	2	6	60	720	10	H	Cons	DJ	DL	20,40,60	SE	1	20	S	0.9
Ramirez-Campillo	2015	Active	19	F	21	Soccer	Uni	-	6	-	-	-	-	-	-	-	-	-	-	20	-NS	-0.3
Ramirez-Campillo	2015	Active	21	M	21	Soccer	Uni	-	6	-	-	-	-	-	-	-	-	-	-	20	NC	0
Ramirez-Campillo	2015	PT	19	F	21	Soccer	Uni	2	6	80-160	1020	NR	NR	Lin	CMJ+BJ*	DL+SL	ND	SE+C	12	20	S	0.9
Ramirez-Campillo	2015	PT	21	M	21	Soccer	Uni	2	6	80-160	1020	NR	NR	Lin	CMJ+BJ*	DL+Sl	ND	SE+C	12	20	S	1.5
Rodriguez-Rosell	2017	Active	10	M	25	Soccer	SP	-	6	-	-	-	-	-	-	-	-	-	-	10/20	NC/-NS/-NS	-0.2/-0.3
Rodriguez-Rosell	2017	(45-60%) BS	10	M	25	Soccer	SP	1	6	-	-	-	-	-	-	-	-	-	-	10/20	S/NC/S	0.7/0.5
Rodriguez-Rosell	2017	PT+BS+ST+COD	10	M	25	Soccer	SP	1	6	15	90	5	Low	Cons	CMJ	DL	ND	SE	1	10/20	S	0.8/0.6
Ronnestad	2008	Active	7	M	24	Soccer	Pro	2	7	-	-	-	-	-	-	-	-	-	-	10/30-40/40		0/1.9/1.5
Ronnestad	2008	RT	6	M	24	Soccer	Pro	2	7	-	-	-	-	-	-	-	-	-	-	10/30-40/40		1.1/0.6/0.9

Ronnestad	2008	PT+RT	8	M	24	Soccer	Pro	2	7	20-60	672	5-10	NR	Step	Alt B+HH+Hop	DL+SL+Alt	NR	Cont	3	10/30-40/40		1.0/0.5/0.9
Salonikidis	2008	Active	16	NR	21	Tennis	Rec	-	9	-	-	-	-	-	-	-	-	-	-	4/12	NC	-0.2/-0.2
Salonikidis	2008	Tennis drills	16	NR	21	Tennis	Rec	3	9	-	-	-	-	-	-	-	-	-	-	4/12	S	0.7/0.2
Salonikidis	2008	PT (one leg)	16	NR	21	Tennis	Rec	3	9	32-50	NR	8-14	M	Cons	CMJ+Hop+DJ+ZZ	SL	ND+20-40	SE+C	4	4/12	S/NC	0.9/0.1
Salonikidis	2008	PT (one leg) + Tennis	16	NR	21	Tennis	Rec	3	9	32-50	NR	8-14	M	Cons	CMJ+Hop+DJ+ZZ	SL	ND+20-40	SE+C	4	4/12	S	0.6/0.3
Sedano	2011	ST+Cond	11	F	18	Soccer	Nat	3	10	-	-	-	-	-	-	-	-	-	-	10	NC	0.1
Sedano	2011	PT	11	F	18	Soccer	Nat	3	10	80-130	2880	5	MH	Cons	Hur +BJ	DL	ND+60	SE+C	3	10	S	0.4
Yanci	2017	No train	12	M	23	Futsal	Rec	-	6	-	-	-	-	-	-	-	-	-	-	5/15	+NS/-S	1.0/-0.3
Yanci	2017	1xPT	12	M	23	Futsal	Rec	1	6	120-176	774	4-21	MH	Lin	CMJ+BJ+DJ	SL	ND+NR	SE	3	5/15	S	1.1/1.0
Yanci	2017	2xPT	15	M	23	Futsal	Rec	2	6	36-108	774	4-21	MH	Lin	CMJ+BJ+DJ	SL	ND+NR	SE	3	5/15	S	0.3/0.5

a, b = differentiate different studies from the same author in the same year
Treatm = treatment + alternate training; Active = control group continuing regular sport training; PT = plyometric training; Aqua = aquatic PT; COD = change-of-direction; ST = sprint training; RST = resisted sprint training; RT = resistance training; UBRT = upper body RT; BS = back squat; HS = hack squat; ECC = eccentric training; OS = overspeed training; LDR = long-distance running; WL = Olympic weightlifting; PT>RT = all sets PT before all sets RT; RT>PT = all sets RT before all sets PT; RT/PT = alternating sets of RT and PT; No train = no exercise control group; N = sample size; S = sex; M = male; F = female; B = both; NR = not recorded; A = age(years)
BB = basketball; HB = handball; VB = volleyball; Rugby L = rugby league; Exp = experience; Rec = recreational or novice; Uni = university; Reg = regional; SP = semi-professional; Pro = professional; Nat = national
F = frequency (days.week^{-1}); W = programme length (weeks); S. Vol = session volume (ground contacts (GC)); P. Vol = programme volume (GC); ^ = approximately calculated off ranges; Rep = rep ranges; Int = overall programme intensity; MH= between moderate and high intensity; L-H = progressively increasing stages from low -high intensity
Prog = volume progression; Step = step loading; Cons = constant volume; Lin = linear loading; L+C = linear + constant volume loading; L+Step = linear and step loading; Und = undulating loading; Pyr = pyramid loading
Ex = exercise; SJ = squat jump; CMJ = countermovement jump; ACMJ = assisted CMJ; DJ = drop jump; BJ = broad jump; Box = box jump; Hur = hurdle; Lhur = lateral hurdle; HH = hurdle hop or jump over mini hurdles; VPG and HPG = vertical and horizontal POGOs; B = bounding; Alt B = alternating B; ZZ= zig zag jump/sprint
Ld = load distribution; DL = double leg; SL = single leg; Alt = alternating; Hdep= height for depth exercises like DJ or hurdles; ND = non-depth; No. Ex = number of exercises; S/E rest = rest between sets and exercises in seconds
Tp = type of plyo; Comb = combined; SE = single effort; Cont = continuous; SE+C = single effort and continuous style exercises; T rest = total rest between sessions in hours
Dist = Test distances; Sig = results reported; S = significant positive results; NS= not significant with + for positive results and – for negative result or within ES>0.2; NC = no change in scores or within ES <0.2; ES = effect size range (rounded to the nearest tenth)

3.3.2. Athlete characteristics

An in-depth analysis of athlete characteristics revealed training experience may significantly affect programme efficacy. Studies investigating semi-professional, regional or collegiate athletes were more likely to report non-significant pre to post changes, between-group differences, or negative effects (n = 7) in at least one group (Table 3.1). In contrast, all the studies investigating professional athletes (n = 8) reported significant effects, ranging from small to very large. Similarly, only two studies investigating novice athletes reported any non-significant outcomes, with most reporting moderate ES. Overall volume loads may have affected programme benefits. Moderate – high intensity resistance and plyometric training programmes has elicited positive benefits in professional athletes (131,326), yet these intensities demonstrated mixed results in regional (185), high-level amateur (102), collegiate (44) and strength-trained athletes (36,224,226). In comparison, semi-professional athletes using light-weight (45 – 60%) back squats and CMJ demonstrated moderate training effects (325). Moreover, comparison of resistance, weightlifting, plyometric, and sprint training most commonly resulted in similar adaptations in novice and young (18 – 22 years) athletes with entry-level experience (36,44,224,226,272). However, when comparing plyometric-only versus combined methods, studies trended to report greater performance changes for plyometric programmes combined with resistance training or sprint training methods as long as volume loads were carefully monitored (44,60,65,325,326,336).

3.3.3. Exercise selection

Initial acceleration

Significant improvements were reported for initial and secondary acceleration performance across initial acceleration periods including: 0 – 5 m (n = 8; ES = 0.85 – 2.83), and 0 – 10 m (n = 14; ES = 0.31 – 1.00) (Figure 3.2). A few authors reported no change or non-significant improvements for 0 – 5 m (n = 2; -0.01 to -0.11 s; ES: 0.50 – 5.50); 5 – 10 m (n = 1; ES: 0.28) 0

– 10 or 0 – 12 m (n = 5; 0.0 to -0.08 s or -0.1 to -0.2 $m.s^{-1}$; ES = 1.34 to -1.34). Within-group ES for plyometric programmes with varied exercise selections across the initial acceleration period are pictured in Figure 3.2. Those programmes reporting large ES across the first 10 m implemented five – six weeks of one – three times weekly training, involving largely moderate intensity, bilateral non-depth plyometric exercises including assisted SJ, SJ, CMJ, BJ, constant volume and low repetitions, while resisted SJ revealed mixed results (228,230,241). However, one study did report large and very large ES following 10 weeks of single-leg vertical-only and horizontal-only DJ programmes (157). Moderate effects were gained from a variety of programmes implementing six – ten weeks of BJ (231), resisted SJ (66,131), hurdles (40 – 60 cm) (293), hurdles (40 – 60 cm) with DJ (40 cm) (58), hurdles (60 cm) with BJ (347), hurdles (height not recorded) with single-leg forward hops and alternate leg bounding (326), single-leg CMJ, BJ and DJ (height not recorded) (394), lightweight resistance training, CMJ and change-of-direction drills (325) or programmes including box, bounding, mini hurdles and DJ (40 cm) (224,226).

Secondary acceleration

Only a few authors investigated secondary acceleration, with most groups exhibiting significant improvements across the 10 – 20 m split (n = 3; ES = 0.69 – 1.63). Very large and large effects resulted from BJ and CMJ, respectively, while CMJ, resistance training and change-of-direction resulted in a moderate ES (325). In contrast, one author reported no change for one group undergoing a largely cyclic programme involving hurdles (20 – 40 cm) and single leg jumps (n = 1; -0.01 s; ES = 0.12) (154).

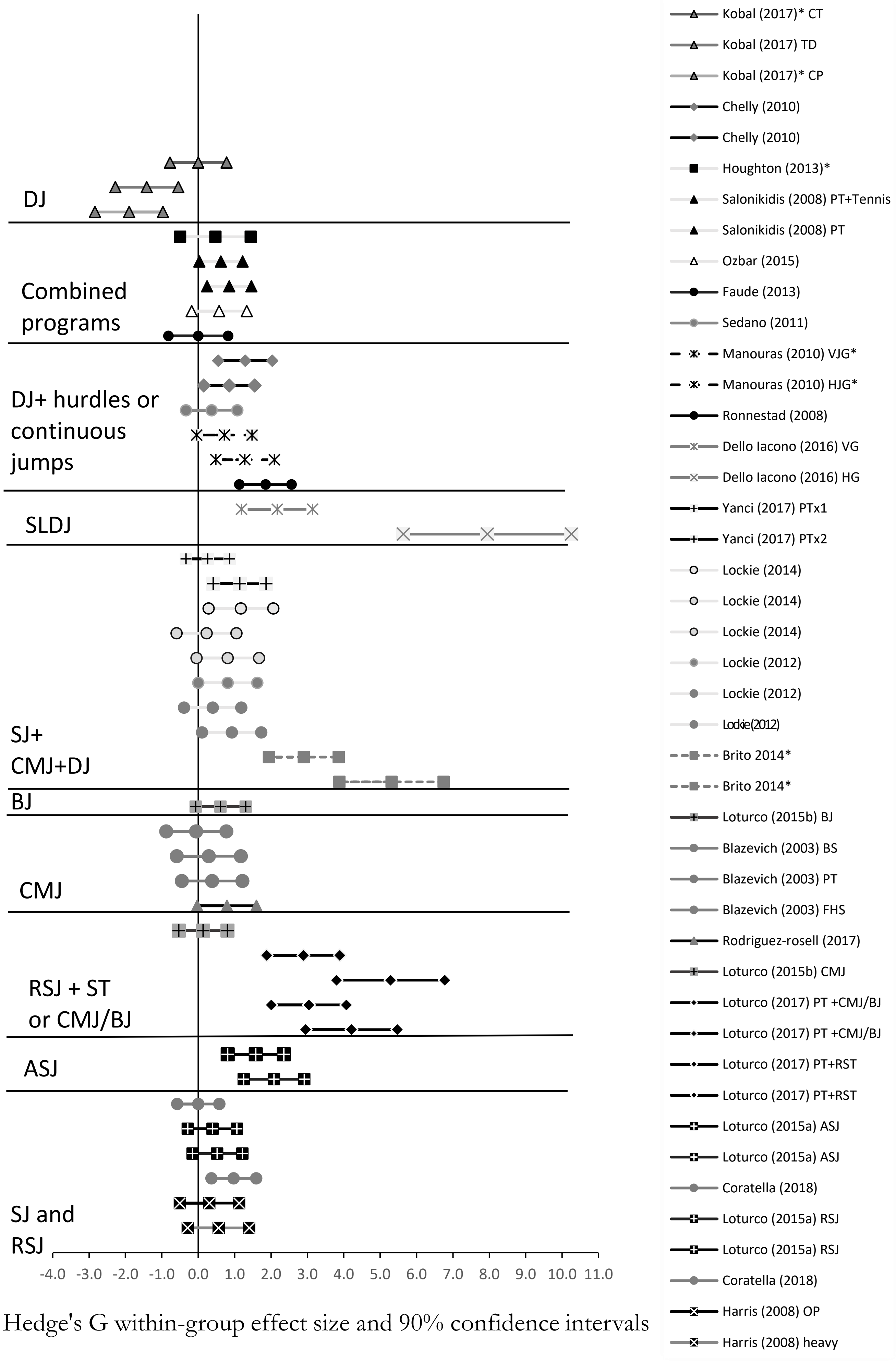

DJ
Combined programs
DJ+ hurdles or continuous jumps
SLDJ
SJ+ CMJ+DJ
BJ
CMJ
RSJ + ST or CMJ/BJ
ASJ
SJ and RSJ
-4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0
Hedge's G within-group effect size and 90% confidence intervals
Kobal (2017)* CT
Kobal (2017) TD
Kobal (2017)* CP
Chelly (2010)
Chelly (2010)
Houghton (2013)*
Salonikidis (2008) PT+Tennis
Salonikidis (2008) PT
Ozbar (2015)
Faude (2013)
Sedano (2011)
Manouras (2010) VJG*
Manouras (2010) HJG*
Ronnestad (2008)
Dello Iacono (2016) VG
Dello Iacono (2016) HG
Yanci (2017) PTx1
Yanci (2017) PTx2
Lockie (2014)
Lockie (2014)
Lockie (2014)
Lockie (2012)
Lockie (2012)
Lockie (2012)
Brito 2014*
Brito 2014*
Loturco (2015b) BJ
Blazevich (2003) BS
Blazevich (2003) PT
Blazevich (2003) FHS
Rodriguez-rosell (2017)
Loturco (2015b) CMJ
Loturco (2017) PT +CMJ/BJ
Loturco (2017) PT +CMJ/BJ
Loturco (2017) PT+RST
Loturco (2017) PT+RST
Loturco (2015a) ASJ
Loturco (2015a) ASJ
Coratella (2018)
Loturco (2015a) RSJ
Loturco (2015a) RSJ
Coratella (2018)
Harris (2008) OP
Harris (2008) heavy

Figure 3.2. Within-group effect sizes and 90% confidence intervals for plyometrically-trained groups using various exercises across acceleration (0 – 10 m). DJ = drop jump; Combined designates programmes with more than five exercises; SLDJ = single-leg DJ; SJ = squat jump; CMJ = countermovement jump; BJ = broad jump; RSJ = resisted SJ; ST = sprint training; ASJ = assisted SJ; * = significant decrease ($p < 0.05$).

Maximal velocity phases

Significant improvements were also reported for 0-20 or 0-30 m (n = 18; ES = 0.26 – 2.80), and 35-50 m (n = 8; ES = 0.40 – 1.20). Only a few authors investigated distances greater than 50 m (n = 2; ES = 0.52 – 1.48), RSA (n = 4; ES = 1.00 – 3.43) or linear sprints with change of direction (n = 8; ES = 0.37 – 5.5). 0 – 20 or 0 – 30 m (n = 1; -0.17 s; ES = 0.26 – 0.44), or repeated sprinting assessments (n = 2; ES = -0.14 to -0.25). Lastly, one study reported significant and non-significant decreases in performance using combined plyometric and resistance training (ES = -0.08 to -1.86) (185). For 20 – 30 m distances, large ES were reported from a number of programmes using assisted SJ (230), SJ, CMJ, and DJ (60 cm)(44), double- and single-leg multidirectional hurdles (40 – 60 cm) (293), or mixed programmes using cyclic and acyclic horizontal and vertical jumps (272,318). Moderate ES were reported for programmes using resisted SJ (66,230), resisted SJ, CMJ and BJ (228), CMJ-only (231), CMJ, change-of-direction and sprint training (325), multidirectional hurdles (294) or mixed programmes using cyclic and cyclic exercises (122). For distances over 35 m, the majority employed cyclic exercises, some authors reporting large and very large ES using ankle POGOS, speed marching, skipping, and JS (7), DJ (40 cm) and hurdles (40 – 60 cm)(58), or assisted CMJ and resistance or eccentric training (65). Moderate ES for distances over 35 were reported with two programmes involving mixed cyclic and acyclic exercises (326,383).

3.3.4. Volume load

Session volume

Session volume did not appear to have a significant effect on programme efficacy so long as overall volume load was monitored appropriately. Within-group ES for initial acceleration (including all splits) in order of session volume are presented in Figure 3.3 for acceleration and in Figure 3.4 for maximal velocity phases.

3.4. Discussion

3.4.1. Main findings

The purpose of this review was to identify key plyometric training variables and the proper manipulation thereof for improving sprint performance. The main findings of this systematic review were: i.) athlete characteristics dictate the rate and magnitude of adaptation; ii.) programme effectiveness is largely affected by volume load, by which optimal exercise choice may differ by target distance; iii.) lower volumes than previously established can be very effective in trained athletes. The findings of this systematic review suggest that athlete characteristics, loading strategies and exercise choice influence the effectiveness of plyometric training for improving sprint performance.

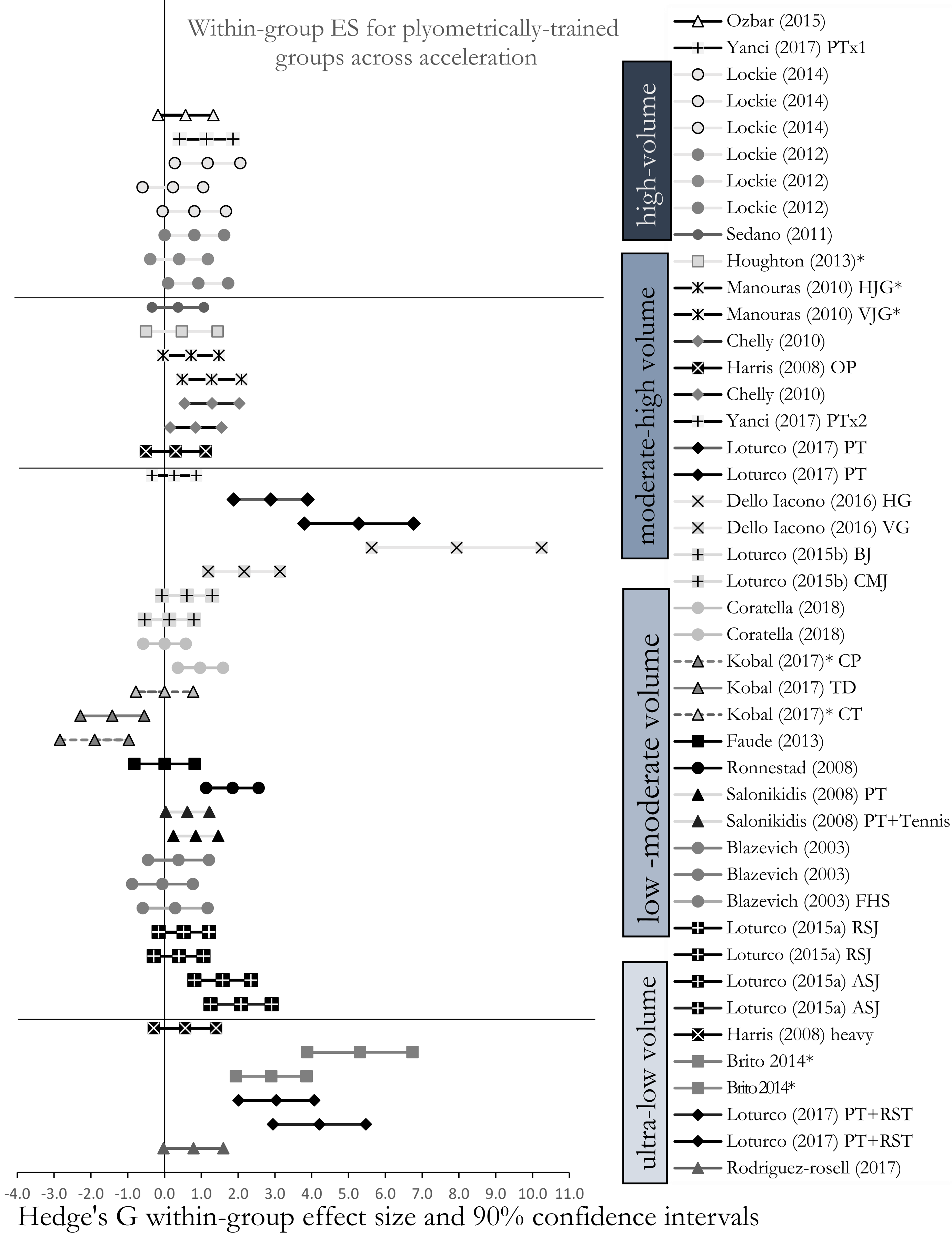


Figure 3.3. Within-group ES for plyometrically trained groups in order of session volume across acceleration (0-4, 0-5, 5-10, 0-10 m). Lines differentiating ultra-low, low-moderate, moderate-high and high-volume programmes approximately. * = not significantly different pre-post assessments ($p > 0.05$). very-low volume < 36 GC; low- moderate = 20 – 80 GC (with one programme including a few sessions up to 108); moderate – high = 50 – 160 GC; high volume = 90 – 368 GC.

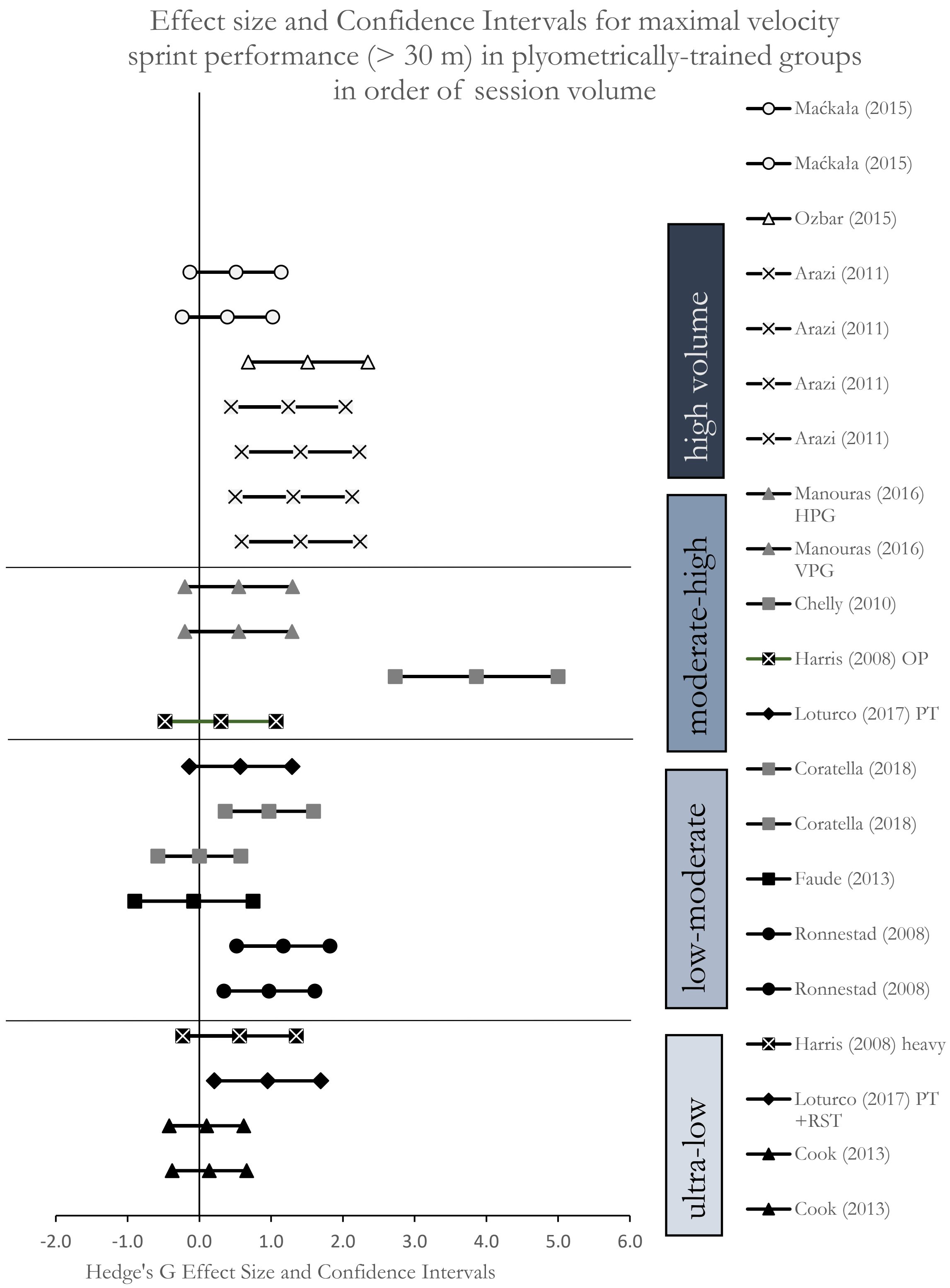


Figure 3.4. Within-group effect sizes for plyometrically-trained groups for maximal velocity phases (>30 m); very-low volume < 36 GC; low- moderate = 20 – 80 GC (with one programme including a few sessions up to 108); moderate – high = 50 – 160 GC; high volume = 90 – 368 GC.

3.4.2. Inter-study analysis

This systematic review reiterates the positive impact plyometric training can have on athletes for improving sprint performance. For effective programming, however, accurate and comprehensive reporting of modifiable variables is crucial for inter-study analysis, reproducibility, and practical applications. Unfortunately, a sizable contingent (n = 8) of studies in the current review investigated only single-distance metrics, limiting our understanding of those specific loading strategies across the entire force-velocity spectrum. Moreover, several studies included in this review lacked important information pertaining to one of the following variables: drop height, inter-session rest, intra-session rest, total volume reported as GC rather than minutes, exercise order or exercise descriptions. Inappropriate loading strategies for any training stimulus (i.e., strength training, cycling) are not likely to prompt adaptation, yet this speaks less to the modality itself and more to the quality of loading. The absence of this information, therefore, restricts our ability to differentiate between plyometric training efficacy and inappropriate loading strategies. Thus, future research investigating PT for improving sprint performance should consider including multiple distance analysis and ensure all possible modifiable variables are reported accurately.

3.4.3. Athlete characteristics

Nevertheless, this review demonstrates athlete characteristics may play an important role in determining the rate and magnitude of adaptation. Strength, movement competency, training experience, load tolerance and previous injury are all important considerations for determining an optimal plyometric programme (168,366). For example, two-three weeks using combined (plyometric + resistance + Sprint) methods was sufficient time to prompt small and large positive shifts in sprint performance for trained sprinters (236) and strong semi-professional rugby players (65). In contrast, college athletes with limited jump training experience, may require more conservative loading strategies to elicit significant benefits (4,44,347). Sedano et al. (347) illustrates the time-course of adaptation in elite young (>18 years) soccer players wherein a programme including hurdles and broad jump exercises (80 – 130 GC.session^{-1}) prescribed thrice weekly for ten weeks resulted in small ES following six and eight weeks and moderate ES after ten weeks. Interestingly, programme length requirements may be attributed to relative strength differences in already strong athletes (2.0 vs 1.2 kg.bm^{-1}), which can affect the magnitude and speed of velocity-based adaptation from the same programme (168). This may also partially explain the similar sprint improvements between low-volume plyometric programmes, combined (plyometric + resistance training) (36,44), resistance training-only or weightlifting (i.e., clean and jerk) strategies (272) in strength-trained (1.0 x kg.bm^{-1} back squat 1RM) collegiate and U-19 athletes. Less experienced athletes may benefit from increasing general strength qualities garnered through several methods, yet there comes a point where increases in maximal strength may no longer yield tangible improvements to sprint performance (391). In these cases, more experienced athletes may benefit additionally from plyometric training or other methods which preferentially target faster, more explosive muscle fibres by influencing their velocity-based characteristics (245,246). Distinctly, this review suggests well-trained athletes typically benefit most from combining plyometric training with either traditional resistance, eccentric, or sprint training or some combination thereof (44,60,65). However, different iterations of exercises may interfere with the adaptive process (31,185), while more load (i.e., volume or frequency) is not always better (241,395). Therefore, when combining plyometric and resistance training, practitioners may want to consider athlete strength, experience and alternate training with respect to exercise order, training frequency and programme duration (185).

3.4.4. Volume load

Volume load was found to be a primary determinant of programme efficacy, with specific emphasis on intensity and exercise choice. The majority of articles in the current review implemented short-term high-intensity plyometric training (27,34,58,185,236,317,318,336,347,360,384,394), moderate intensity non-depth (i.e., SJ, CMJ, BJ) plyometrics using constant and variable load methods (36,65,66,131,228,230,231,247,375), or chronic periods using progressively-increased intensity programmes (122,126,336), where initial exercises are low intensity and throughout the weeks, exercises and intensity were progressed. Very few cases implemented primarily low-intensity programmes except in some endurance athletes (120,298), collegiate athletes with entry-level sport experience (44,272) or trained athletes with no prior RT experience (7,154). Notably, these programmes implementing limited volumes (36,44,66,102) or low-intensity programmes (154,336) were likely to report mostly non-significant effects, pre – post changes, or between-group differences. As an example, Coratella et al. (66) reported moderate improvements to T-test, 10- and 30-m times following loaded, but not bodyweight JS or non-exercise control groups, citing inadequate eccentric loading as the primary factor. Interestingly, one author demonstrated how properly managed volume loads using primarily low-intensity high-volume continuous protocols can result in very large improvements in maximal velocity for semi-professional athletes with a limited RT background (7).

3.4.5. High intensity exercises

Substantial literary evidence demonstrates SSC and MTU interaction depend on the magnitude and rate of loading, wherein the exercise, drop height, touchdown velocity, rebound time, load distribution and number of contacts in sequence will determine the resulting adaptation (162,165,217). As such, dynamic systems theorists argue optimal exercise choice may differ by target distance due to kinetic and kinematic differences across sprint phases. In the current review, the most commonly prescribed DJ and hurdle heights ranged from 40 – 60 cm, where the majority of studies reported moderate – very large training effects, with the greatest influence on maximal velocity phases (44,100,122,139,224,226,241,247,293,294,347,383). Modern-day research suggests high-intensity DJ exercises (75% and 125% CMJ height) are associated with a greater elastic response and pre-activation levels than non-stretch jumping actions (i.e., CMJ and SJ) which is likely to benefit high-velocity sprinting phases due to rapid force transmission demands (17,253). Likewise, multiple-repetition hurdle exercises using heights of 100 – 140% CMJ consist of similar kinetic properties (Peak vertical GRF = 2.9 – 5.5 $N{\cdot}bw^{-1}$ vs. 2.7 – 5.5 $N{\cdot}bw^{-1}$) and GCT (0.178 – 0.190 s vs. 0.115 s – 0.227 s) as maximal sprinting, indicating a high level of transference (52,170,209,260). While no studies in the review included heights above 60 cm, extreme-height DJ (72 – 84 cm) performances have previously been found to be the best predictor of 0 – 10 m (r = -0.66), 10 – 30 m (r = -0.86), and 30 – 60 m (r = -0.86) split times in rugby union athletes, suggesting the greater tendon stretch during high-intensity DJ exercises may stress the MTU similarly to high-velocity sprinting (24). In comparison, short-contact DJ (< 250 ms) may not optimize elastic recoil, yet shorter GCT result in high levels of pre-contact muscle activation, stretch reflex stimulation and faster conduction velocities than more extreme heights (17,24,165,215,366). This may partially explain why single-leg DJ varieties (~20 – 25 cm), particularly in the horizontal direction, offer specific benefit to increase step length and greatly improve acceleration speed during similar durations (157,394).

Ultimately, the optimal height will vary significantly based on athlete characteristics and maximal strength (251). However, some authors suggest heights less than 20 cm and greater than 80 cm may not be preferential for motor unit recruitment and reactive strength (3). Determining individualised optimal drop heights by determining the height before which RSI decreases and GCT increases is becoming increasingly popular with some authors reporting greater contraction velocities at optimum heights than compared to just ~10 cm above (342). Although, these increases in short-contact DJ drop height are not without increases in GRF and eccentric stress (348). Importantly, unfavourable increases in GCT previously seen in periodized extreme-height DJ training (366) may result from a pre-stretch intensity relative to the participants' lack of experience with SSC shock absorption, rather than the absolute height. Stretch rates beyond mechanical capabilities have been shown to invoke protective movement strategies, increased Golgi tendon innervation, and/or mechanical failure (165). However, long-contact (>400 ms) DJ may influence braking phase times and tendon shortening velocities (358). Therefore, it seems high-intensity stretch-inducing plyometrics are beneficial so long as induced stress does not go beyond the athlete's MTC mechanical threshold. Additionally, practitioners may want to consider load specific adaptations, whereby short-contact times (< 250 ms) may preferentially stimulate stretch reflexes and decrease GCT. For example, single leg DJs may specifically target step length and acceleration performance, and long-contact (>400 ms) or higher drop heights (40 – 60 cm) high-intensity double-legged varieties , may primarily improve maximal velocity phrases through tendon and elastic recoil adaptations.

3.4.6. Moderate intensity exercises

As opposed to high-intensity depth-based plyometrics (i.e., exercises which involve a significant falling depth), the current review suggests that moderate-intensity, non-depth exercises (i.e., those starting on the ground like SJ, BJ, CMJ) were typically more effective at improving acceleration, with varying results for resisted, assisted and variable loading strategies (66,228,230,231). In line with previous research, this review suggests horizontal exercises may better translate to initial acceleration, while vertical exercises may preferentially improve transitional and approaching maximal velocities (231). Although, in some cases low volume (60 – 110 GC.week^{-1}) programmes of these exercises alone were not enough to stimulate significant changes in acceleration performance (36,66,247). The results suggest that loaded SJ can be a viable solution for managing load. However, since similar results arise from light (20 – 45% 1RM) and heavy (>80% 1RM) methods leave optimal loading scheme is still up for debate (66,131). However, caution is advised for protocols aimed at decreasing mean propulsive velocity to a large extent (~20%), as specific neural adaptations (e.g. motor unit activation and firing rate) may require greater movement velocities (328). In contrast, assisted or overspeed SJ and CMJ, or those which increase maximal velocity above bodyweight variations may better facilitate rapid contraction dynamics, resulting in large sprint adaptations across a wide array of distances (65,230).

3.4.7. Volume

While previous literature gives ample support for higher intensity plyometrics, increased volume programmes reveal mixed results. Studies in the current review including low (20 – 60 GC.session^{-1}), moderate (60 – 150 GC.session^{-1}) and high (150 – 230 GC.session^{-1}) volume sessions were found to be effective for improving sprint performance. However, high volume programmes often resulted in small – moderate ES, while many low-volume (8 – 60 GC.session^{-1}) moderate – high intensity protocols prompted moderate – very large ES when properly managed or paired with alternate training (65,66,131,157,230,231,325). Notably, studies reporting little or no sprinting improvement tended to include very-low (~25 GC.session^{-1}) or very-high volumes (~200+ GC.session^{-1}) indicating improper loading (36,102,154,336). In some cases, very-trained sprinters may require high volumes over short periods to elicit even small adaptations (236). In the same manner, low-intensity programmes required much greater volumes (162 – 368 GC.session^{-1}) over chronic periods (10 – 12 weeks) to stimulate significant returns (7,272). Acute analysis of training volumes (i.e., 100, 200, or 300 hurdle jumps) indicates similar systematic stress from different volumes is not likely to incite vastly different performance benefits in elite male rugby players post-exercise (49). Similar results can be found from RT protocols using different velocity loss thresholds, while high and low volume programmes frequently report comparable adaptations post-training, indicating less volume achieved all at greater velocities may be superior (173,295,296). Furthermore, chronically increased stress levels increase the tendency to overwork the MTU, decrease performance and increase the required stimulus threshold for future adaptations (75). Therefore, sufficient evidence exists for the inclusion of low-volume plyometric training in athletes. Such predominance further warrants the need to investigate the most efficient dose-response in elite athletes for optimal speed and acceleration adaptation, and maintenance. However, maturity levels, training status and loading capacity are all highly likely to affect heightened volume efficacy, highlighting the need for future research to evaluate dose repose of plyometric training in elite athletes.

3.5. Practical Applications

In conclusion, external resistance, drop height, stretch rate, and other exercise parameters vastly change joint-specific mechanical demands, physiologically loading response and elastic potentiation during SSC exercises. Strength and conditioning coaches can manipulate plyometric exercise variables specific to the desired neurophysiological response in a progressive manner. The SSC system recognises the greatest performance benefit in experienced populations during high-intensity plyometric programmes via hurdles (>100% CMJ maximum height) DJ (40 – 60 cm or >75% CMJ height), or the alteration of load (i.e., assisted protocols with +20% mean propulsive velocity). Additionally, non-depth exercises and SLDJ variations may be more apt to improving acceleration, while high-intensity DJ and hurdles prompt superior benefit to maximal velocity phases. Including exercises emphasising horizontal force production are important for realising functional improvements in FV expression during sprinting and accelerative efforts. Lastly, there is increasing support for including low volumes (25 – 60 GC.session^{-1}) of moderate – high intensity exercises during prolonged training periods to optimise training efficiency for the purposes of increasing speed and acceleration in elite athletes.

Section II – Acute analysis of performance determinants, force-velocity profiles, adaptation rates, and dose response.

Chapter 4 – Force-velocity profiles of rugby union players: A competition-level and position-specific analysis.

Reference

Watkins, CM, Storey, AG, McGuigan, MR, and Gill, ND. Horizontal force velocity power profiling of rugby players: A cross-sectional analysis of competition-level and position-specific movement demands. *J Strength Cond Res* 35(6): 1576–1585, 2021.

Author contribution

Watkins CM, 85%, McGuigan MR 5%, Storey AG 5%, Gill, ND 5%.

4.0. Prelude

Collective analysis of published literature resulted in several key findings which were investigated acutely in the following section. Published literature has demonstrated numerous physiological and functional benefits pertinent to rugby players in all positions (29,157,373,377) (Chapter 2). Moreover, a systematic analysis of plyometric programme efficacy highlighted numerous variables for consideration (Chapter 3). Most notably, both low- and high- volumes were effective in eliciting sprint adaptations. However, programmes reporting insignificant, trivial, or negative adaptations likely implemented inappropriate volume loads. Interestingly, most programmes that reported substantial ES utilised moderate – high intensity programmes. Although, optimal exercise choice appeared to differ by target distance. These results suggest more information on position-specific sprint demands was necessary for optimal exercise prescription.

Previous GPS analysis of running profiles has demonstrated significant differences across rugby positions in their ability to express force and velocity, yet more clarity is required to better understand the magnitude of these differences (178,309). While speed and acceleration are important to all positional groups, these distinct running and tactical demands may dictate specific sprint profiles that are best suited (45,356). These profile characteristics serve to better inform current practice for appropriate plyometric manipulation to address position-specific demands. However, there is limited research investigating sprint profile attributes across specific positional groups. As such, further studies investigating force-velocity profiles to better target relevant adaptations across positional groups.

4.1. Introduction

Speed and acceleration qualities are pivotal to competitive success in rugby union (144). Specifically, GPS analyses reveal professional rugby players cover 4,500 – 7,500 meters per game, with large discrepancies between positions in absolute high-speed running distance (HSRD; ≥ 4 $m.s^{-1}$, 14.4 $km.h^{-1}$), work-to-rest ratios and high-intensity static exertions (83,86,178). Most notably, backs players sprint longer distances per bout and cover more total distance at very high speeds (>8 $m.s^{-1}$, 28 $km.h^{-1}$), with a primary focus on gaining territory, and scoring points (309). In contrast, forwards generally cover more distance at slow-moderate speeds (2 – 4 $m.s^{-1}$, 7.2 – 14.4 $km{\cdot}h^{-1}$) contesting for possession during frequent rucks, scrums, and tackles (86,309). However, there seems to be no difference in the number of accelerations, decelerations, or the relative percentage of distance spent striding and sprinting (31 – 34%) between forwards and backs, validating the importance of speed and acceleration to all positions, albeit to differing degrees (309).

Forwards encompass tight-5 (no. 1 – 5) and loose forwards (no. 6 – 8), while backs players consist of inside (no. 9 and 10), mid-field (12 and 13), and outside (11, 14, and 15) backs players. Specifically, the tight-5 are the main drivers of the scrum and are primarily responsible for high-intensity contact actions including rucks, mauls and lineouts (83,309). On the other hand, previous literature portrays loose forwards' running patterns as more akin to half-backs than other forwards positional groups (178,309). For example, both loose forwards and half backs exhibit similar player loads, moderate to high-speed running distances (3.8 – 5 $m.s^{-1}$:140 m vs. 155 m; >5.6 $m.s^{-1}$: 112 – 268 m vs. 177 – 253 m), mean (9.1 – 15.5 m vs. 12.8 – 19.1 m) and maximum sprint (29.4 m vs. 40.2 m) distances, yet loose forwards are required to perform contact actions twice as often (38 vs. 19) with less recovery time (~35 s vs. ~80 s) highlighting key tactical nuances (94,178). Across the back line, inside backs handle and pass the ball most frequently and have the highest kicking loads (83,309), while inside (11 ± 4) and mid-field (9 ± 4) backs typically perform a greater number of tackles than outside backs (6 ± 3)(94). For sprint performance, mid (20 ± 6 sprints) and outside backs (20 ± 7 sprints) typically complete the greatest number of sprinting bouts (inside backs: 12 ± 5 sprints; loose: 10 ± 6 sprints; tight: 4 ± 3 sprints), while outside backs perform the greatest mean (3.84 s vs. 2.01 – 2.53 s) and maximum sprint duration (9.00 s vs. 5.92 – 6.93 s) compared all other positional groups (83,94,178). These strategic roles direct the expression of acceleration and maximal speed during matches, thereby guiding the training prescription to fit the specific positional needs.

An important consideration underpinning athletic performance is the interaction between an athlete's force and velocity capabilities (176,352). All athletes naturally exhibit the same fundamental force-velocity (FV) relationship, whereby movement speed influences their potential for force generation. While force output improves with movement speed during eccentric (muscle lengthening) actions, the same is not true for concentric (muscle shortening) actions (349). The speed of muscle fibre shortening is limited by load, slowing as the demand for force increases to allow more time and availability for cross-bridge cycling (303,349). What differentiates athletes is the magnitudes of their individual FV profile, and more importantly, their ability to express FV qualities during sport-specific activities (81,310,357). For example, rugby players with similar maximal velocities could differ in how quickly they accelerate over 10 m or their ability to transition to faster velocities, resulting in functional on-field playing performance differences (81,177,279). Delivering the same training programme for athletes with disparate FV characteristics may fail to appreciate individual athletic characteristics. As such, coaching staff often use individualized training approaches to accommodate for the specific strengths and weaknesses of each player with respect to their position-specific needs (279).

Recent technological advances enable strength and conditioning coaches to calculate FV and power-velocity relationships from a simple maximal sprint assessment, using spatiotemporal data from radar or timing gates (280,338). These relationships portray an athlete's mechanical strengths, weaknesses, and play a primary role in regulating maximal sprinting speed (264). Accordingly, there has been a recent expansion in horizontal FV profiling investigations across a wide variety of sports including rugby (73,134,175), American football (81), soccer (135,176) and track athletics (362). These studies highlight how tactical demands can affect FV expression across different Olympic sports (134), between sprinters and hurdlers (362), rugby codes (45,73), club-level forwards and backs (45), as well as discriminating between playing standard (135) and specific positional groups in soccer and American football athletes (81,135). However, little is known about the differences in sprint profiles between competition levels and specific positional groups within rugby union.

Therefore, the aim of the present investigation was to compare the horizontal sprint profiles between semi professional and professional rugby union players across different competition levels and positional groups. We hypothesised that sprint performance and FV profiles would improve from domestic to international level competition. Our second hypothesis was that significant differences in sprint performance and FV profiles would exist between positional groups due to unique tactical demands. Specifically, outside backs would have the greatest sprint velocity and least force-dominant profile, while tight-5 players would portray the reverse. Additionally, loose forwards would have similar maximal velocity characteristics to inside backs, but with a more force-dominant profile.

4.2. Methods

4.2.1. Experimental approach to the problem

A cross-sectional study design was implemented to examine the differences in the horizontal sprint profile between semi professional and professional rugby union players across different competition levels and positional groups. Teams were tested in 2019 and 2020 in the lead up to the 2019 Rugby World Cup, or just following. Testing occurred during their respective competition's pre-season, either January or July. All testing procedures were in line with elite rugby testing protocols and collected as part of their pre-season athletic profile. All athletes were informed of the risks and benefits, prior to giving written informed consent. Auckland University of Technology Ethics committee approved this project.

4.2.2. Participants

Male rugby players (n = 176) volunteered for this study. Participants were included if they were over 18 years of age, injury-free, and currently competing in one or more of New Zealand's rugby union leagues: amateur club, Mitre 10 (semi-professional), or Super Rugby (professional) competitions. Additionally, rugby players were included if they participated in a World Rugby Tier 1 or Tier 2 international team competing at the 2019 Rugby World Cup. As such, the international group consisted of one Tier 1 and one Tier 2 World rugby teams, while professional and club athletes were collated from multiple New Zealand franchises. Participants were categorized into three competition-level groups: international (n = 53), professional (Super Rugby + Mitre 10 competitions; n = 47), and club (n = 76) (Table 4.1). In some cases, participants competed in two competition levels simultaneously (e.g. Super Rugby and international) or had elevated their competition status between assessments and had tested for both teams. In those cases, participants were categorised into their highest level of competition group at the time of testing and deleted from the lower-level competition sample, such that they only represented one data point. For example, Super Rugby players who were also contracted for their international team were only included as an international-level player only. Participants were also categorized into five positional groups within each respective competition level: tight forwards (n = 63); loose forwards (n = 35); inside backs (n = 29); mid backs (n = 22); and outside backs (n = 27). The specific positional make-up is as follows: props (no. 1 and 3; n = 32); hookers (no. 2; n = 16); locks (no. 4 and 5; n = 15); flankers (no. 6 and 7; n = 29); no. 8 (n = 6); scrum halves (no. 9; n = 16); flyhalves (no. 10; n = 14); wings (no. 11 and 14; n = 13); centers (no. 12 and 13; n = 21); fullbacks (no. 15; n = 11); utility outside backs (no. 11, 14, and 15; n = 3).

Table 4.1. Competition descriptives. Data presented as means ± 95% CI *= significant difference between international and professional ($p < 0.001$); $^{\phi}$= significant difference between international and club ($p < 0.001$); $^{♀}$= significant difference between professional and club (age = $p < 0.001$; mass = $p< 0.05$; height = $p <0.01$).

	International (n = 53)	Professional (n = 47)	Club (n = 76)
Age (years)	27.3 ± 1.0$^{*\phi}$	23.3 ± 0.9$^{*♀}$	20.1 ± 0.7$^{\phi ♀}$
Mass (kg)	107.3 ± 3.8	107.9 ± 3.2$^{♀}$	102.7 ± 3.2$^{♀}$
Height (m)	1.9 ± 0.0	1.9 ± 0.0$^{♀}$	1.8 ± 0.0$^{♀}$

4.2.3. Testing procedures

Sprint profiling

Upon arrival, athletes underwent height and body mass measurements using a portable stadiometer (SECA 216, Germany) and weight scale (SECA 876). Prior to warm-up, athletes were given five minutes of individual prep followed by a standardized general dynamic warm-up given by the team's head strength and conditioning coach, ending with stride outs of increasing intensity. Sprint performance was then measured across 30 metres with radar (Stalker ATS 5.0, Texas, USA) and dual beam infrared timing gates (Swift Performance, Lismore, Australia). To comply with elite testing protocols, a subset of tight players across professional and international groups (n = 11) were instructed to only run 20 m. In these instances, these players were removed from maximal velocity characteristic analysis, appropriate sample sizes are reported in these instances below.

The radar system was set up three metres behind the first timing gate pair, with a tripod height of one metre, positioned approximately at their lumbosacral joint. The radar gun was positioned directly in line with the sprinting direction to reduce any error from measurement angle. To keep in line with the competitive agenda of elite testing, the Tier 1 World Rugby team requested the radar be set up ten metres behind the start line, potentially improving linearity of radar and reducing initial noise (352). However, to the author's knowledge there has not been any published literature directly supporting this and this distance was not possible at all venues. Various distances (1.5, 3, 5, and 10 m) have been reported and comparisons made without bias, thus three metres was used for all other teams (210,289,327). Timing lights were set one metre apart at 10, 20, and 30 metres from the first timing light pair. Participants lined up at the start line in a two-point split stance 50 cm behind the first set of timing gates. The radar system was initiated via a laptop prior to the start of any movement. Participants were then instructed to be still for approximately one second and without using a countermovement, sprint as fast as they could past the last set of timing gates before slowing down. Cones were set out five metre intervals behind the last set of timing gates to discourage premature deceleration. Participants completed two successful trials with three minutes rest in between trials.

Data processing and analysis

Sprint times were recorded directly from timing gates during the maximal sprint assessments. To characterise increasing sprint velocity (SV), the average SV for each 10-m distance (0 – 10 m, 10 – 20 m, and 20 – 30 m) was calculated. Specifically, the 10-m split time in seconds (0 – 10 m, 10

– 20 m, and 20 – 30 m time) was divided from 10 in accordance with previous methods (25). Each average SV (SV0-10, SV10-20, and SV20-30) was then multiplied by the athlete's body mass to calculate average sprint momentum (SM) across those distances (SM0-10, SM10-20, and SM20-30). For maximal velocity (Vmax) and accompanying FV variables (Table 0.1), raw distance-time data files collected from the radar during two sprint assessments were rectified and the average of two trials was analysed using previously validated methods (352). For each trial, data points prior to the onset of movement above system baseline values (~0.7 $m.s^{-1}$), past the point of Vmax, and any erroneous data points outside the movement range were manually deleted. Trials were analysed via LabVIEW, using least-square regression linear and quadratic equations to determine the FV and power-velocity relationships. Theoretical maximum values for horizontal force (F_0) at zero velocity and velocity (V_0) at zero force were identified as the y- and x- intercepts of the extrapolated line (Table 0.1) (338). The slope of the FV relationship (S_{fv}) characterises the steepness or rate of decline in horizontal force production with increasing velocity ($S_{fv} = -F_0 \cdot V_0^{-1}$), with more negative values representing a more force-dominant athlete. The ratio of forces (RF) was calculated as the percentage of horizontal force to the resultant force at the peak, for the onset of movement (>0.2 m.s-1; RFpeak) and as distance increased to determine technical ability to maintain horizontal force during acceleration (RF2, RF5, RF10, RF15, and RF20) (Table 0.1). Dependent variables include split times (10-, 20-, 30-, 10 – 20 and 20 – 30 m), average SV and SM for all calculated distances (0 – 10 m, 10 – 20 m, and 20 – 30 m), peak and relative FV profile variables (Table 0.1), and RF (RFpeak, RF2, RF4, RF10, RF15, and RF20).

4.2.4. Statistical analysis

All statistical analyses were performed in SPSS. Data values are presented as estimated means, standard error, and confidence intervals (CI; 95%) unless otherwise stated. A one-way ANOVA was performed to identify differences in age, height, and mass between competition levels. A two-way mixed factor (competition level x position group) ANOVA was performed to determine differences in sprint performance and FV variables. Significance level was set at $p \leq 0.05$. For significant relationships, post-hoc analysis was then conducted to determine specific group differences and p-values were adjusted using the Fischer's LSD adjustment. Effect sizes (ES) were determined between groups according to Cohen's D where thresholds of <0.2, 0.2, 0.5, 0.8 correspond to trivial, small, medium and large ES (62). A sensitivity analysis was conducted in G*Power, using $\alpha = 0.05$, $\beta = 0.80$, and sample sizes ranging from 49 – 179. Results indicate the lowest detectable ES = 0.20 – 0.38, depending on sample size. Intra-class correlations (ICC) and coefficient of variation (CV) for repeated trials were calculated for reliability according to previous methods. Previously accepted thresholds for interpreting ICC results are: 0.20 – 0.49, 0.50 – 0.74, 0.75 – 0.89, 0.90 – 0.98 and ≥0.99 for low, moderate, high, very high and extremely high, respectively (147). For CV, values of ≤ 10% were considered small (32). Acceptability was determined for measures when ICC ≥ 0.75 and CV ≤ 10%, moderate when either ICC < 0.75 or CV > 10%, and unacceptable/poor when both ICC < 0.75 and CV > 10%.

4.3. Results

Reported split times and FV profile variables for each position split by competition are presented in Appendix 9 and Appendix 10. All sprint variables were deemed acceptable with ICC values for sprint times considered high (ICC = 0.92 to 0.93, 90% CI = 0.89 to 0.95; CV = 1.3 to 1.5, 90% CI = 1.1 to 1.7) and FV variables considered high and very high (ICC = 0.79 to 0.96, 90%

CI = 0.73 to 0.97; CV = 1.7 to 9.7, 90% CI = 1.5 to 10.8). Significant differences occurred in age, with the average player age increasing with each competition level (Table 4.1; $p < 0.001$).

4.3.1. Split times

There were main effects for competition level across all time points (Figure 4.1; $p \leq 0.01$). Specifically, international and professional players had significantly lower (i.e., faster) split times than club players across all distances (10 – 20 m: -0.03 s; ES = 0.47 – 0.50; $p \leq 0.01$; all other distances: -0.06 to -0.10 s; ES = 0.70 – 1.42; $p < 0.001$), apart from 10-20 m where only professional players portrayed significantly lower times than club players (-0.02 vs. +0.00 s; ES = 0.30 vs. 0.04; $p = 0.023$ vs. 0.95; Figure 4.1). Compared to professional players, international players had significantly lower split times across 0 – 10 m (-0.03 s; ES = 0.44; $p = 0.03$), but greater 10 – 20 m split times (+0.02 s; ES: 0.37; $p = 0.01$; Figure 4.1). There were no significant differences between international and professional players for 0 – 20 m, 20 – 30 m, or 0 – 30 m split times (< 0.01 s; ES: 0.02 – 0.07; $p > 0.7$).

There were also main effects across positional groups ($p < 0.001$ in all cases; Figure 4.1). Tight-5 forwards had significantly greater times than all other positional groups across all distances (+0.05 to +0.36 s; ES: 0.93 – 2.48; $p < 0.001$). Loose forwards had significantly greater times than all backs groups across all distances (+0.05 to +0.18 s; ES: 0.92 – 1.36; $p \leq 0.001$ in all cases except inside backs, where +0.05 to +0.08 s; ES: 0.52 – 0.64; $0.016 \geq p \geq 0.05$). Inside backs had greater times compared to outside backs significantly (+0.03 to +0.10; ES: 0.43 – 0.82; $p \leq 0.016$ in all cases), and non-significantly compared to mid backs (+0.02 to +0.07 s; ES: 0.28 – 0.52; $0.067 \leq p \leq 0.097$). Mid backs portrayed greater times for all distances than outside backs, but the difference was not significant (+0.01 to +0.04 s; ES: 0.18 – 0.41; $p > 0.100$).

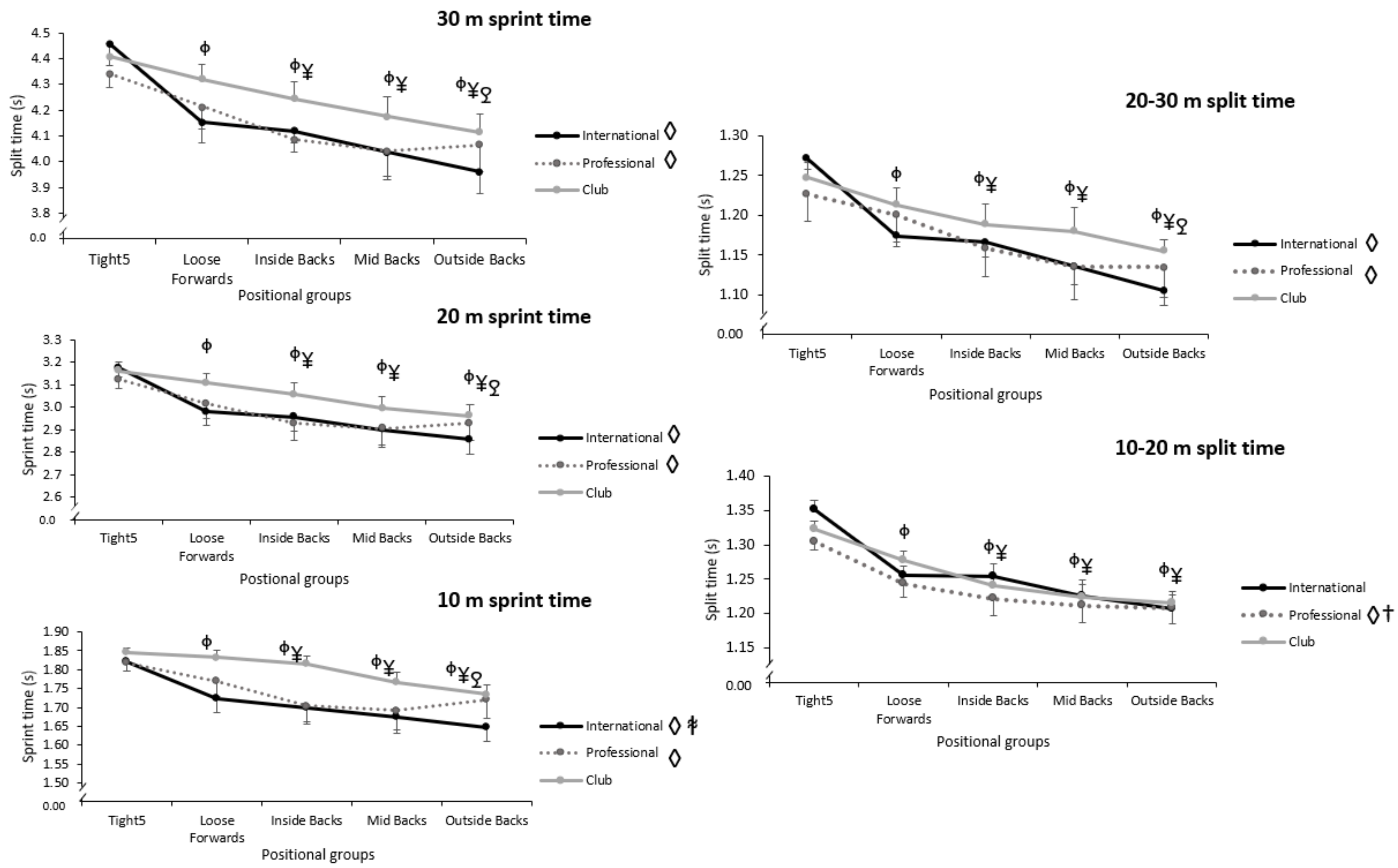


Figure 4.1. Sprint split times for competition and positional groups. Data represented as estimated means and 95% Confidence intervals. ◊ = less than club players (p< 0.001); ⱡ = less than professional players (p <0.05); † = less than international players (p < 0.05); ϕ = less than tight-5 players (p < 0.001); ¥ = less than loose forwards (p < 0.03); ϙ = less than inside backs (p < 0.02).

4.3.2. Sprint velocity and momentum

There were main effects across competition level for average sprint velocity and momentum for all calculated distances (0 – 10 m, 10 – 20 m, and 20 – 30 m; p <0.001 in all cases; Figure 4.2). Specifically, international and professional players portrayed greater average sprint velocities (ES = 0.96 – 1.46; p < 0.001 in all cases) and had significantly greater average sprint momentums across all distances than club players (ES = 0.67 – 1.10; p < 0.001 in all cases). International players had significantly greater SV0-10 (ES = 0.47; p = 0.015) than professional players, whereas the latter had significantly greater SV10-20 (ES = 0.51; p = 0.013). There were no differences for SV20-30. Additionally, there were no significant differences between international and professional players for any sprint momentum calculations ($p > 0.100$).

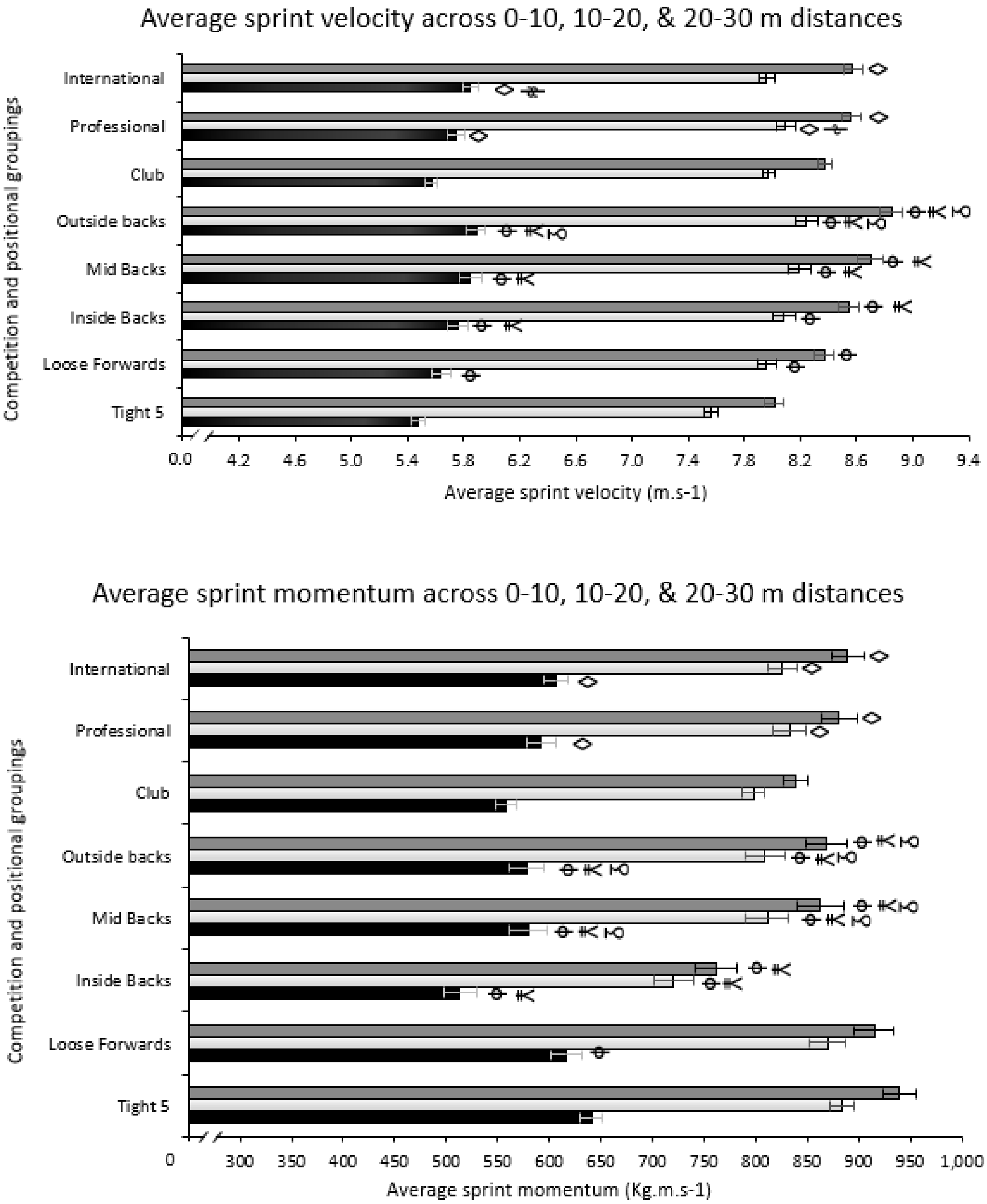


Figure 4.2. Average sprint velocity and momentum for competition and positional groups.
Data is presented as estimated means and 95% confidence intervals for 0-10 m (black), 10-20 m (light grey), and 20-30 m (dark grey) distances for competition levels and positional groups. ◊ = greater than club players ($p < 0.001$); ǂ = greater than professional players ($p < 0.05$); ƚ = greater than international players ($p < 0.05$); ᶲ = significantly different to tight-5 players ($p \leq 0.02$); ¥ = significantly different to loose forwards ($p < 0.02$); ϙ = greater than inside backs ($p < 0.02$). *Note - axes truncated to better portray sprinting performance (running fast defined as > 4 $m.s^{-1}$) between groups.

There were also main effects across positional groups, regardless of competition level across all sprint velocities and momentums ($p < 0.05$; Figure 4.2). Tight-5 forwards were significantly slower than all other positional groups across all distances (-0.16 to -0.83 m·s-1; ES = 0.91 – 2.35; $p < 0.001$) but had greater momentum for all distances than all other backs groups (+61.1 to +176.8 kg·m-1·s-1; ES = 0.91 – 2.97; $p < 0.001$). Additionally, tight-5 forwards had significantly greater SM0-10 (+24.0 kg·m-1·s-1; ES = 0.56; $p = 0.01$) than loose forwards, but not SM10-20 (+22.9 kg·m-1·s-1; ES = 0.32; $p = 0.09$) or SM20-30 (+24.4 kg·m-1·s-1; ES = 0.32; $p = 0.12$). Loose forwards were slower than all backs groups across all time points (-0.21 to -0.48 m·s-1; ES = 0.96 – 1.31; $p \leq 0.001$ in all cases except inside backs, where -0.12 to -0.18 m·s-1; ES = 0.53 – 0.61; $p \leq 0.05$) but had greater average momentum for all distances (+45.8 to +152.4 kg·m^{-1}·s^{-1}; ES: 0.66 – 2.33). Inside backs were significantly slower across all time points than outside backs (-0.13 to -0.30 m·s^{-1}; ES = 0.54 – 0.87; $p \leq 0.016$ in all cases), and approached significance compared to mid backs, (-0.09 to -0.15 m·s^{-1}; ES = 0.34 – 0.44; $0.067 \leq p \leq 0.097$). Mid backs and outside backs were not significantly different at any time point (mid: -0.04 to -0.15 m·s^{-1}; ES = 0.19 – 0.43; $p > 0.18$). Inside backs had significantly lower average sprint momentums across all distances than all other positional groups (-66 to -106.6 kg·m^{-1}·s^{-1}; ES = 1.35 – 1.50; $p < 0.01$).

4.3.3. Peak force-velocity profile values

There were main effects for competition levels for all FV variables (Table 4.2). Specifically, international and professional players had a significantly greater F_0, V_0, P_0, V_{max} and a more negative S_{fv} than club level players ($p < 0.01$ in all cases; Table 4.2). Professional players had significantly greater F_0, P_0, a more negative S_{fv} ($p < 0.001$ in all cases; Table 4.2), but similar V_{max} and V_0 than international players (+0.112 to +0.128 m·s^{-1}; $p = 0.08 – 0.17$).

Table 4.2. Force-velocity profile characteristics across competition and positional groups. Data presented as estimated means, with standard error and 95% confidence intervals. Symbols indicate significant difference between matched pairs for each vertical variable ($p < 0.05$).

	F_0 (N)	**V_0 ($m \cdot s^{-1}$)**	**P_0 (W)**	**S_{fv}**	**V_{max} ($m \cdot s^{-1}$)**	**F_{rel} ($N \cdot kg^{-1}$)**	**P_{rel} ($W \cdot kg^{-1}$)**	**S_{rel}**
International[1]	**845.7** (25.3)	**8.86** (0.06)	**1,857** (53)	**-96.9** (3.2)	**8.57** (0.05)	**8.21** (0.22)	**18.1** (0.5)	**-0.96** (0.03)
	(795.7, 895.8)	(8.76, 8.97)	(1752, 1961)	(-103.2, -90.5)	(8.47, 8.67)	(7.77, 8.64)	(17.2, 19.0)	(-1.02, -0.91)
	23	3	23	23	3	23	23	2
Professional[2]	**986.7** (29.2)	**8.98** (0.06)	**2,199** (61)	**-111.0** (3.7)	**8.73** (0.06)	**9.64** (0.26)	**21.5** (0.5)	**-1.11** (0.03)
	(929.0, 1044.4)	(8.86, 9.09)	(2079, 2319)	(-118.3, -103.7)	(8.62, 8.85)	(9.14, 10.15)	(20.5, 22.6)	(-1.17, -1.05)
	13	3	13	13	3	13	13	13
Club[3]	**753.5** (20.8)	**8.73** (0.05)	**1,638** (43)	**-86.9*** (2.6)	**8.47** (0.04)	**7.59** (0.39)	**16.6** (0.4)	**-0.90** (0.02)
	(712.5, 794.6)	(8.64, 8.82)	(1553, 1724)	(-92.1, -81.7)	(8.39, 8.55)	(7.23, 7.95)	(15.8, 17.)	(-0.94, -0.85)
	12	12	12	12	12	12	12	2
Tight-5[a]	**918.6** (22.0)	**8.31** (0.06)	**1,880** (46)	**-112.6** (2.8)	**8.02** (0.04)	**7.89** (0.19)	**16.2** (0.4)	**-0.99** (0.02)
	(875.2, 962.07)	(8.20, 8.42)	(1790, 1971)	(-118.31, -107.1)	(7.93, 8.11)	(7.51, 8.27)	(15.4, 17.0)	(-1.04, 0.94)
	ce	bcde	b	cde	bcde	bc	bcde	—
Loose[b]	**955.7** (31.4)	**8.73** (0.06)	**2,088** (65)	**-109.5** (4.0)	**8.51** (0.06)	**8.80** (0.27)	**19.2** (0.6)	**-1.03** (0.03)
	(893.8, 1017.6)	(8.61, 8.86)	(1959, 2217)	(-117.4, -101.7)	(8.39, 8.62)	(8.25, 9.34)	(18.1, 20.4)	(-1.10, -0.97)
	cde	ade	ac	cde	ade	b	a	—
Inside[c]	**771.3** (34.3)	**8.89** (0.08)	**1,717** (72)	**-86.8** (4.3)	**8.64** (0.07)	**8.71** (0.30)	**19.4** (0.6)	**-1.01** (0.04)
	(703.6, 839.1)	(8.75, 9.05)	(1576, 1858)	(-95.4, -78.2)	(8.51, 8.78)	(8.12, 9.30)	(18.1, 20.6)	(-1.08, -0.94)
	a	ae	be	cde	ae	a	a	—
Mid[d]	**833.2** (38.6)	**9.09** (0.09)	**1,887** (81)	**-92.2** (4.9)	**8.82** (0.08)	**8.47** (0.34)	**19.2** (0.7)	**-0.96** (0.04)
	(756.9, 909.5)	(8.92, 9.25)	(1728, 2046)	(-101.8, -82.5)	(8.67, 8.97)	(7.81, 9.14)	(17.8, 20.6)	(-1.05, -0.88)
	—	ab	—	cde	ab	—	a	—
Outside[e]	**831.0** (34.9)	**9.25** (0.08)	**1,919** (73)	**-90.2** (4.4)	**8.97** (0.07)	**8.53** (0.30)	**19.7** (0.7)	**-0.96** (0.04)
	(762.1, 900.0)	(9.10, 9.40)	(1775, 2062)	(-98.9, -81.5)	(8.83, 9.10)	(7.93, 9.14)	(18.4, 21.0)	(-1.03, -0.88)
	—	abc	c	cde	abc	—	a	—

There were also main effects across positional groups ($p < 0.001$ in all cases; Table 4.2; Figure 4.3) for all FV variables. Tight-5 forwards had significantly less V_0 and V_{max} values than all other positional groups ($p < 0.001$; Figure 4.3) and a more negative S_{fv} than all backs positions ($p < 0.001$; Table 4.2). Tight-5 forwards also demonstrated a greater F_0 than inside and outside backs, but a significantly less P_0 than loose forwards. Loose forwards had a significantly greater V_0 and V_{max} than tight-5 forwards, similar values to inside backs, and significantly less than mid and outside backs. Loose forwards had significantly greater F_0 and a more negative S_{fv} than all backs positional groups, and significantly greater P_0 than inside backs. Inside backs had a significantly lower V_0, V_{max}, and P_0 than outside backs, while mid backs were not significantly different to either backs positional group for any FV variable (Table 4.2).

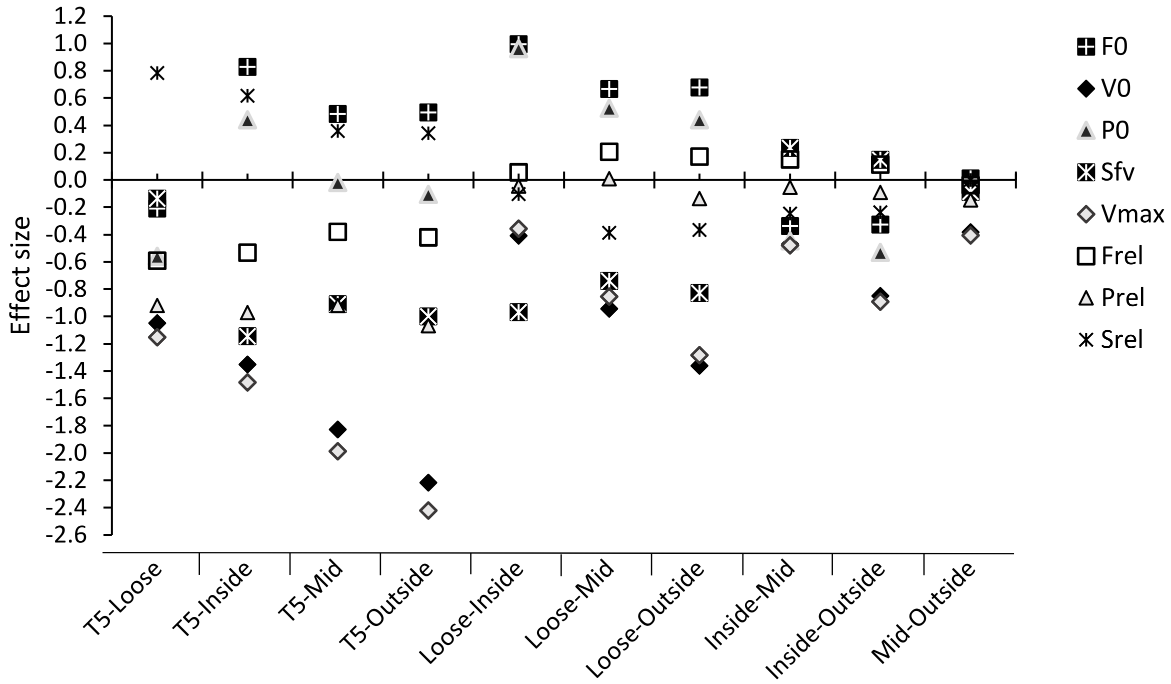


Figure 4.3. Cohen's D effect sizes for force-velocity profile variables across positional groups.
Effect sizes for force-velocity profile variables across positional groups. Comparisons denote significance ($p < 0.05$). T5 = tight-5 forwards; F0 = theoretical maximum force; V0 = theoretical maximum velocity; P0= maximum power; Sfv = the slope of the linear FV relationship; Vmax = maximal velocity achieved during the sprint assessment; Frel = relative maximum force; Prel = relative maximum power; Srel= relative slope.

4.3.4. Relative force-velocity profile variables

For relative FV profile values (S_{rel}, F_{rel}, and P_{rel}), there were main effects for competition level (Table 4.2; $p < 0.001$). Professional players had a greater S_{rel} (i.e., more negative), F_{rel}, and P_{rel} than both international and club players (ES = 0.71 – 1.42; $p \leq 0.001$), while international players had a greater F_{rel} and P_{rel} than trended to have a more negative S_{rel} than club players (ES = 0.22 – 0.43; $p = 0.077$).

There were also main effects for relative FV profile variables across positional group (Table 4.2) for F_{rel} ($p = 0.039$) and P_{rel} ($p < 0.001$) but not S_{rel} ($p > 0.100$). Tight-5 forwards had significantly less F_{rel} than loose forwards ($p < 0.01$; Figure 4.3) and inside backs ($p = 0.023$). Mid and outside backs were not significantly different from any position. For P_{rel}, tight-5 portrayed significantly lower values than all other positions ($p < 0.001$ in all cases).

4.3.5. Ratio of forces

There were main effects for competition for RF that varied based on distance. International and professional players had a significantly greater RFpeak than club players ($p \leq 0.01$), while professional players had a greater RFpeak than international players ($p = 0.01$). For RF2 and RF5, professional players had greater values than both international and club players ($p < 0.01$), while there was no difference between international and club. For RF10, international players were significantly less than club players, while neither were significantly different to professional players. For RF15 and RF20, club players were significantly greater than international and professional players ($p \leq 0.001$), while there was no difference between international and professional players.

Between positional groups, there were main effects that increased with distance ran (Figure 4.4). For all values (RFpeak, RF2, RF5, RF10, RF15, RF20), tight-5 forwards were significantly less than all other positions ($p \leq 0.10$). For RF5, outside backs also had significantly greater values than loose forwards ($p = 0.003$). For RF10, RF15 and RF20, outside backs also had significantly greater values than loose forwards ($p < 0.001$), inside ($p \leq 0.015$) and mid backs ($p \leq 0.05$). Additionally, for RF15 and RF20, mid backs had significantly greater values than loose forwards ($p < 0.04$; Figure 4.4).

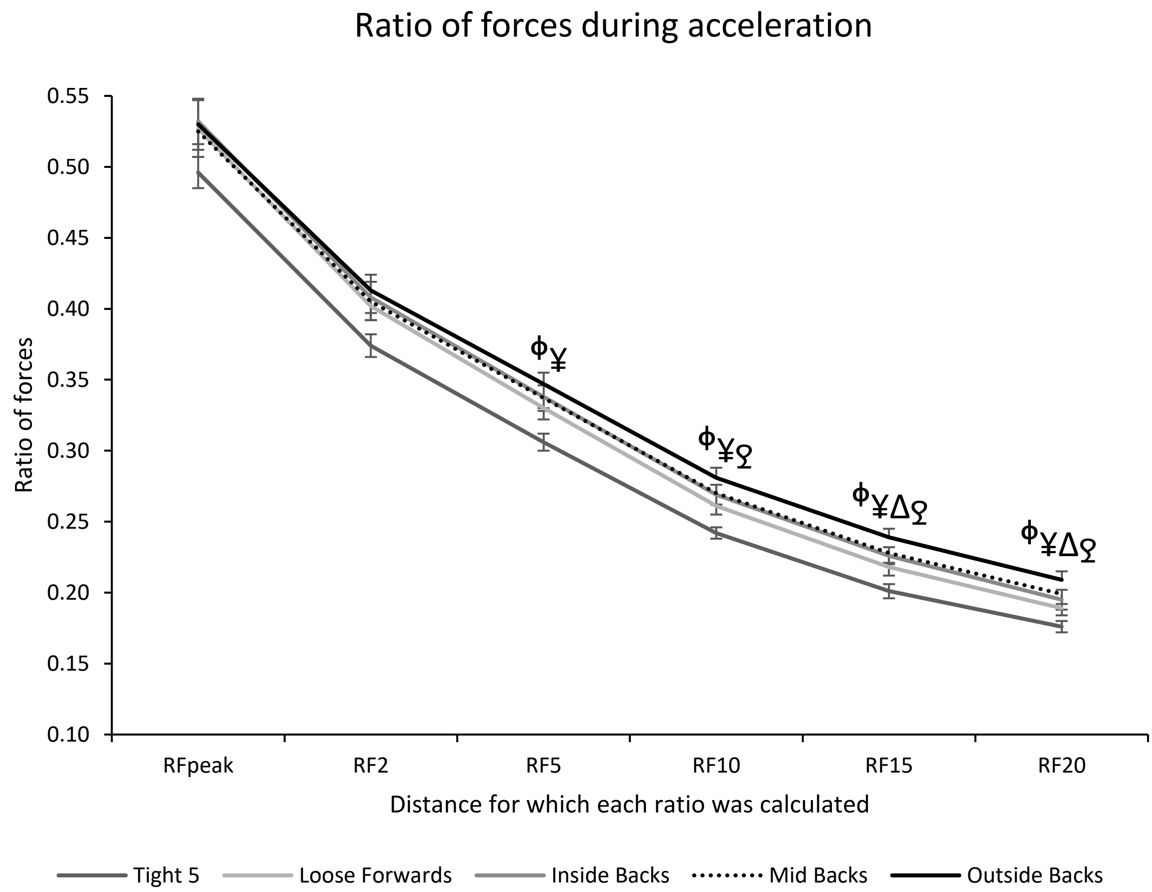


Figure 4.4. Ratio of forces (RF) at the start of the sprint (RFpeak) and with increasing distances (RF2, RF5, RF10, RF15, RF20) for positional groups. Data presented as estimated means and 95% confidence intervals. ϕ = all groups significantly greater than tight-5 players ($p < 0.001$); ¥ = outside backs greater than loose forwards ($p \leq 0.003$); ♀= outside backs significantly greater than inside and mid backs ($p < 0.05$); Δ= mid backs greater than loose forwards ($p < 0.05$).

4.4. Discussion

4.4.1. Main findings

The purpose of this study was to examine and compare sprint performance and mechanical properties for rugby players across competition levels and positional groups. The results of this investigation demonstrate competition-level differences regardless of position, with the most noticeable differences occurring in the first 10 m. Results also show significant differences in sprint performance across positional groups, with velocity increasing linearly with positional number. The sprint performances from the current study are similar to those previously reported in New Zealand rugby union players (73,356). However, to the author's knowledge this is the first study to investigate such a large sample of sprint FV profiles from different competition levels and positional groups in rugby union. The results herein provide initial benchmarks for strength and conditioning practitioners on the specific competitive demands of different positional groups.

4.4.2. Competition-level differences

Sprint split times

There were significant differences across competition levels for sprint times (0.028 – 0.085 s) and FV profile variables, most prominently in the first 10 m of the sprint performances. Not surprisingly, both international and professional groups had significantly faster 10-, 20-, and 30-m split times, and superior sprint profile attributes (F_0, V_0, P_0, S_{fv}, V_{max}, F_{rel}, P_{rel}) than club players, highlighting the caliber of athlete required for professional and international leagues (135,356). Smart et al. (356) reported similar differences in split times (1.9 – 4.5%) between provincial, Super Rugby and international competitions in a large (>1000 athletes) cohort of New Zealand rugby players, but unfortunately they did not collect FV profile characteristics. It is important to note these small differences seen in sprint times can represent large on-pitch differences in performance for trained athletes. Practically speaking, small differences (0.06 – 0.07 s) between professional rugby union and rugby league backs represent an absolute difference of ~0.44 m and ~0.73 m distance covered after sprinting for two and four seconds (73). Considering small attacking spaces, short decision-making windows and imperceptible ground contact times for sprinting, small changes in speed can largely influence line breaks and attacking opportunities (144).

Ratio of forces

Interestingly, both international and professional players had greater RFpeak than club players (52 – 55% vs. 50%), while there was no difference for RF20 (19% vs. 20%). Results suggests club players were less effective at producing high levels of horizontal force at the start, but similarly able to mitigate loss of horizontal force with increasing distance and speed. Elite sprinters commonly portray RFpeak values of 56 – 57%, while reported values of up to 72% have been noted in world-class Olympic sprinters using force plate methods (134,311). These trends are not uncommon, bearing in mind that as athletes graduate from amateur competitions, they are expected to transform many anthropomorphic and strength-based attributes to tolerate elevated competition stress. In some cases, from high school age to professionalism rugby players are required to increase their weight by 30 kg, which can hinder their bandwidth for improving mechanical effectiveness at high velocities. These results reinforce the importance of prioritising individualised speed training according to positionally-based directives in addition to team-based brute athleticism (177,320).

Sprint velocities and momentums

Comparisons between international and professional levels reveal significant differences on either end of the velocity spectrum. International players were significantly faster than professional players across the first 10 m, resulting in lower split times (Figure 4.1; -0.028 s) and greater average sprint velocity (+0.10 $m \cdot s^{-1}$), but not momentum (+14 $kg \cdot m \cdot s^{-1}$) (Figure 4.2). In contrast, professional players achieved significantly lower 10 – 20 m times (-0.021 s), thus greater SV10-20, and a more force-oriented FV profile. While not significant, professional players trended to portray greater V_{max} to small effect (+0.16 $m \cdot s^{-1}$; ES = 0.40; p = 0.08). Previous literature on international and professional athletes is mixed with some studies reporting trivial-small differences in 10 – 40 m split times using only New Zealand rugby players (356), while others report no differences in sprint times or mechanical variables in European soccer players (135).

Differences between professional and international players may be attributed to competition characteristics, yearly travel schedules and training frequency, or organisational-specific goals (267). There's sufficient evidence to support the ability for meaningful increases in strength and power in professional rugby players across a full season (118). Although, small increases in maximal strength for strong (>140 kg maximal front squat) international rugby players may not always translate to superior sprint performance (26) or winning percentage. Additionally, in-season maximal speed seems to be less pliable in elite (world ranking 11^{th} – 15^{th}) international rugby players (26). This could be because similar long-haul travel requirements to international rugby sevens players may sometimes produce small-moderate decrements in strength and power (267). Barr et al. (2014) also suggest momentum is more trainable over long periods (>2 years) than velocity characteristics (25). Alternatively, there are factors relating to strategy, skill and experience that direct selection beyond athletic prowess (155).

4.4.3. Positional comparisons

Across positions, sprint times and maximal velocity characteristics followed a linear trend, with performance increasing with positional number and the absolute difference between positions increasing with the distance covered. The current positional split times were in between previously reported soccer players (135) and American football players (81), but similar to previously reported New Zealand rugby players, highlighting rugby-specific tactical roles (90,356). Unsurprisingly, the maximal velocity achieved during a 30 m sprint in the current study is slightly less than previously reported for backs players during a 60 m sprint (90), suggesting some backs players may be able to continue accelerating past 30 m. Indeed, elite sprinters will continue to accelerate for 50 – 60 m and reach excess speeds greater than 11 $m.s^{-1}$ during a maximal sprint (275).

Tight-5 and loose forwards

Collectively, the results demonstrate differences between tight and loose forwards in sprint performance specific to their strategic roles on the field. Tight-5 players demonstrated having significantly lower average sprint velocities for all distances (0 – 10, 10 – 20, and 20 – 30 m), but greater average sprint momentum across the first 10-m. Additionally, tight-5 and loose forwards had similar force-generating capacity, but loose forwards had significantly greater P_0, and maximal velocity characteristics (ES = 0.56 – 1.15). While tight-5 players rarely sprint maximally, greater initial SM10 is likely to benefit a ruck-dominated "pick and go" style of play. Conversely, GPS analysis typically portrays loose forwards having running patterns more similar to inside backs, but with a significantly greater work-to-rest ratio, number of repeated high-intensity actions and tackles performed of any position (178). Indeed, in the current study, both tight-5 and loose forwards had a more force-dominant profile, greater average sprint momentum and sprint split times across all distances than all backs positional groups. Yet, loose forwards demonstrated significantly less V_0 and V_{max} than outside and mid, but not inside backs. Smart et al. (356) similarly reported ~0.04 – 0.10 s decrement between loose forwards and inside backs during a single maximal 20 m sprint. Greater maximal acceleration may be necessary for increased ball handling of inside backs and successful execution of offensive plays off set pieces. Whereas greater force and power production will aide loose forwards in performing lineouts, tackling, and rucks (94). However, both positional groups may benefit from having similar maximal velocity capacities.

Backs positional groups

Mid and outside backs require greater peak speeds in game, perform more high-velocity running, a significantly greater number of sprints and present a greater maximum sprint distance than loose forwards and inside backs (178). As such, outside backs were significantly faster than inside backs across all distances. At the same time, outside backs portrayed greater RF values than both inside and mid backs over 10 m. Results suggests outside backs were better able to maintain horizontal force application and continue accelerating across longer distances (134,278). Mid backs achieved faster times and velocities compared to inside backs (-0.03 to -0.07 s; ES = 0.48 – 0.52) and slower times and velocities compared to outside backs (+0.01 to +0.04; ES = 0.18 – 0.41); although, none of these differences were statistically significant ($p > 0.067$). Interestingly, consistent mean responses across all time and velocity-based metrics portrayed increasing absolute differences and larger ES values between backs groups with increasing speed. Results suggest there may be small differences this study was unable to detect, and that any such differences may become more pronounced as velocity increases. Future research may want to incorporate larger backs group sample sizes from professional and national competitions to provide more clarity. Moreover, mid and outside backs had significantly greater sprint momentum across all distances than inside backs, which may be particularly beneficial when working to break defensive lines at speed. This is consistent with other anthropomorphic studies on rugby players highlighting less weight allows inside backs to more easily and quickly move around the field (88,356).

4.4.4. Limitations

While this investigation is the first to examine mechanical sprint properties in such a large cohort of rugby players (n = 176), there are some limitations. First, decisions were made to consistently prioritise elite testing protocols and be the least hindrance possible to organisations. As such, teams could not all be tested at the same time of year, however longitudinal studies show this is unlikely to drastically affect maximal sprint velocities (25,26). Scheduling conflicts and short pre-season windows prevented additional team testing opportunities. As a result, there were insufficient sample size of hookers and locks to create subgroups within the tight-5 comparison. Specific positional demands between props, hookers and locks may likely result in different mechanical parameters for these groups (356). It is also worth noting Tier 2 rugby nations are often characterized by World Rugby as having poor infrastructure or underdeveloped professional leagues, which consequently may affect the breadth of physicality available for selection. Future studies may want to compare differences in sprint performance between World Rugby Tiers for enhanced clarity.

4.5. Practical Applications

Sprint times and mechanical FV variables from the current study can aid strength and conditioning personnel in directing training priorities and providing benchmarks for competitions and positional groups. Sprint performance across all distances was significantly greater for international and professional players compared to club players, most prominently across the first 10 m (1.71 s and 1.74 s vs. 1.79 s). Moreover, 20- and 30-m group averages were under 2.98 s and 4.15 s for professional and international players irrespective of position. Thus, these times may act as an initial benchmark for club players wanting to advance to professional leagues. Across positions, sprint velocity increased, and split times decreased, linearly with increasing positional number across all distances. Outside backs had the greatest Vmax reaching 8.97 $m \cdot s^{-1}$, and lowest split times, while both forwards positions had a more force-dominant profile (F0: > 900 N and S_{fv}: > 100) than all backs positions. Inside backs had greater acceleration, but similar maximal velocity to loose forwards, while the latter had the greatest P_0 of all positions. These results give some indication to athletic qualities beneficial for position-specific demands. For example, a primary objective for tight-5 and loose forwards might be improving horizontal force application during initial and secondary acceleration, directing their FV profile to be more force-dominant. Loose forwards will also require faster acceleration than tight-5 forwards, but similar maximal velocity to inside backs. Whereas, inside backs may benefit from having a much more velocity-oriented FV profile and faster acceleration than loose forwards. Priorities for mid and outside backs might be to improve their maximal velocities, such that they approach 9 $m \cdot s^{-1}$. Additionally, maintaining a greater RF with increasing velocities will be crucial to maximise acceleration during long-distance sprinting.

Chapter 5 – Implementation and efficacy of plyometric training: Bridging the gap between practice and research.

Reference

Watkins, CM, Storey, AG, McGuigan, MR, and Gill, ND. Implementation and efficacy of plyometric training: Bridging the gap between practice and research. *J Strength Cond Res* 35(5): 1244–1255, 2021.

Author contribution

Watkins, CM, 85%, Storey, AG, 5%, McGuigan, MR, 4%, Gill, ND, 6%.

5.0. Prelude

The results from Chapter 4 highlighted important performance determinants and position-specific characteristics. Sprint split times, velocities, momentums and horizontal FV profile characteristics portrayed significant differences relative to positional group. Competition-level differences reaffirmed the importance of speed to all players, while positional comparisons revealed specific considerations for optimal plyometric prescription. Accordingly, there was a need to acknowledge expert opinion for developing recommendations for best practice. The current literature lacks clarity on dose response for optimal sprint performance. While the literature is supportive of both low-and high-volume programmes, the systematic review did not show a clear beneficial effect for increased session volume in athletes. Difficulty has previously arisen with monitoring plyometric exercises due to their reliance on movement velocity and primary use of bodyweight rather than external load as a stimulus. Thus, appropriate exercise manipulation including training axis, periodisation, and volume loads are important considerations. These are areas in which expert strength and conditioning coaches may have experienced. Reported programmes offer specific information relating to current dosing strategies. Thus, through quantitative, and qualitative analysis of perceived practical applications and interpretation of programme details within the context of research evidence, we intended to create a more comprehensive understanding of optimal plyometric training practices. Specifically, this thesis aimed to provide evidence-based recommendations that are ecologically valid.

5.1. Introduction

Most athletes benefit from being stronger, faster, and more powerful, the degree to which depends on their sport. While a powerlifter will primarily benefit from improving absolute maximum strength (typically ~3 – 5 s), many athletes are regulated by the time available for force production during more ballistic jumping and sprinting actions with short ground contact times (~0.1 – 0.6 s) (24,227). Thus, practitioners are always looking for ways to bridge the gap between strength gained in the gym and functional competition performance. Plyometrics is one such method used globally to improve linear speed, power, change-of-direction ability, and running economy which uses the athlete's own mass as a stimulus rather than external weight as traditionally used in resistance training (157). Originally termed "the Shock method" by Yuri Verkhoshansky in the 1950's, a critical component of plyometric exercises is to induce mechanical shock that forces a maximal build–up of tension invoking the stretch reflex. An important distinction: originally true plyometrics only involved very high-intensity (i.e., 50 – 100 cm DJ) exercises using "the Shock method," but now presently encompasses a wide spectrum of low–intensity extensive and intensive plyometric exercises.

After years of practice- and research-driven investigation, there is sufficient empirical evidence confirming that plyometric training organises the structural, neural and elastic components of the human body to achieve greater power output than isolated muscle actions alone (393). Specifically, the accumulation of kinetic energy during the eccentric portion of stretch-shortening cycle (SSC) movement is conserved and recycled during the subsequent isometric and concentric portions, creating a stretch-recoil action similar to that of a rubber band (164,187,188,233). Concurrently, CNS motor programmes initiate high levels of muscular activation prior to ground contact. The "pre-activity" of the associated musculature alongside the stretch reflex initiates the facilitation of energy transfer and force transmission resulting in greater mechanical efficiency

(188). However, for an action to be truly considered elastic (i.e., optimal use of the SSC), active eccentric lengthening must occur and the eccentric-concentric coupling action must be performed quickly, resulting in a small amortisation (i.e., transition) time (188). If the aforementioned criteria are not met, energy will likely be dissipated as heat, as in static stretching (367).

The benefit from using plyometric training is primarily dependent on the rate and magnitude of MTU loading, due to the reliance on collision forces. Newtonian laws dictate every collision (i.e., between an athlete and the ground surface) conserves momentum, while kinetic energy conservation regulates ballistic performance (188,333,358). The difference being CNS energy-dissipating protective or energy-recoiling performance-based strategies that results in slow and fast GCT (16,108). Historically, this has presented some difficulty in correctly identifying the intensity of plyometric training exercises, leaving coaches to rely on subjective visual ratings. Recommendations by the National Strength and Conditioning Association (NSCA) have attempted to add clarity on this topic, suggesting that jump height is a primary determinant of intensity and that unilateral jump variations are more intense than their bilateral counterparts. However, an important distinction lies in the velocity at which one falls and the direction of landing relative to that of the take-off, rapid landings below the take-off point being more eccentrically stressful. A surplus of scientific publications investigating GCT classifications, reactive strength index (RSI), kinetic forces and joint power absorption now bring into question the traditional classifications of plyometric training and provide more advanced analysis on the specific stress from different exercises (193,219). For instance, analysis of lower body jump exercises revealed that jumping movements in the forward direction have ~19 – 24% greater summed, ankle, knee, and hip joint peak power than the box drop and jump up exercises, although classified as low compared to moderate intensity via subjective ratings (219). Moreover, specific joint analysis reveals intensity rankings differ by joint contribution; forward jumps being classified as high intensity for the ankle, but low for the hip (219).

At present, there seems to be some discontinuity between literary recommendations for plyometric training and practitioner-led plyometric programming. Both the NSCA in 2007 and International Journal of Sports Physical Therapy in 2015 have published guidelines directing high–volume session loads of 40 – 80 and 80 – 100 GC for beginners and 100 – 140 GC for advanced athletes (96). Both organisations went on to recommend high-intensity session volumes of 200 – 400 GC for elite athletes (78,207). However, new evidence continues to emerge, questioning whether more volume is more beneficial (49,55,99,173,394). Anecdotally, some elite strength and conditioning coaches are regularly using as few as 15 – 40 GCs in conjunction with other training modalities for international athletes.

Other recommendations have included significant strength requirements (1.5 – 2.5x body weight) for athletes prior to including even low-level plyometrics (78). In addition, body weight restrictions (~100 kg), the avoidance of depth jumps, and only the use of resilient surfaces are additional criteria that have been proposed (78,97,207). Newer evidence suggests MTU mechanical tolerance restricts performance (346). For instance, athletes with requisite MTU strength, effective SSC mechanics and tissue integrity at high velocities will better tolerate large impact forces during high-intensity plyometrics and benefit accordingly (346). In contrast, athletes with poor MTU capabilities relative to their body mass risk injury and are likely to adopt a more compliant strategy to absorb forces over longer durations as an injury prevention strategy (345). Additionally, adaptations may be surface- and exercise-specific (8,9,332).

Currently there is no agreement on optimal periodisation strategies with traditional and undulating strategies resulting in similar adaptations (78). However, there is consensus that any periodisation strategy does in fact trump a constant volume approach (375). Some authors recommend using plyometrics throughout all phases of training (78), whereas others claim plyometrics should only be used in preparatory phases (97). Therefore, the primary aim of this investigation is to have a clearer understanding of the practitioner's implementation of plyometric training, including training direction dose, periodisation strategies and efficacy in a real-world setting. Specifically, this survey aimed to determine how closely the current literary recommendations match current practice. Secondly, this survey investigated trends in programme variables by competition level, sport, or training axis.

5.2. Methods

5.2.1. Experimental approach to the problem

The current study employed an integrative mixed methods online survey (Google Forms, Mountain View, CA, USA) to understand the practitioner's perspective on plyometric training in a real-world setting. The online survey was sent via an email link and included an information sheet intended to introduce the survey and provide details about the aims and benefits of the research project. All coaches were assured of the survey's voluntary nature and their ability to withdraw from the survey at any time. All responses were anonymous and no identifying information was ever collected.

5.2.2. Participants

Globally, 61 adult strength and conditioning practitioners volunteered for this study (Table 5.1). Strength and conditioning coaches were recruited from semi-professional, professional, national, and international-level teams and performance centers around the world. Participants varied in coaching experience, the number of years using plyometric training and the current level of competition level they work with. Of the participants, 32.8% of respondents (n = 20) have coached for longer than nine years, 37.7% of respondents (n = 23) having used plyometric training longer than nine years and 34.4% of respondents (n = 24) were coaching at the Olympic or international level. The breakdown of responses by practitioner role, coaching experience, country and sport is shown in Table 5.1. The Auckland University of Technology ethics committee (14/22) approved this research project, and all participants provided informed consent.

Table 5.1. Background information for survey respondents. Data presented as frequency percentage and total respondents for that category in parentheses. S&C = strength and conditioning coach; Asia-Pacific includes New Zealand, Australia, and Japan; PT = plyometric training; BS = back squat; DL = deadlift.

Background coach information						
Competition Level	International 34.4% (21)	Professional 24.6% (15)	Semi-pro & Amateur 41.0% (25)		Total 100% (61)	
What is your primary job?						
Primary Job	Head S&C 62.3% (38)	Assistant S&C 23.0% (14)	Sport coach 8.2% (5)	Academic 6.6% (4)	Total 100% (61)	Chi-square NS, $p > 0.05$
Region	Asia-Pacific 44.3% (27)	Canada 24.6% (15)	Europe 6.6% (4)	USA 21.3% (13)	Total 97.7% (59)	Chi-square NS, $p > 0.05$
Sport category	Field team sports*	Non-field team sports[$]	Individual sports*[#]	Mixed[$#]	Total	Chi-square
All	50.8% (31)	13.1% (8)	11.5% (7)	24.6% (15)	100% (61)	$p < 0.001$, C_2=26.506
International*	38.1% (8)	14.3% (3)	33.3% (7)	14.3% (3)	100% (61)	$p = 0.026$
Professional	53.3% (8)	33.3% (5)	0.0%(0)	13.3% (2)	100% (61)	
Semi-pro & amateur*	60.0% (15)	0.0% (0)	0.0%(0)	40.0% (10)	100% (61)	
Primary source of knowledge						
Educational	Empirically-based research	Anecdotal (i.e., blogs, websites)	Personal experience	Combination	Total	Chi-square
41.0% (25)	21.3% (13)	16.4% (10)	13.1% (8)	6.6% (4)	100% (61)	NS, $p > 0.05$
Experience	0-3 years	4-9 years	9+ years	Total	Chi-square	
Coaching, all	26.2% (16)	41.0% (25)	32.8% (20)	100% (61)	$p = 0.024$, C_2=7.47	
International	23.8% (8)	33.2% (7)	42.9% (9)	100% (61)		
Professional[$]	13.3% (2)	33.3% (5)	53.8% (8)	100% (61)	$p = 0.031$, C_2= 13.95	
Semi-pro & amateur[$]	36.0% (9)	52.0% (13)	12.0% (3)	100% (61)		
Experience	0-3 years	4-9 years	9+ years	Total	Chi-square	

PT	19.7% (12)	42.6% (26)	37.7% (23)	100% (61)	p= 0.001, C_2=13.86
International*	19.0% (4)	33.3% (7)	47.6% (10)	100% (61)	p= 0.043, C_2=11.12
Professional$	0.0% (0)	33.3% (5)	66.7% (10)	100% (61)	p< 0.001, C_2=19.47
Semi-pro & amateur*$	32.0% (8)	56% (14)	12.0% (3)	100% (61)	

Background athlete information

Sport experience	0-3 years	4-9 years	9+ years	Total	Chi-square
All	6.6% (4)	62.3% (38)	31.1% (19)	100% (61)	p= 0.016, C_2=8.21
International	4.8% (1)	52.4% (11)	42.9% (9)	100% (61)	
Professional$	0.0% (0)	53.3% (8)	46.7% (7)	100% (61)	p= 0.037, C_2= 12.40
Semi-pro & amateur$	12.0% (3)	76.0% (19)	12.0% (3)	100% (61)	

Resistance experience	0-3 years	4-9 years	9+ years	Total	Chi-square
RT age, all	44.3% (27)	52.5% (32)	3.3% (2)	100% (61)	p= 0.006, C_2= 10.28
International*	28.6% (6)	71.4% (15)	0.0% (0)	100% (61)	p= 0.035, C_2= 11.63
Professional$	26.7% (4)	60.0% (9)	13.3% (2)	100% (61)	p= 0.013, C_2= 14.46
Semi-pro & Amateur*$	68.0% (17)	32.0% (8)	0.0% (0)	100% (61)	

Training requirement prior to performing plyometric training

Experience	None	1-3 years	4-9 years	9+ years	Total	Chi-square
Sport requirement	73.8% (45)	18.0% (11)	6.6% (4)	1.6% (1)	100% (61)	NS, p> 0.05
RT requirement	78.7% (48)	18.0% (11)	3.3% (2)	0.0% (0)	100% (61)	NS, p> 0.05

Strength requirement prior to performing plyometric training

	None	0.5x BW	1.0x BW	1.5x BW	≥2.0 x BW	Total	Chi-square
BS	49.2% (30)	6.6% (4)	23.0% (14)	19.7% (12)	1.6% (1)	100% (61)	NS between levels, p> 0.05
DL	57.4% (35)	3.3% (2)	14.8% (9)	18.0% (11)	6.6% (4)	100% (61)	NS between levels, p> 0.05
Clean	73.8% (45)	8.2% (5)	14.8% (9)	1.6% (1)	1.6% (1)	100% (61)	NS between levels, p> 0.05

5.2.3. Procedures

The survey was sent out through direct communication lines to a broad network of primary and secondary connections, as well as shared through social media resources (i.e., Twitter, Instagram, LinkedIn). Additionally, national performance centers from multiple countries were contacted using a brief introduction paragraph along with the survey link. This survey aimed to obtain responses from both northern and southern hemisphere countries, including a broad variety of individual and team sport settings of differing competition levels.

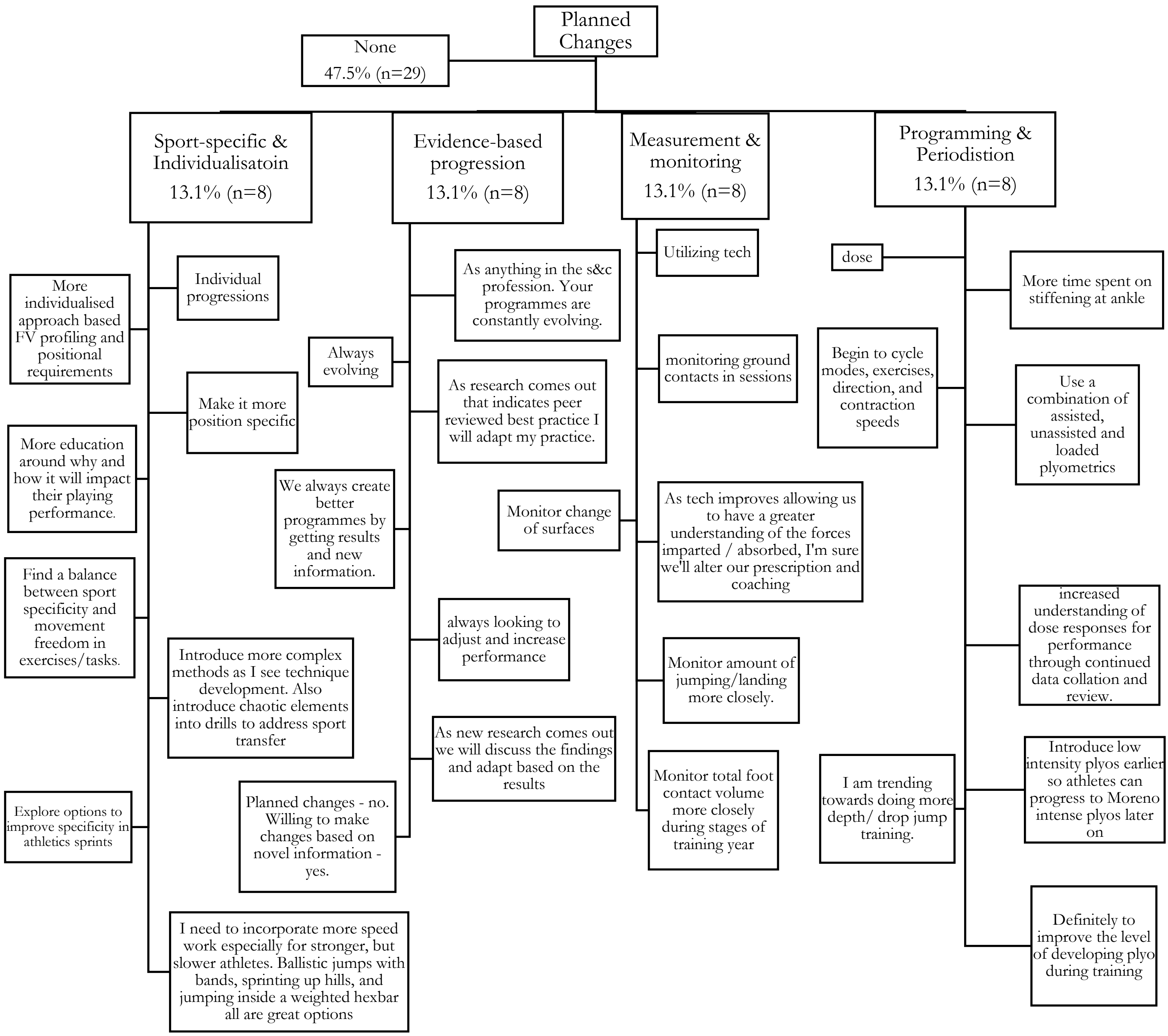
5.2.4. Survey

This survey comprised of five sections: 1. Sport and coaching background information, 2. Plyometric training focus, 3. Periodisation strategy, 4. Plyometric programme details, and 5. Efficacy of plyometrics for sport performance. Response types included yes/no, multiple choice, Likert scale, percentage based and open-ended questions. Multiple choice answers were divided into single answer and multiple answer questions, but always included a "fill-in" option. Open-ended questions were divided into direct answer and more subjective probing type questions. The survey was originally piloted with a group of expert strength and conditioning coaches (n = 15), and areas that were identified as unclear were edited or removed from the survey.

5.2.5. Data processing and analysis

Both quantitative and qualitative analysis methods were used to analyse survey responses. Following completion, all responses were downloaded to Microsoft Excel, and answers were coded such that different variations (e.g. United States vs. US) were grouped, and all single-answer multiple choice responses converted to numerical expressions. For answers where multiple choices were allowed, a variable was created for each possible response, such that each participant had an entry (0 or 1) for each possible answer, and all variables were analysed separately. All statistical analysis was subsequently completed in R (Auckland, New Zealand) Version 4.0.2 software. For all statistical analysis, an alpha level of 0.05 was used. For categorical variables, a Chi-square test was conducted. In accordance, groups with less than five responses, or <4% of the analysis, were combined to make broader categories. In cases where this was not possible, a Fisher's exact test was conducted. For analysis between categorical and ordinal variables, a Kruskal Wallace test was conducted. P-values were adjusted via the Holm method. For paired ordinal data, a t-test was conducted, whereas a Friedman's test was conducted for paired categorical data or a Cochran's Q test for paired binary variables, with McNemar post-hoc analysis. All categorical variable analyses are presented as a percentage (frequency), otherwise as means ± SD. For open-ended questions, answers were categorized into themes by two separate researchers using an inductive method and collated for analysis. Final themes were then coded similar to multiple choice answers. A copy of the questionnaire is provided as a supplemental file in attempts of full transparency. However, due to the magnitude of data provided, only a subset of relevant questions was reported on in the current manuscript.

Figure 5.1. Planned changes qualitative answer coding map.



5.3. Results

5.3.1. Background coach and athlete information

The background information for survey respondents and their athletes are reported in Table 5.1. There was a difference between sport and competition level of responses ($p < 0.05$). Notably, all seven individual sport responses competed at the international level, which has been considered during further analysis. Significant differences also occurred between competition levels and years of plyometric training ($p< 0.001$), years coaching ($p = 0.024$) as practitioners and sport and resistance training experience of athletes ($p< 0.01$; Table 5.1). Overwhelmingly, 96.7% (n = 59) of practitioners reported positive feedback from athletes, 1.6% (n = 1) responded athletes are "warming to them slowly" and 1.6% (n = 1) responded that some athletes, referring to large force-dominant front-row forwards, "do not love it as much." Emergent themes for positive attitudes towards plyometric training included: 1. Increased social engagement using different variations, being competitive, challenging and fun; 2. Perceived effectiveness in the context of speed, or "feeling and moving fast;" 3. Direct transferability and "resemblance to sporting actions;" 4. Positive technological feedback, and results (i.e., Gymaware, GPS, jump height); 5. Good rationale, credibility, alternative inspiration including "improvements from friends," "older athletes who excel," and exercises "they see on Instagram." A large consensus emerged on the critical role education and "having a valid reason" played in the perception of plyometric training with their athletes, citing "lack of understanding" or "intent is sometimes an issue."

5.3.2. Extent of plyometric training

The reported extent of plyometric training (1 – 10) in a programme did not significantly differ by competition level, with 47.6%, 53.3% and 29.2% of international, professional, and semi-professional or amateur practitioners, respectively, reporting a seven out of 10 or greater (p =

0.38). Including the entire cohort, the average plyometric confidence level of and the extent to which survey respondents used plyometric training in programmes was 7.5 ± 1.6 and 5.4 ± 2.6 out of ten, respectively. Furthermore, 78.7% (n = 48) and 41% (n = 25) of respondents reported their plyometric training confidence and their extent of plyometric programming as seven out of 10 or higher. An overwhelming majority, 70.5% (n = 43) of respondents reported yes to using plyometric training with all their athletes (barring injury or other specific cases), 24.6% (n = 15) responded no and 4.9% (n = 3) reported it depended on circumstance. There were no differences in planned programme changes between sport categories, or competition levels ($p > 0.05$). Categories and response types are shown in Table 5.1.

5.3.3. Perceived limitations

Limitations significantly differed by competition level (Figure 5.2). For international level practitioners, 42.9% (n = 9) reported no limitations. Conversely, 40.0% (n = 6) of professional practitioners reported programme and periodisation limitations and 44.0% (n = 11) of semi-professional practitioners reported resources as limitations ($p < 0.05$). There were no differences in injury or athlete characteristics limitations between groups or sport categories (Figure 5.2).

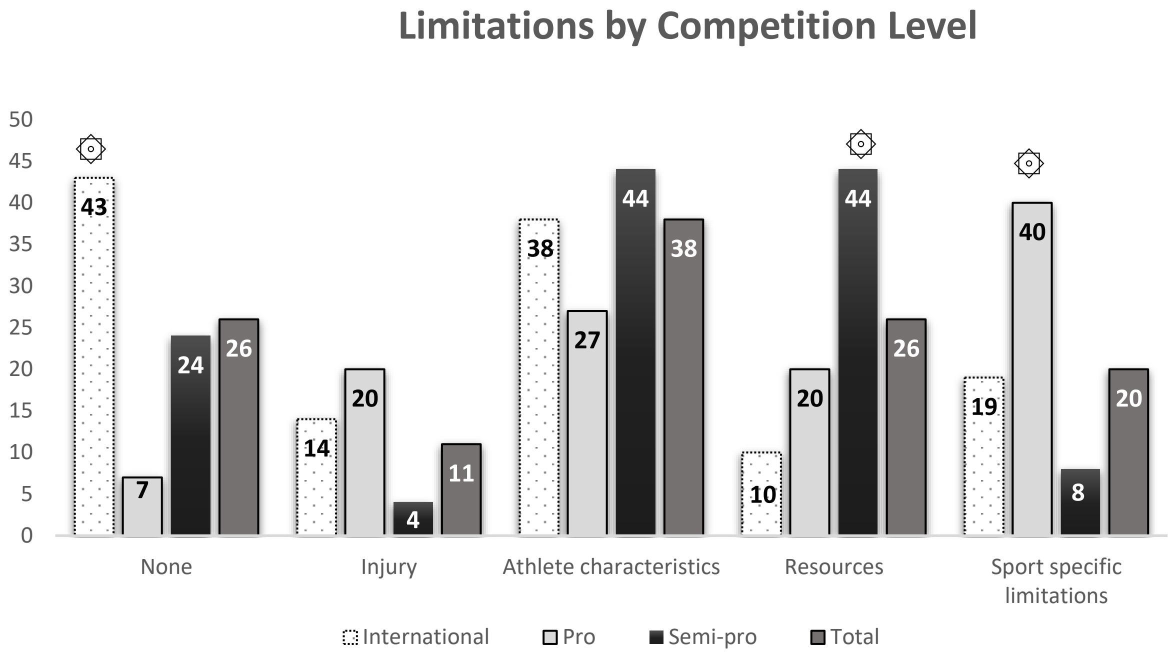


Figure 5.2. Limitations by competition level. Answers presented as percentage of total respondents in each competition level group (international= 21, professional= 15, semi-professional= 25). Open answer where answers were coded and could contain multiple categories. Each category analysed separately so each participant had only one response (0 or 1) for each category. ۞ =significant different to other groups (p< 0.05).

5.3.4. Programme variables

Significant differences in programme details are reported in Table 5.2. Typical training surface differed across sport categories ($p < 0.05$; Table 5.2). Training on track demonstrated significant differences across competition, with 52.4% (n = 11) and 40.0% (n = 10) of international, and semi-professional or amateur practitioners reporting regular use of a synthetic track, compared to 6.7% (n = 1) of professional practitioners ($p = 0.016$, $C_2 = 8.215$, df = 2).

Table 5.2. Reported programme variables. Presented as frequency percentage (absolute number). NS= not significant; C2= Chi-square; RT= resistance training; WL= the sport of weightlifting.

Programme variables							
Footwear	Uncontrolled	Bare feet	Sport-specific shoes	Cross-training shoes	Total		Chi-square
All	13.1% (8)	11.5% (7)	19.7% (12)	54.1% (33)	98.4% (60) @		p= 0.022, C_2=13.24
What surface do you typically train on? (Respondents were allowed to answer with multiple, as such, each variable is analysed separately)							
	Turf	Grass*	Track$	Wood floor	Mixture	Other	Chi-square
All	49.2% (20)	21.1% (19)	36.1% (22)	23% (14)	60.7% (37)	9.9% (6) @	
Field sports	54.8% (17)	38.7% (12)	35.5% (11)	16.1% (5)	58.1% (18)		
Court sports	37.5% (3)	0.0% (0)*	0.0% (0) $	37.5% (3)	75.0% (6)		*p=0.019, C_2=9.234
Individual	14.3% (1)	0.0% (0)*	85.7% (6) $	0.0% (0)	28.6% (2)		$p= 0.006, C_2= 11.688
Mixed	60.0% (9)	46.7% (7)	33.3% (5)	40.0% (6)	73.3% (11)		
Plyometric frequency as a specific focus							
	0x week	1x week	2x week	3x week	4x week	Total	Chi-square
Frequency	1.6% (1)	13.1% (8)	52.5% (32)	24.6% (15)	8.2% (5)	100% (61)	NS p> 0.05
Inter-session rest	0 days	1 day	2 days	3 days	≥4 days	Total	Chi-square
	1.6% (1)	24.6% (15)	39.3% (24)	21.3% (13)	13.1% (8)	100% (61)	NS, p> 0.05
Pre-competition rest	0-2 days		3-5 days	≥ 6 days		Total	Chi-square
	59% (36)		36.1% (22)	4.9% (3)		100% (61)	NS, p> 0.05
Inter-set rest	30-60 seconds	1-2 minutes	>2 minutes	Other	Total	Kruskal-Wallace	
All	19.7% (12)	39.3% (24)	31.1% (19)	4.9% (3) @	90.1% (55)	p= 0.032, C_2=6.90	
International*	10.0% (2)	40.0% (8)	50.0% (10)	0.0% (0)	95.2% (20)	p= 0.026, C_2=13.95	
Professional*	46.2% (6)	38.5% (5)	15.4% (2)	0.0% (0)	86.67% (13)		
Semi-pro & amateur	18.2% (4)	50.0% (11)	31.8% (7)	0.0% (0)	88.0% (22)		
Other modalities used in conjunction with plyometric training							
	RT	Eccentric	Gymnastics	WL	Sprinting	Chi-square	
All	78.7% (48)	31.1% (19)	9.8% (6)	68.9% (42)	62.3% (38)	NS p> 0.05	

@ Categories equalling <5% were eliminated from analysis due to insufficient data.

5.3.5. Periodisation

There were no significant differences between periodisation styles. However, 96.7% (n = 59) of practitioners reported using a form of periodisation strategy over constant volume. Of periodisation styles, 42.6% (n = 26) reported using undulating, 24.6% (n = 15) reported changes in exercise selection, 18% (n = 11) reported linear periodisation and 11.5% (n = 7) reported using a combination, depending on the circumstance. For incremental increases in volume, there was no difference across competition levels. Including all respondents, 54.1% (n = 33) responded 10 GC per week, 23% (n = 14) reported no increases, instead citing constant volume, 21.3% (n = 13) responded with 20 GC per week, and 1.6% (n = 1) of practitioners reported 40+ GC increases. Across sport categories, significant differences existed with 62.5% (n = 5) and 37.5% (n = 3) of non-field team sports and 73.3% (n = 11) and 26.7% (n = 4) of mixed sports reporting only increases of 10 and 20 GC per week. On the other hand, field and individual sports that were more varied, 38.7% (n = 12) and 28.6% (n = 2) of respondents reporting constant volume. Otherwise, 41.9% (n = 13) of field sports and 57.1% (n = 4) of individual sports reported increases of 10 GC, with 16.1% (n = 5) and 14.1% (n = 1) reporting 20 GC, and 3.2% (n = 1) of field team sports reporting increases of 40 or more GC per week ($p < 0.05$, $C_2 = 15.07$, df = 3). Overwhelmingly, 68.9% (n = 42) of survey respondents reported using a taper before competition, 29.5% (n = 18) reported not using one, and 1.6% (n = 1) of practitioners reported that it depended on the circumstance. There was no difference between competition level for incremental increases, or for inclusion of taper for either competition level or sport ($p > 0.05$).

5.3.6. Weeks of plyometric training

There were no differences in total weeks of plyometric training per year (international= 25 ± 15 weeks; professional = 23 ± 14; semi-professional = 24 ±13; $p > 0.05$). However, there were significant differences across competition phases ($p < 0.001$; Figure 5.3) and between competition levels for different phases of training. For international level practitioners, 81.0% (n = 17) reported 1 – 4 weeks of plyometric training compared to 46.7% (n = 7) of professional and 52.0% (n = 13) of semi-professional practitioners during late competition ($p < 0.05$, C2 = 8.06, df = 4) and 71.5% (n = 15) compared to 46.7% (n = 7) and 48.0% (n = 12) during play-offs ($p < 0.05$). Across sports, there were significant differences for weeks programmed during play off periods. Mixed sports were significantly less likely to report using 1 – 4 weeks of plyometric training during play off periods, with 26.7% (n = 4) compared to 67.7% (n = 21) of field sports, 71.4% (n = 5) individual sports, and 50.0% (n = 4) of non-field team sports. Mixed sports were significantly more likely to report using zero weeks of plyometrics during play-off periods, with 66.7% (n = 10) compared to 32.3% (n = 10) field sports, 50.0% non-field team sports, and 14.3% (n = 1) individual sports. Neither team-sport category reported planning >5 weeks of plyometrics during play offs, whereas 14.3% (n = 1) of individual sport and 6.7% (n = 1) of mixed sport reported so (p = 0.03).

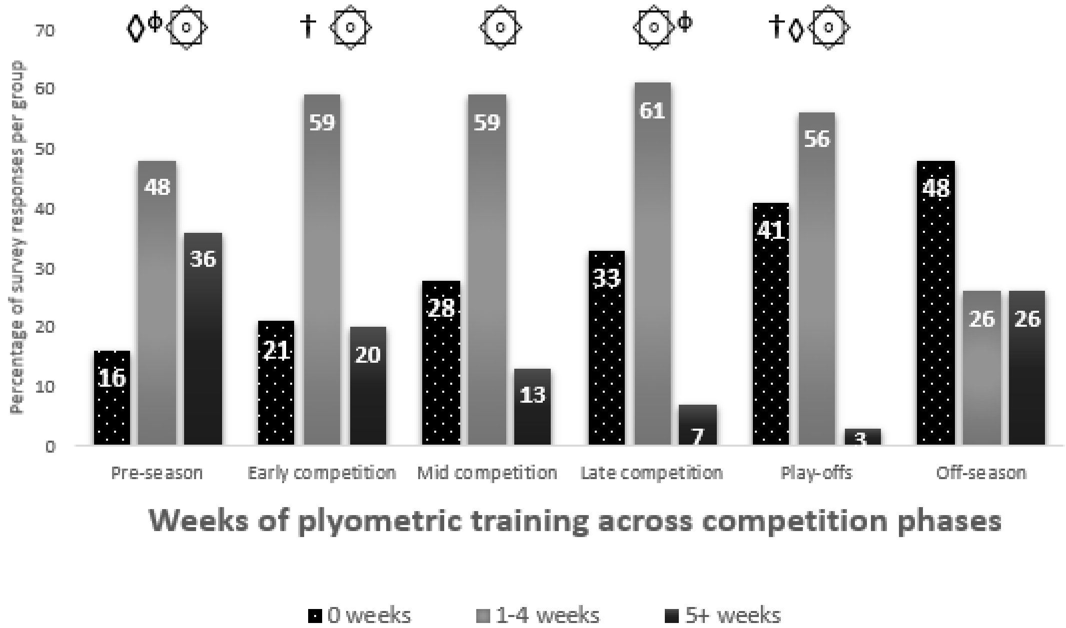


Figure 5.3. Reported weeks of plyometric training across competition phases (p< 0.001; Chi-square = 50.65; df = 10); ۞ =significantly different to off-season (p≤ 0.01); ◊= significant difference between variables (p <0.001); ᶲ= significant difference between variables (p≤ 0.01); †= significant difference between variables (p= 0.03).

5.3.7. Sessional ground contacts

Sessional GC volumes differed significantly across competition phases, within competition phases for each competition level and between competition levels for the same competition phase ($p < 0.05$; Figure 5.4; Table 5.3).

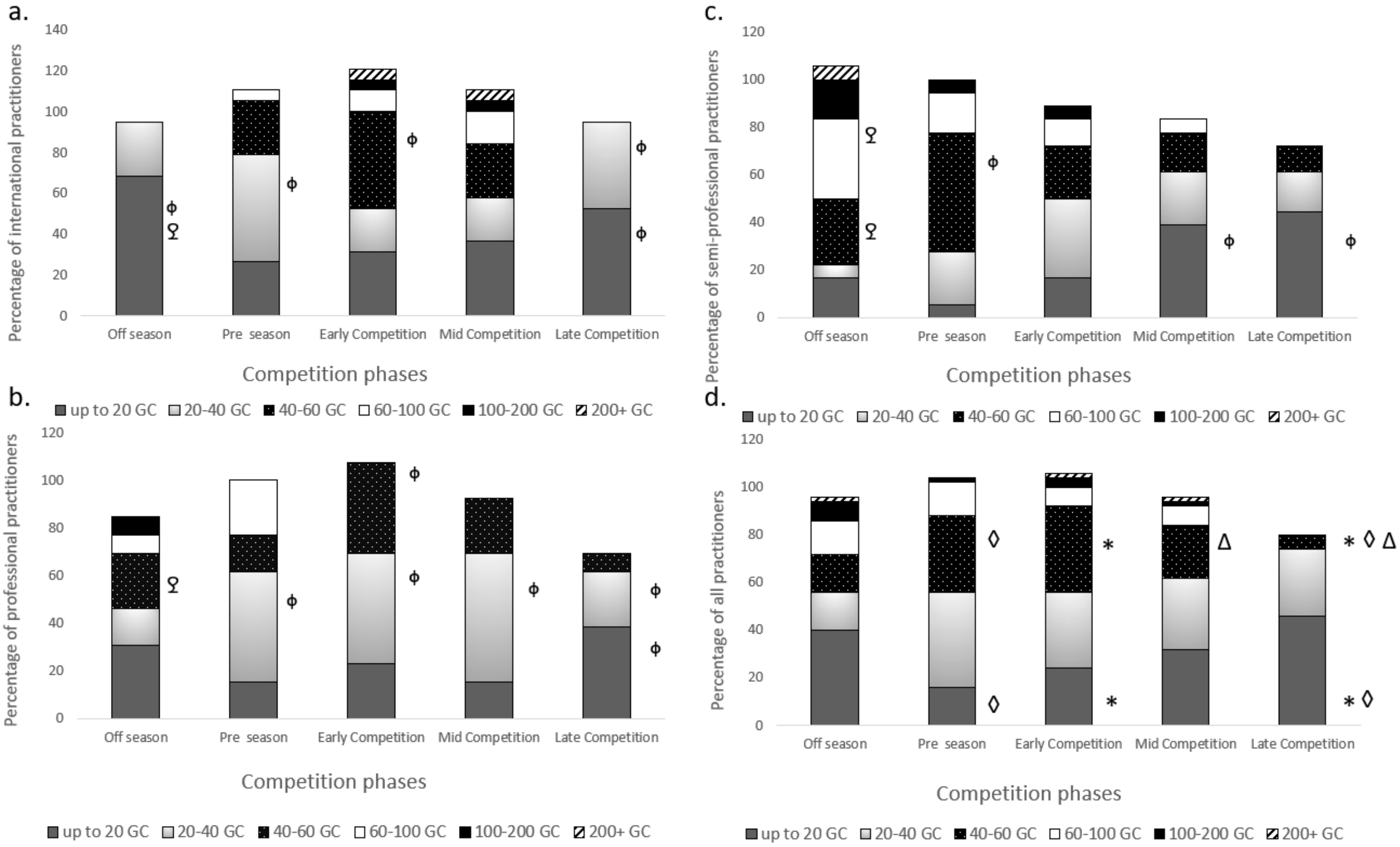


Figure 5.4. Reported session ground contacts (GC) across competition phases for international practitioners (3a.), professional practitioners (3b.) semi-professional practitioners (3c.), and all respondents collated (3d.)

*Note: Responses presented as a percentage of group responses, missing (n = 11), international (n = 19), professional (n=13), semi-professional (n = 18), all practitioners (n = 50). Q = Cochran's Q; C_2 = Chi-square. *= GC volume significantly differed between season (Up to 20 GC: Q = 15.74, p = 0.04; 40 – 60 GC: Q = 18.58, p < 0.001); ◊= GC volume significantly differed between season (Up to 20 GC: Q = 15.74, p=0.01; 40 – 60 GC: Q = 18.58, p= 0.037); Δ= GC volume significantly differed between season (40 – 60 GC: Q = 18.58, p < 0.01); ɸ=significant differences compared to other GC volumes for same phase, in all cases df = 5 (international: off-season(up to 20; Q = 46.67, p < 0.001), pre-season (20 – 40 GC; Q = 23.48, p < 0.001), early competition (20 – 40 GC; Q = 15.10, p = 0.01), late competition (Up to 20 & 20 – 40; Q = 36.66, p< 0.001); professional: pre-season (20 – 40; Q: 11.82, p = 0.037), early competition (20 – 40 & 40 – 60; Q = 16.97, p< 0.01), late competition (Up to 20 & 20 – 40; Q = 14.33, p = 0.014); semi-professional: pre-season (40 – 60; Q = 18.41, p < 0.01), mid-competition (Up to 20; Q = 15.00, p = 0.01), late competition (Up to 20; Q = 22.54, p< 0.001); ϱ = significantly greater than other competition levels during off-season (Up to 20 GC: C_2 = 10.94, df = 2, p = 0.004; 40 – 60 GC: C_2 = 5.96, df = 2, p = 0.027; 60 – 100 GC: C_2 = 9.11, df = 2, p = 0.008).

Table 5.3. Reported ground contacts (GC) across competition phase and competition level. Presented as frequency percentage (absolute number) Q= Cochran's Q; NS= not significant; C2= Chi-square.

	Off-season	Pre-season	Early-competition	Mid-competition	Late-competition	Cochran's Q (df=4)
Up to 20 GC all (n=50)	40.0% (20)	16.0% (8)	24.0% (12)	32.0% (16)	46% (23)	Q=15.74, p< 0.001
International (n=19)	68.4% (13)*	26.3% (5)	31.6% (6)	36.8% (7)	52.6% (10)	Q= 11.88, p= 0.01
Professional (n=13)	30.8% (4)	15.4% (2)	23.1% (3)	15.4% (2)	38.5% (5)	NS
Semi-professional (n=18)	16.7% (3)	5.6% (1)	16.7% (3)	38.9% (7)	44.4% (8)	Q= 11.00, p =0.02
Between competition levels	C_2= 10.94, df=2, p= 0.004	NS	NS	NS	NS	
20-40 GC all (n=50)	16.0% (8)	40.0% (20)	32.0% (16)	30.0% (15)	28.0% (14)	NS (p=0.09)
International (n=19)	26.3% (5)	52.6% (10)	21.1% (4)	21.1% (4)	42.1% (8)	NS
Professional (n=13)	15.4% (2)	46.2% (6)	46.2% (6)	53.9% (7)	23.1% (3)	NS
Semi-professional (n=18)	5.6% (1)	22.2% (4)	33.3% (6)	22.2% (4)	16.7% (3)	NS
Between competition levels	NS	NS	NS	NS	NS	
40-60 GC all (n=50)	16.0% (8)	32.0% (16)	32.0% (16)	22.0% (11)	6.0% (3)	Q= 18.58, p< 0.0001
International (n=19)	0% (0)*	26.3% (5)	47.4% (9)	26.3% (5)	0% (0)	Q= 18.96, p< 0.0001
Professional (n=13)	23.1% (3)	15.4% (2)	38.5% (5)	23.1% (3)	7.7% (1)	NS
Semi-professional (n=18)	27.8% (5)	50.0% (9)	22.2% (4)	16.7% (3)	11.1% (2)	Q= 9.73, p= 0.04
Between competition levels	C_2= 5.96, df=2, p= 0.027	NS	NS	NS	NS	
60-100 GC (n=50)	14.0% (7)	14.0% (7)	8.0% (4)	8.0% (4)	0% (0)	NS (p=0.09)
International (n=19)	0% (0)	5.26% (1)	10.5% (2)	15.8% (3)	0% (0)	NS
Professional (n=13)	7.7% (1)	23.1% (3)	0% (0)	0% (0)	0% (0)	NS
Semi-professional (n=18)	33.3% (6)*	16.7% (3)	11.1% (2)	5.6% (1)	0% (0)	NS (p= 0.055)
Between competition levels	C_2= 9.11, df=2, p= 0.008	NS	NS	NS	NS	
100-200 GC (n=50)	8.0% (4)	2.0% (1)	4.0% (2)	2.0% (1)	0% (0)	NS (p>0.1)
International (n=19)	0% (0)	0% (0)	5.26% (1)	5.26% (1)	0% (0)	NS
Professional (n=13)	7.7% (1)	0% (0)	0% (0)	0% (0)	0% (0)	NS
Semi-professional (n=18)	16.7% (3)	5.6% (1)	5.6% (1)	0% (0)	0% (0)	NS
Between competition levels	NS	NS	NS	NS	NS	
200+ GC (n=50)	2.0% (1)	0% (0)	2.0% (1)	2.0% (1)	0% (0)	NS (p>0.6)
International (n=19)	0% (0)	0% (0)	5.26% (1)	5.26% (1)	0% (0)	NS
Professional (n=13)	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)	NS
Semi-professional (n=18)	5.6% (1)	0% (0)	0% (0)	0% (0)	0% (0)	NS
Between competition levels	NS	NS	NS	NS	NS	
Cochran's Q level across all GC for each individual competition phase (df = 5)						
International	Up to 20, Q= 46.67, p< 0.001	20-40 Q= 23.48 P< 0.001	40-60 Q= 15.10 p= 0.01	NS	Up to 20 & 20-40 Q= 36.66 p< 0.001	
Professional	NS	20-40 Q= 11.82 p= 0.03	20-40 &40-60 Q= 16.97 p< 0.01	20-40 Q= 19.66 p< 0.001	Up to 20 & 20-40 Q= 14.33 p= 0.01	
Semi-Professional	NS	40-60 Q=18.41 p<0.01	NS	Up to 20 Q= 15.00 p= 0.01	Up to 20 Q= 22.54 p< 0.001	

5.3.8. Frequency and rest

There were no differences in weekly session count, intersession rest, or pre-competition rest between competition levels, or sports ($p > 0.05$). However, there was a significant difference between competition levels for inter-set rest time (Table 5.2; $p < 0.05$), but not sport.

5.3.9. Load determination and intensity

There was no difference between competition levels or sport categories for sessional load determination ($p > 0.05$), with the majority 45.9% (n = 28) electing to use GC, 27.9% (n = 17) using subjective scores and athlete wellness, 14.8% (n = 9) using performance output, and 11.5% (n = 7) using a combination of quantitative, subjective and GC considerations. There was, however, a significant difference between competition levels for average programme intensity ($p = 0.026$; $C_2 = 10.98$, df = 4), but not direction ($p > 0.05$). Professional practitioners were significantly less likely to report using low intensity programmes, compared to semi-professional practitioners (3.3% (n = 1) vs. 24% (n = 12), $p = 0.03$). Of international practitioners, 9.5% (n = 4) reported prescribing low-intensity programmes. In comparison, 54.8% (n = 23) and 35.7% (n = 15) of international practitioners, 43.3% (n = 13) and 53.3% (n = 16) of professional practitioners, and 50.0% (n = 25) and 26.0% (n = 13) of semi-professional practitioners reported moderate and high-intensity programmes, respectively. There were also significant differences for quantifying plyometric intensity, regulating intensity, and loaded intensities ranges for horizontal exercises between competitions ($p < 0.05$, Figure 5.5).

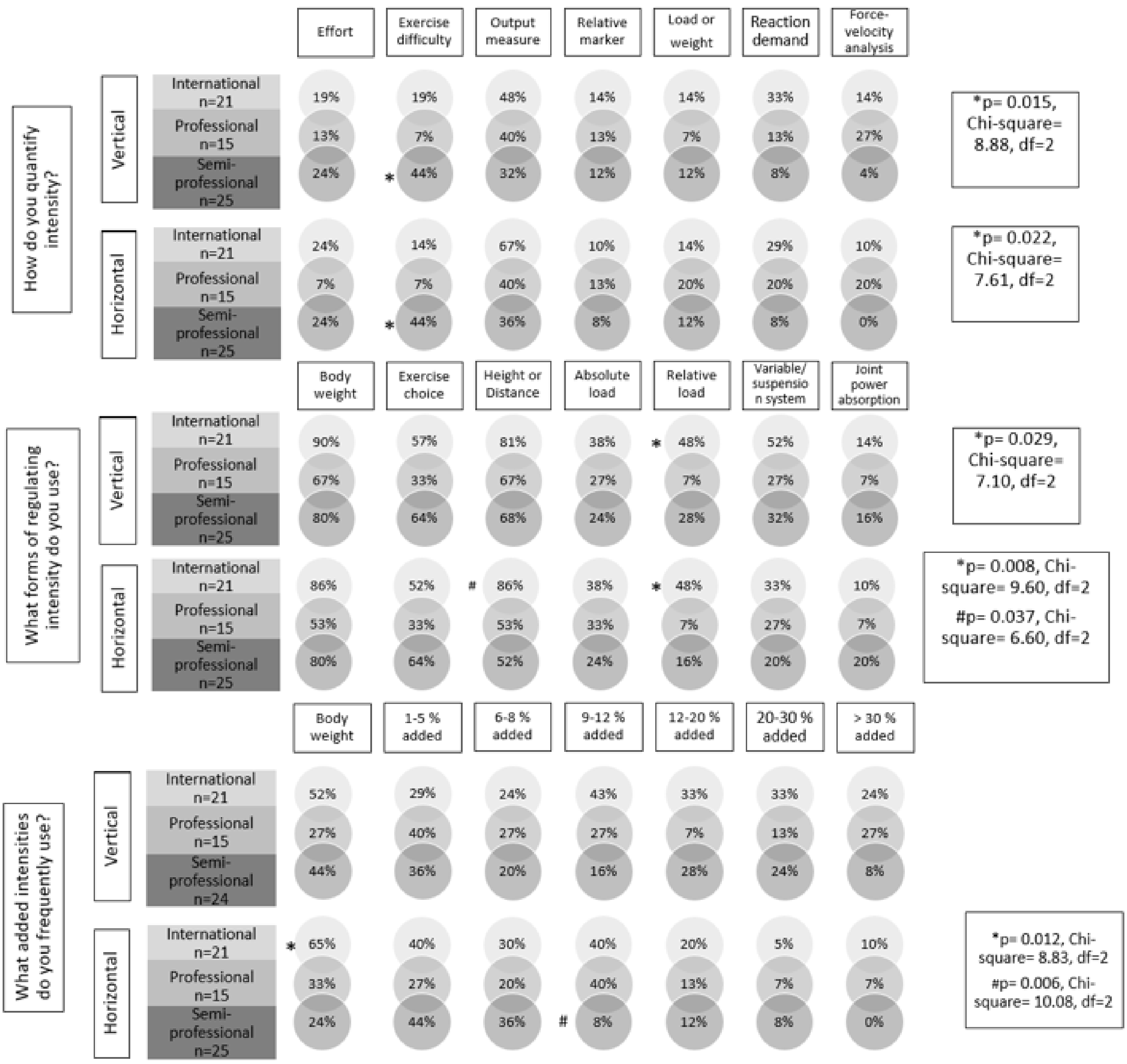


Figure 5.5. Percentage of responses reported by competition level for methods of quantifying, regulating and adding intensity for vertical and horizontal plyometric exercises. Questions allowed for multiple responses if applicable, thus intra-group analysis between methods was not conducted.

5.3.10. Exercise choice

In terms of combined plyometric use with other exercise modalities, 78.7% (n = 48) reported resistance training, 31.1% (n = 19) eccentric training, 9.8% (n = 6) gymnastics, 68.9% (n = 42) using weightlifting, and 62.3% (n = 38) sprint training. There were no significant differences between competition level or sport category ($p > 0.05$).

In contrast, exercise choice highlighted significant differences across competition level and sport categories ($p < 0.05$). For the single leg drop jump (SLDJ), 47.6% (n = 10) of international-level practitioners reported using this exercise compared to only 20.0% (n = 3) of professional and 16.0% (n = 4) of semi-professional practitioners ($p = 0.043$). Similar non-significant trends could be seen for bilateral vertical ($p = 0.055$) and horizontal DJ ($p = 0.059$), and SL box jump downs ($p = 0.060$). Across sports, mixed sport categories were significantly less likely to use CMJ, while field team sports and mixed sports were less likely to use SL box jump downs, and individual sports were less likely to use SL hurdle jumps ($p < 0.05$). Differences in commonly used exercises across sports are shown in Figure 5.6.

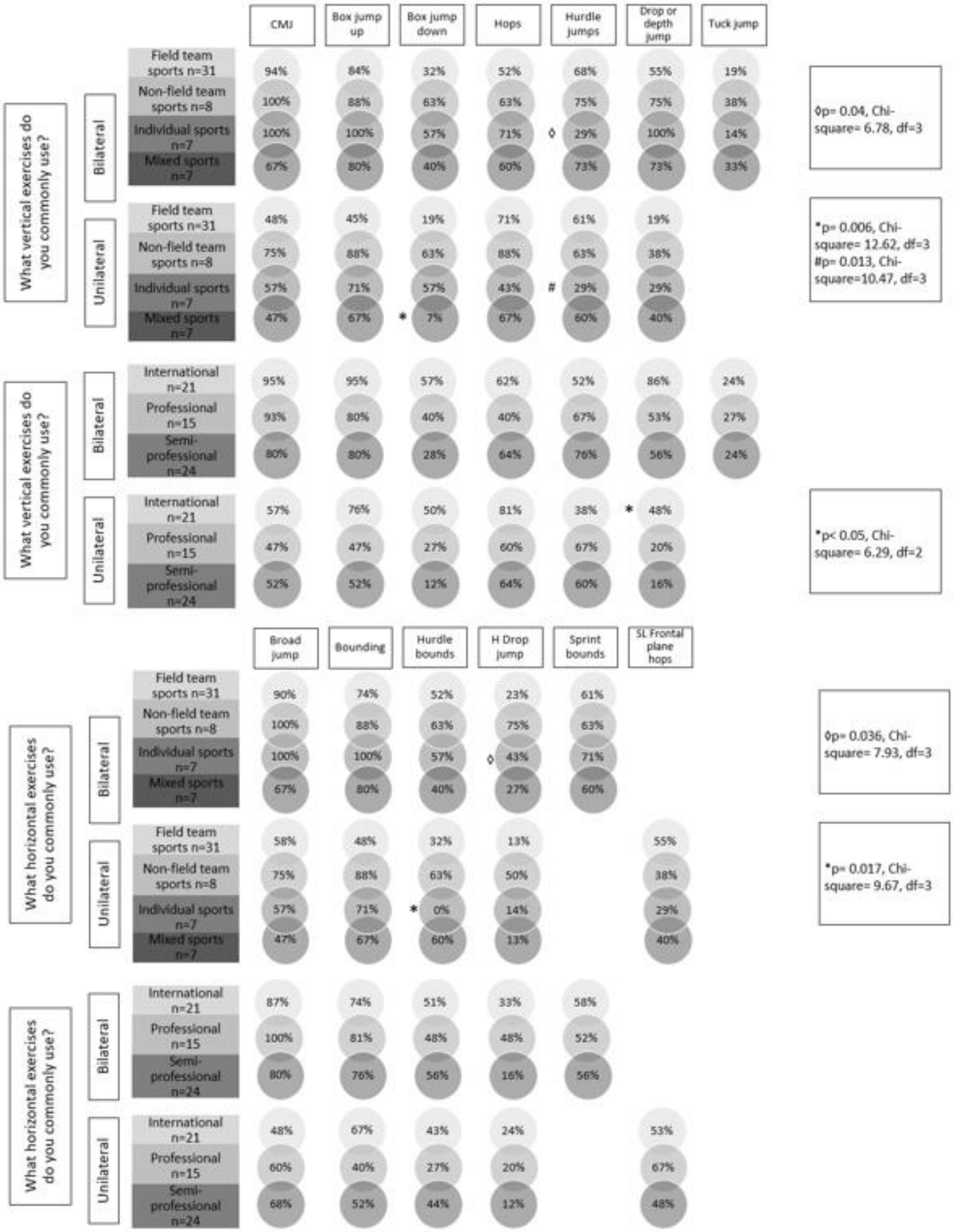


Figure 5.6. Percentage of responses reported by competition level and sport categories for vertical and horizontal plyometric exercise choice. Questions allowed for multiple responses if applicable, thus intra-group analysis between exercises was not conducted.

5.3.11. Training direction

Overwhelmingly, 68.9% ($n = 42$) of all respondents reported regularly combining both horizontal and vertical components, whereas 27.9% ($n = 17$) predominately used directionally specific training sessions, and 3.3% ($n = 2$) of practitioners did not provide an answer. Interestingly, there was a significant difference between the average amount of time spent using vertical (54.8 ± 15.9%) and horizontal exercises, (43.0 ± 15.2%), respectively ($p < 0.01$). Similarly, the proportion of a programme spent in bilateral as opposed to unilateral exercises significantly differed between vertical and horizontal axes, with practitioners reportedly spending more time bilaterally during vertical exercises than horizontal exercises (58.4 ± 17.1% vs. 48.0 ± 20.4%; $t(60) = 19.3$, $p < 0.001$). Across one set, there were no differences in GC rep ranges between vertical and horizontal exercises ($p > 0.05$). The majority of practitioners reported using low rep ranges, 16.4% ($n = 10$) and 21.3% ($n = 13$) reported one to three GC for vertical and horizontal exercise; 67.2% ($n = 41$) and 52.5% ($n = 32$) reported three to six; 9.8% ($n = 6$) and 18% ($n = 11$) reported 10 – 20 GC per set. There were no differences between sport category or competition level ($p > 0.05$). Similarly, there were no differences between average programme intensity and direction, with 11.5% ($n = 7$) and 16.4% ($n = 10$) reporting low average intensity for vertical and horizontal programming, 52.5% ($n = 32$) and 45.9% ($n = 28$) reporting moderate average intensity, and 36.1% ($n = 22$) and 37.7% ($n = 23$) reporting high average intensity for vertical and horizontal plyometrics.

5.4. Discussion

5.4.1. Main findings

The primary aim of this investigation was to better understand strength and conditioning practitioner's perspectives and implementation of plyometrics while obtaining more clarity on how well their reported programmes match current literary recommendations. The primary finding showed several differences in reported programmes compared to previous literature, most notably with lower sessional volume loads. The secondary aim was to investigate trends in programming across different competition levels, sport categories, and training axes, in which reported findings highlighted discernable trends for all three considerations, but more so for competition level than sport category.

5.4.2. Current practice versus literary recommendations

Several reported findings from this survey differ from literary recommendations. Most notably, sessional GC were considerably lower than previous recommendations (78,96,207). Very few practitioners in the current investigation reported using frequently researched moderate-high volumes (>100) regularly with their athletes (232,236). Practically speaking, >60 GC per session may offer diminishing returns for athletes working to maintain a multi-faceted athletic profile. Indeed, previous session volumes of >100 have left athletes feeling sore for 5 – 7 days, hindering the athlete's ability to compete on a weekly basis (151). More recently, investigations have reported equivocal benefit from high and low volume protocols, questioning the need for increased volumes (49,99). In fact, sessional volumes of just 40 SLDJ have demonstrated an effective stimulus for improving sprint performance in elite athletes (157). Such findings highlight the need for further research surrounding the optimal dose response, particularly in well-trained athletes.

In contrast with published evidence, most practitioners (49.2 – 78.7%) did not require athletes to possess a minimum strength or sport experience requirement prior to starting plyometric training, and only 11% of practitioners cited injury as a limitation. Instead, many practitioners reported progression, movement screens and modifications as key characteristics to successful plyometric training. Consensus surrounds the frequency of training with the majority of literature and practitioners reporting twice weekly for the greatest training efficiency (380). Although, some authors suggest 72 over 48 hours rest between sessions for maximal velocity, if training on sand (11). Interestingly, although quite prevalent in research, only 26.0% of practitioners reported using tuck jump as a common exercise. From this survey, it is difficult to say whether this cohort believed it to be sub-optimal, difficult to execute, or just opted for different exercises. Kinetic analysis of plyometric exercises suggests the tuck jump may be of lower priority to practitioners, having greater take-off ground reaction forces, but slower time to take off than DJ, and lesser power, jump height, and eccentric velocity than both CMJ and DJ varieties (98). Some debate exists around it's viability as an injury screen (220). The results provide a rationale for researchers to consider dissimilarities for future investigations.

5.4.3. Competition-level analysis

Reported findings demonstrate unique competition-specific programming considerations. Both international and professional practitioners tended to have greater coaching, plyometric training, and athlete experience than semi-professional and amateur practitioners. One can assume practitioners working in elevated competitions with greater stakes will typically have athletes and coaching staff with more coaching experience; however, this relationship was even stronger for plyometric training that emphasizes the importance of identifying optimal practice.

Interestingly, reported limitations offer some insight into competition-level programming considerations, with each increasing level offering more resources, specific scheduling constructs, and unique constraints. International practitioners were more likely to report no limitations, citing the ability to "vary the nature of the drill to accommodate the athlete" as an important characteristic. In contrast, professional-level practitioners were more likely to cite sport-specific limitations such as "other coach's requirements and practice times that can negate training stimulus," "total workloads", and "post game fatigue". Furthermore, semi-professional practitioners were most likely to report lack of resources as a limitation. Interestingly, expert practitioners have been identified by their ability to effectively coach large groups while still tending to individual needs, and prescribing athlete-based modifications that are easily understood (212). This suggests limitations may be a facet of coaching capability, subsiding as a practitioner gains more experience. Alternatively, competition level differences in workload, athlete ability, schedules, and resources may be important drivers for programming decisions. Professional and semi-professional level practitioners were less likely to use relative loading to modify vertical and horizontal intensity compared to international practitioners, presumably due to added resources and set-up time required. Furthermore, semi-professional practitioners were more likely to use primarily bodyweight horizontal exercises, and only 4.0% (n = 1), compared to 40.0% (n = 6) of professional and 40.0% (n = 8) international practitioners, reported using added intensities of 9 – 12%, despite the fact that some authors deem this load to be optimal for improving lower body power (70).

Overall weeks of plyometric training per year across competition levels were almost identical (~24 weeks); however, differences existed in the periodisation across different competition phases, highlighting unique athlete characteristics. International-level practitioners were more likely to programme 1 – 4 and >5 weeks of plyometrics during late competition and playoff periods, and non-significant trends followed a similar pattern during other in-season competition phases. Conversely, international practitioners tended to programme less plyometrics during off-season periods. Sporadic schedules, heightened competition, high workloads and sufficient strength may prime athlete to withstand and benefit from more plyometric training especially during later-season periods. Alternatively, professional athletes often endure lengthy seasons with frequent (1 – 3x weekly) contests, where fatigue-induced performance decrements in later competition phases is well reported (21). In contrast, reported findings suggest semi-professional practitioners may focus more on developmental athlete progression, using exercise difficulty to quantify exercise intensity, and tending to use more low-intensity programmes (24% vs. 5% professional and 0% international practitioners). Additionally, semi-professional practitioners were more likely to programme higher session volumes during the off-season period, suggesting increasing work capacity and SSC tissue resiliency may be a priority for lesser-trained athletes (200). On the other hand, not one international-level practitioner reported programming >40 GC during off-season. Findings may reflect the high level of intensity during the competitive season, requiring considerably reduced training volumes in off-season periods. Alternatively, considering the caliber of competition, athletes may instead retain high MTU capacity, potentially allowing for more advanced plyometric exercises like SLDJ and requiring less volume.

5.4.4. Differences between sports

The reported findings demonstrated differences between sport categories mainly in exercise choice, and training surface. While there were differences in training surface between competition levels as well, these results are more likely a factor of uneven professional individual sport group frequencies, rather than a true representation of competition level characteristics. Not surprisingly, training surface typically fell in line with training availability, field-sport athletes reporting turf and grass more so than individual sport athletes.

Differences in exercise choice may reflect kinematic characteristics relating to that sport. For example, non-field team sports (i.e., court, rink) were most likely to use horizontal drop jumps, single-leg box jump down, single-leg hurdle hop, single-leg hurdle bounding, and trended similar for the SLDJ. Considering these sports involve frequent short sprints and substantial change-of-direction demands, these athletes will rely heavily on eccentric force absorption and single-leg power during deceleration and reacceleration. Thus, practitioners may preferentially choose eccentric and single-leg variations to accommodate sport-specific needs (206).

5.4.5. Training axis

The reported findings demonstrate subtle differences in vertical vs. horizontal programme details. Results showed practitioners typically used ~10% more vertical exercises in their programme and were more likely to use bilateral vertical exercises as opposed to horizontal exercises. This may be a result of vertical exercises historically being researched to a greater extent or reference to subjective perception of traditional bilaterally based CMJ compared to unilaterally based horizontal sprinting athlete assessments. Proponents of the force-vector theory suggest training sport-specific characteristics of jumping and sprinting, contending unilateral exercises performed horizontally will preferentially improve sprint performance (127). In contrast, unilateral hops performed vertically have also been shown to preferentially increase speed and explosive power compared to their bilateral counterparts (206). On the other hand, some horizontally oriented exercises may cause more stress than commonly prescribed vertical exercises due to added anterior-posterior forces and pelvic stability, and thus may require less volume (193).

5.4.6. Study limitations

As with any study, this project is not without limitations. While efforts were taken to seek advice from qualitative research experts, and multiple pilot trials were conducted with elite strength and conditioning practitioners to ensure answers provided matched the question intent, no formal reliability analysis was conducted. Additionally, low sample sizes from certain countries primarily prevented any cultural analysis. However, that does not eliminate the potential for societal differences in perceived efficacy or programming styles. The impact of culture and ethnicity on sport management, participation and training practices is well understood (370). Moreover, while anonymity was prioritised, no further probing or interviewing to clarify vague or non-responses was able to occur. Finally, due to the nature of individual reports, this study can only comment on the perceived efficacy and reported programming practices of the respondents. Future studies should investigate reported information through experimentally designed protocols to determine optimal training practices and to further bridge the disconnect between theory and practice.

5.5. Practical Applications

Practitioners appear to use significantly lower plyometric training volumes than what is currently recommended in the literature. Researchers should consider this observation when formulating plyometric programme interventions that are both beneficial and ecologically valid. Additionally, practitioners would benefit from researchers providing more comprehensive reporting on monitoring tools including GCT for specific exercises, and relevant force-time or velocity-based metrics for improved programming and periodisation. Our reported findings additionally allude to competition-level characteristics and specific programming considerations that seem to be more prevalent than across sports. Particularly, periodisation across competition phases, horizontal intensities and the inclusion of SLDJ indicate unique considerations between practitioners working in international, professional and semi-professional or amateur competitions. Lastly, training differences also exist in vertical and horizontal programming strategies which may reflect sport-specific kinematic characteristics, an exercise progression spectrum, or coaching familiarity. Investigating these reported programming practices is necessary to provide ecologically valid recommendations to help bridge the gap between theory and real-world applications.

Chapter 6 – Kinetic analysis of a low-volume vertical versus horizontal plyometric stimulus with progressively increased volume on jump performance and kinetic characteristics.

Reference

Manuscript in preparation for journal submission.

Author contribution

Watkins CM, 80%, Gill ND, 4%, McGuigan MR, 4%, Spence AJ, 2% Maunder EM, 2% Neville, J, 2% and Storey AG 6%.

6.0. Prelude

Analysis of published literature (Section I) and expert practitioner reports (Chapter 5) has enabled a comprehensive understanding of critical plyometric programming components including volume, intensity, and exercise choice. Literary recommendations has supported wide ranging session volumes, proposing 140 – 400 $GC.session^{-1}$ in some cases (78,96). Conversely, expert practitioners' reports revealed much lower volumes (Chapter 5) (389). In particular, those practitioners working in the international and Olympic competitions rarely reported volumes above 60 $GC.session^{-1}$. This may be a result of the way intensity is monitored, the use of higher-intensity exercises such as SLDJ or specific periodisation reported to accommodate international competitions. Interestingly, most survey participants reported ~10% greater use of vertical plyometrics to horizontally oriented exercises. Additionally, vertical exercises were more likely to occur bilaterally as opposed to horizontal exercises, which were primarily implemented unilaterally. In light of these findings, it is difficult to conclude whether this is a result of perceived efficacy, induced MTU stress, or familiarity. As such, there were still literary gaps in the understanding of acute physiological stress and performance effect of high-volume sessions with progressively increased volume. Furthermore, more clarity is required on the specific influence of training axis on structural fatigue and force production throughout high jump volumes.

6.1. Introduction

While there is a strong agreement that plyometric training is beneficial for sprint performance (58,157,231,377), the optimal manipulation of volume and training direction for improving sprint profiles is poorly understood. Of particular interest to many practitioners is determining the minimum dose for an effective training stimulus that maximizes performance whilst minimizing unnecessary fatigue during the preparation for weekly competitions. Yet, current recommendations for plyometric session volumes range from 40 – 140 GC for novice to intermediate trained individuals, reaching as high as 200 – 400 GC for advanced athletes with little clarity on dosing necessity or effectiveness (78,96,207). As a result, strength and conditioning practitioners make frequent programming decisions, weighing up training costs vs. benefits, adaptation priority, transference, and time. Rugby union players, for instance, are required to maintain a varied athletic profile, with opposing athletic qualities including strength, power, speed, speed endurance, and aerobic fitness (178). Thus, questions arise concerning how much plyometric volume is necessary during individual sessions to elicit a positive adaptation, and when does an increase in training volume become maladaptive or harmful.

Substantial research has investigated neuromuscular fatigue resulting from long-duration (i.e., marathon running) (19,301), exhaustive (149,151,161,218,286,321) and non-exhaustive (79,85,123,124) SSC exercise bouts. At present though, the vast majority of this literature has focused on endurance running and vertically oriented jumping interventions. Generally, a consensus exists around the consequences of exhaustive and non-exhaustive, but intensive, bouts whereby neuromuscular function and jump performance can be inhibited for two – seven days post-session (149,151,364). Typically, the recovery pattern following a prolonged bout of exhaustive SSC exercise is bimodal in nature, resulting in an immediate performance decrement, a slight recovery and a secondary performance decline two – three days post-exercise depending on the severity of induced fatigue (151). For active males, even non-exhaustive volumes of only 100 GC either CMJ or DJ was sufficient to decrease maximal muscle force and impaired contraction dynamics for one – four days post-session (148,354). Long-lasting fatigue from high-volume dosing strategies may not be desirable in a competitive team environment with multiple training stimuli and short recovery windows to consider. Yet trained athletes will have a greater threshold for stress than untrained cohorts, requiring more research into the effect of progressively added volumes in-session. Acute analysis of rugby players performing a single bout of high-volume non-exhaustive plyometrics (i.e., 212 GC) reveals immediate peripheral fatigue-induced decrements had mainly recovered following two hours of rest (85). In contrast, comparison of different session volumes (100, 200, and 300 GC) in a similar cohort demonstrated an equally suppressed ability to jump and produce force for at least 24-hours post session (49). While these reports did not investigate proposed performance benefits of high-volume jumping, international and national level strength and conditioning practitioners report using significantly less session volume than practitioners in lower-level competitions and rarely programme session volumes above 120 GC.session^{-1} (Chapter 5) (389). Practitioner reports are consistent with recent literature proposing the benefits of low-volume plyometric protocols on an acute (158,372) and chronic basis (157,388).

One consideration for high-volume plyometric training that is rarely investigated is jump quality or in-session monitoring with progressively increased volume. The benefits resulting from plyometric intervention is innately dependent on the magnitude and rate of loading, and due to primarily body weight only stimuli, relies on movement velocity to regulate SSC stimulated adaption (287,358). Interestingly, there is some evidence to suggest some trained athletes are able to maintain jump height despite training induced fatigue by altering movement patterns and motor programmes (119). For example, an athlete might increase the duration of the jump or the downward displacement in a CMJ in the presence of fatigue to allow more time to build up force and produce the same jump height (119). In these cases, one might argue the athletes may not be receiving the proposed benefits of the SSC, as a delayed ability to switch between eccentric and concentric actions often times results in energy being dissipated as heat, rather than used for performance (367). Moreover, eccentric fatigue has been shown to modulate the effectiveness of stretch reflex sensitivity (364), affect pre-contact and motor unit activation levels (150), alter calcium release and contraction dynamics and regulate stiffness and tendon compliance (151,364). Collectively, these fatigue-related decrements may compartmentalise the SSC system to isolated structures, thereby reducing their integrated performance augmentation.

Furthermore, there is scant information surrounding the effect of training direction on acute fatigue in-session. Some authors theorise horizontal plyometrics may be more preferable for acceleration phases where horizontal forces make up a greater proportion of the resultant force (157,231). Conversely, it is theorised that vertically oriented training may preferentially benefit secondary acceleration and maximal speed phases (231). For instance, performing vertical and horizontal SLDJ both resulted in improved sprint performance following 10-weeks of low-volume (40 – 70 $GC.session^{-1}$) training (157). However the horizontal group demonstrated superior differences for both sprint and change-of-direction time, whereas the vertical group preferentially increased leg stiffness and vertical kinetics during vertical jumping tasks, highlighting distinct adaptations (157). Nevertheless, previous literature reporting the absence of any sprint performance benefit has typically been void of horizontal training (373), yet these horizontally-induced adaptations may not be without additional cost. Acute analysis of horizontal and vertical plyometrics reveal much greater peak landing forces in all directions for horizontal exercises, which may subsequently affect exercise and appropriate dosing strategies (193).

Therefore, the purpose of this study was to investigate acute in-session kinetic performance following a low-volume plyometric session (40 GC) and subsequent fatigue during progressively increased non-depth (i.e., BJ or CMJ) plyometric volume during both horizontal and vertically oriented jumping sessions. It was hypothesised the low-volume plyometric stimulus would prompt a potentiated response in both BJ and CMJ assessments, but that fatigue may alter kinetic performance with increased volume.

6.2. Methods

6.2.1. Experimental approach to the problem

Academy level male rugby players (n = 20) were recruited from two competitive teams to perform one horizontal and one vertical, high-volume plyometric session each in a random order. Sessions took place one week apart at the same time of day to minimize circadian rhythm interference (213). Additionally, participants were instructed to refrain from any exercise at least 48 hours rest prior to each session. Both sessions consisted of baseline strength and jump testing, a low-volume plyometric stimulus phase, a progressively increased jump (CMJ or BJ) volume phase with reoccurring kinetic measurements every 10 jumps, and a final post-session jump assessment. This approach allowed the researchers to investigate in-session acute fatigue with progressively increased plyometric volumes during individual sessions, while comparing kinetic differences based on training direction.

6.2.2. Participants

Initially, a sample size calculation was performed in G*Power using similar research reporting an eta-squared of 0.59 which estimated a sample size of eight participants. Considering drop out, scheduling conflicts, and technology issues, 20 club and semi-professional rugby players were recruited and volunteered for this study, consisting of both forwards and backs positions. However, three participants dropped out following one session (horizontal = 2; vertical = 1) due to excessive soreness, and technical difficulties with force plate collection prevented an additional subject from completing the vertical session. Therefore, 16 participants (age = 20.0 ± 2.0 years; mass = 103.0 ± 17.6 kg; height = 184.3 ± 5.5 cm; $IMTP_{abs}$ = 2104.4 ± 345.7 N) who completed both sessions were included in the analysis. All participants were tested in the off-season as not to hinder competition but were currently involved in resistance training and rugby-specific training two-three times weekly. As such, all participants were familiar with standard CMJ and BJ assessments, nevertheless researchers confirmed their proficiency pre-trial. Additionally, all participants were considered trained males (back squat 1RM = 1.0 – 2.0+ x body mass) and were free from any musculoskeletal injuries that would prevent them from participating in sport practice. Auckland University of Technology ethics committee approved this study. All participants were informed of the voluntary nature of the project, and all participants provided written informed consent.

6.2.3. Isometric mid-thigh pull

During the first assessment, participants were tested for maximal strength using an Isometric Mid-Thigh Pull (IMTP) assessment (63,387). Force data was collected at 1000 Hz via a custom designed portable load cell prototype, interfaced with a custom software (SPRINZ Laboratories, Auckland University of Technology). Raw unfiltered force-time data was exported for subsequent analysis in CSV format. The data was then imported and analysed in MATLAB (MathWorks, Natick, MA), using a custom algorithm. Each trial was trimmed to length to include a pretension period of at least one second, force onset, isometric contraction for three – five seconds, and a force offset. The onset of force was defined as an increase in force that was greater than 6 standard deviations of force calculated from a 500 ms pretension window within 0.5 – 1 s before the contraction.

Participants stood in a power athletic stance similar to that of the second pull during a clean; upright torso, shoulder blades retracted and depressed, feet hip width apart with their hip, knees, and ankles slightly flexed (63). The bar was positioned mid-thigh and attached via chains and a base plate positioned directly underneath the athlete, such that the athlete acted as their own counterweight. Prior to the initiation of the pull, the participants were instructed to maintain minimal tension, but to remove any slack that would result in joint angle fluctuations (63). Once positioned correctly, participants were given one or two practice repetitions and the bar was adjusted to allow the athlete to obtain a comfortable position within optimal knee angle range (approximately 120 – 135°). Participants were instructed, "to pull up and back as hard and as fast as possible" and hold for three – five seconds. Researchers used visual feedback to confirm a successful trial. Trials were excluded if a pre-countermovement occurred, the athlete's weight shifted during the trial, or the athlete was not able to maintain a steady pulling force and successive "peaks and valleys" occurred after the initial peak force.

6.2.4. Plyometric stimulus

During both sessions, participants completed a direction-specific (i.e., horizontal or vertical) low-volume (40 GC) plyometric stimulus following baseline assessments. Each intervention included four exercises matched for volume load and kinematic characteristics (Table 6.1). Both sessions started with a 30 cm DJ performed either vertically or horizontally to foster rapid MTU stretch rates. Participants were encouraged to "attack the ground and jump as high or as far as possible." The following three exercises were cyclic to encourage greater energy reutilization. For the vertical session, power step ups, single-leg CMJ, and ankle POGO hops were employed. For the horizontal sessions, double-leg bounds, single-leg bounds, and lateral skater hops were completed. Rest was set at 15 s for single-rep exercises and 90 s between cyclic sets and separate exercises (319).

Table 6.1. Low-volume plyometric protocol. DJ = drop jump; SL = single-leg; CMJ = countermovement jump.

Vertical "low-volume" protocol		Horizontal "low-volume" protocol	
Vertical DJ (30 cm)	1 x 5	Horizontal DJ (30 cm)	1 x 5
Power step-ups	2 x 5 each	Double leg bounds	2 x 5
SL CMJ	1 x 5 each	SL bounds	1 x 5 each
Ankle "POGO" hops	2 x 10 each	Lateral "skater" hops	2 x 10 each

6.2.5. Jump assessment

The CMJ and BJ were used to assess vertical and horizontal jump performance, respectively. All kinetic jump assessments were performed on a Kistler force platform (Victoria, Australia), sampling at 1000 Hz. Additionally, for the BJ, a measuring tape was positioned in line with the middle of the force platform and laid horizontally for five metres, such that athletes jumped forwards from the force plate and landed on the ground. Successful trials required participants to stick the landing, wherein a wooden dowel marked the position of the participants' back heel for BJ distance. Prior to each assessment, researchers zeroed the force platform, then instructed participants to step on the force plate and stand still for ~one second to measure body mass. Hands were placed akimbo, and the command, "ready, set, jump" was given for each trial. Verbal encouragement was given prior to and following each jump to ensure maximal effort. Participants were aiming to jump as high or as far as possible, depending on the direction. For the CMJ, participants dipped down to a self-selected distance before rebounding vertically, aiming to "touch the ceiling with their head," prior to landing back down on the force plate. Each trial was visually checked for modifications that might falsely alter flight time (e.g., knee bent on landing, use of hands, etc.). For the BJ assessment, participants were instructed to jump as far as they could horizontally, with the aim of, "touching their head to the opposing wall." Thus, no landing kinetics were recorded during horizontal assessments. Of note, BJ distances may be altered slightly due to the fact participants were standing on a force plate for the assessments that was approximately ~10 cm above the landing position on the ground. However, all non-assessment training reps were conducted on the ground.

Kinetic jump assessments were performed PRE-0, following the low-volume (P-40 GC) plyometric stimulus, and subsequently after every 10 GC until the end (P-50, P-60, P-70…P-200 GC). PRE-0 assessments followed dynamic warm-up after which, participants performed two-three practice trials to reach a maximal baseline value. Each subsequent time point consisted of two trials performed in-set in order to avoid additional sessional GC, such that the last two repetitions in each set (e.g. repetition 9 and 10 of a 10-repetition set) were conducted on the force place. A trial cut-off percentage (-16%) was calculated off PRE-0 jump output (i.e., height or distance) to mitigate chance of injury, wherein if two successive jumps were below this threshold, the session would be stopped. A decrement in CMJ height of up to 12% is likely following an extremely fatiguing bout of RT in trained collegiate males (387). Due to the athlete's experience, weekly training load and the significant landing stress from jumps, an additional 4% decrement was allotted without concern of injury. Thus, a decrement of more than 16% PRE-0 output (i.e., height or distance) in two consecutive trials was deemed would unnecessarily fatiguing and potentially damaging to the athlete. Continuing the session with performance below this level was deemed inappropriate for semi-professional athletes and for improving speed performance. However, all participants successfully finished all initiated sessions without height or distance declining below the specified cut-off point.

6.2.6. Force plate file processing

All jump files underwent similar pre-processing preparation, but different analysis according to the jump direction, such that all BJ and CMJ trials were analysed separately. Unfiltered, tri-axial (x, y, and z) 1000 Hz force data was collected and imported into MATLAB for processing with a custom algorithm. Participants were required to stand still for one second prior to jumping for determination of body weight (270). A moving average window was used to calculate bodyweight and SD by finding the smallest SD in bodyweight within a 0.5 s window, meaning if the bodyweight SD was greater than 10 N, the window was progressed 10 samples (1/100 s) and the bodyweight and SD metrics were recalculated. Onset of movement for CMJ was determined as the point in which the vertical force fell below a threshold; equal to 6x the SD of respective 0.5 s window bodyweight measures. The unweighting phase was measured from the onset of movement to the instant the vertical force returned to bodyweight (256). Flight phase of the jump was found using a 20N vertical force threshold (363). After determination of point of interest, a 20Hz 4^{th} order low pass Butterworth filter was applied to the force data. Vertical and horizontal acceleration data were calculated from the filtered force data and then integrated with respect to time to get velocity (257,292).

6.2.7. Statistical parametric mapping

To investigate force production patterns within session, Statistical Parametric Mapping (SPM) methods analysed within-subject within-session files via MATLAB (299). This analysis technique provides insight into force-time patterns, enabling the comparison of these with progressively increased volume. The SPM process requires the time-normalisation of data files to remap the force production period to a range of 0 – 100% (onset of movement to take-off). Once data files were processed as mentioned previously, the average of two time-normalised trials was calculated for each time point. Therefore, each participant had one force-time curve spanning 0 – 100%. The SPM implemented a two-tailed t-test with confidence intervals set to 95%. This process was repeated for the horizontal channel during BJ propulsion, and the vertical channel during CMJ landing and stabilisation phases.

6.2.8. Statistical analysis

All statistical analysis apart from SPM was performed in R statistics. Data values are presented as estimated means and 95% confidence intervals unless otherwise stated. A two-way within-within repeated measures (direction x volume) ANOVA was used to investigate kinetic variable performance with increasing volume within-session and between directions. Significance level was set at $p \leq 0.05$. For significant relationships, post-hoc analysis was performed, and p-values were corrected using FDR adjustment. Using the PASS 15 software and a repeated measures analysis, we performed a post hoc power calculation given our observed data for Jump Output.

We based this on an F test with two within-subject factors: jump condition (2 levels) and jump repetition (18 levels). We set alpha set to 0.05, the autocorrelation among the repeated measurements to 0.5, the between-subject SD to 10, and applied the Greenhouse–Geisser degrees of freedom adjustment. We based our means for each within-subject factor on our observed data: jump condition (221, 39) and jump repetition (129, 131, 128, 130, 131, 132, 132, 130, 132, 131, 132, 132, 132, 132, 132, 130, 131, 132). We had >99% power to detect a difference between both of the within-subject conditions, and 82% power to detect an interaction effect. Additionally, within-session reliability was assessed on pre-session trial one and two data for jump height, durations, and impulse variables. Intraclass correlation values ranged from 0.89 – 0.99 with lower and upper confidence limits of 0.71 – 1.00. Within-subject coefficient of variance scores ranged from 1.4 – 6.5% with lower and upper confidence limits of 1.0 – 10.4%.

6.3. Results

6.3.1. Jump output

There was a significant interaction between direction and jump volume for jump output ($p < 0.001$; Figure 6.1). For BJ distance, P-40 and all subsequent time points were significantly greater than PRE-0, whereas CMJ height significantly decreased in height P-50, P-60, P-70 and P-160 compared to PRE-0 ($p < 0.05$; Figure 6.1).

6.3.2. Phase durations and ground contact time

There was a significant interaction between direction and jump volume for concentric duration ($p < 0.001$; Figure 6.2) and GCT ($p < 0.001$; Figure 6.3), but not eccentric duration ($p = 0.2$;

Figure 6.2). For GCT, there was also a main effect for volume ($p < 0.01$), but not direction ($p = 0.052$). For concentric duration, BJ PRE-0 may have been greater than many subsequent time points (P-40, P-70 to P-200), although none of the comparisons reached significance ($p = 0.058 – 0.079$). For vertical concentric duration, CMJ P-40 was significantly lower than all subsequent time points (P-50 to P-200; Figure 6.2). For eccentric duration, there were main effects for both direction ($p < 0.01$) and volume ($p < 0.001$; Figure 6.2). Eccentric duration was significantly greater for BJ compared to CMJ at PRE-0 and all subsequent time points, except P-130. In addition, BJ eccentric duration PRE-0 was significantly greater than P-60 to P-100 and P-120 to P-200. For horizontal GCT, PRE-0 was significantly greater than all subsequent time points (P-40 to P-200), while P-40 was significantly greater than P-80, P-130, and P-150 to P-200 (Figure 6.3). There were no significant differences for CMJ volume or between directions at any specific time point. However, many GCT comparisons (PRE-0, P-40, P-50, P-60, P-90, and P-170) approached significance between horizontal and vertical assessments ($p = 0.070 – 0.079$).

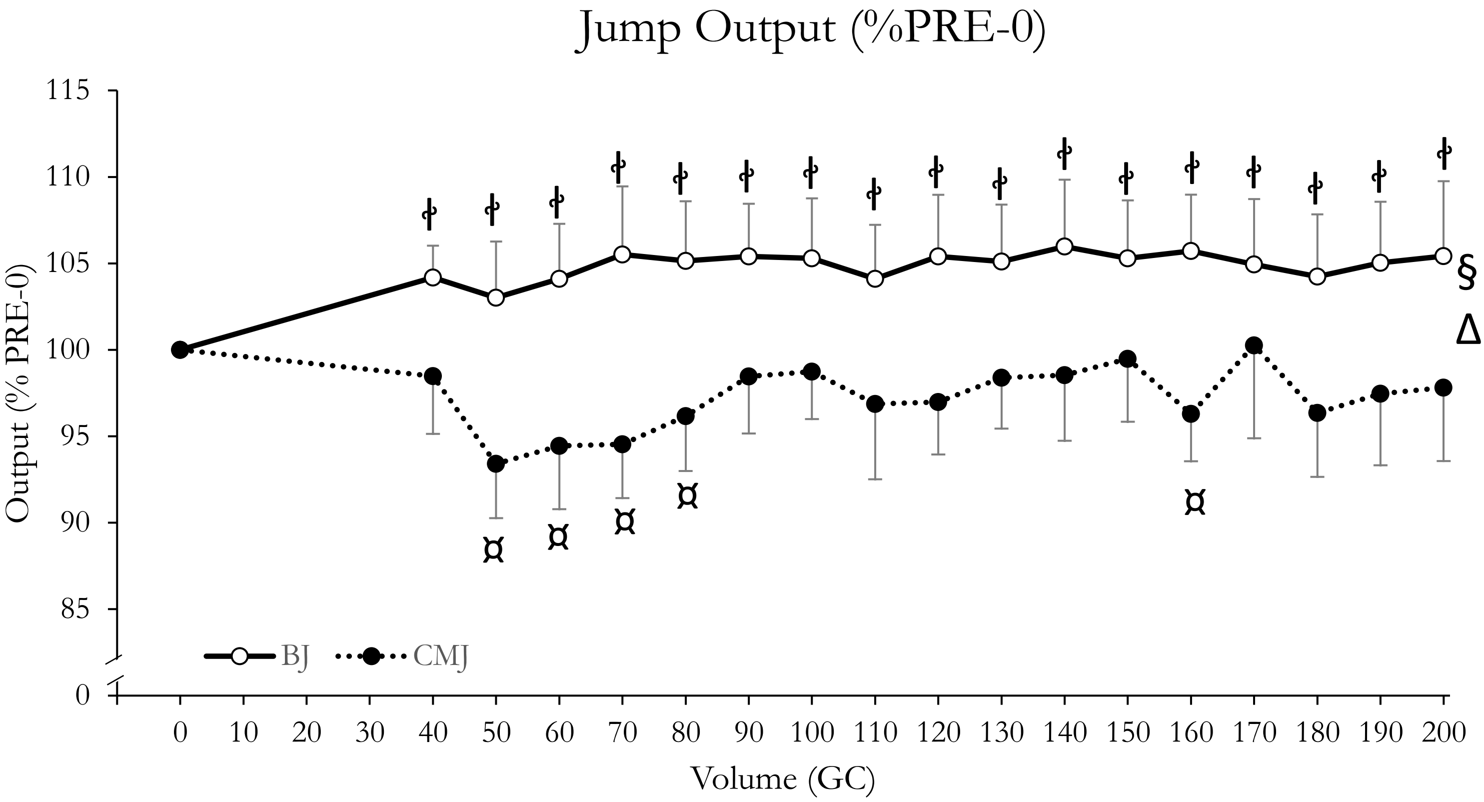


Figure 6.1. Estimated means and 95% confidence intervals for horizontal BJ and vertical CMJ jump output (i.e., distance or height) represented as a percentage of pre-assessment scores (PRE-0) as volume (measured in ground contacts (GC)) is progressively increased in-session. Symbols indicate significance ($p < 0.05$). § = significant interaction between direction and volume; Δ = main effect for direction, where all BJ assessments were significantly greater than all CMJ; ꝑ= Horizontal BJ volume significantly greater than PRE-0; ¤ = vertical CMJ significantly less than PRE-0.

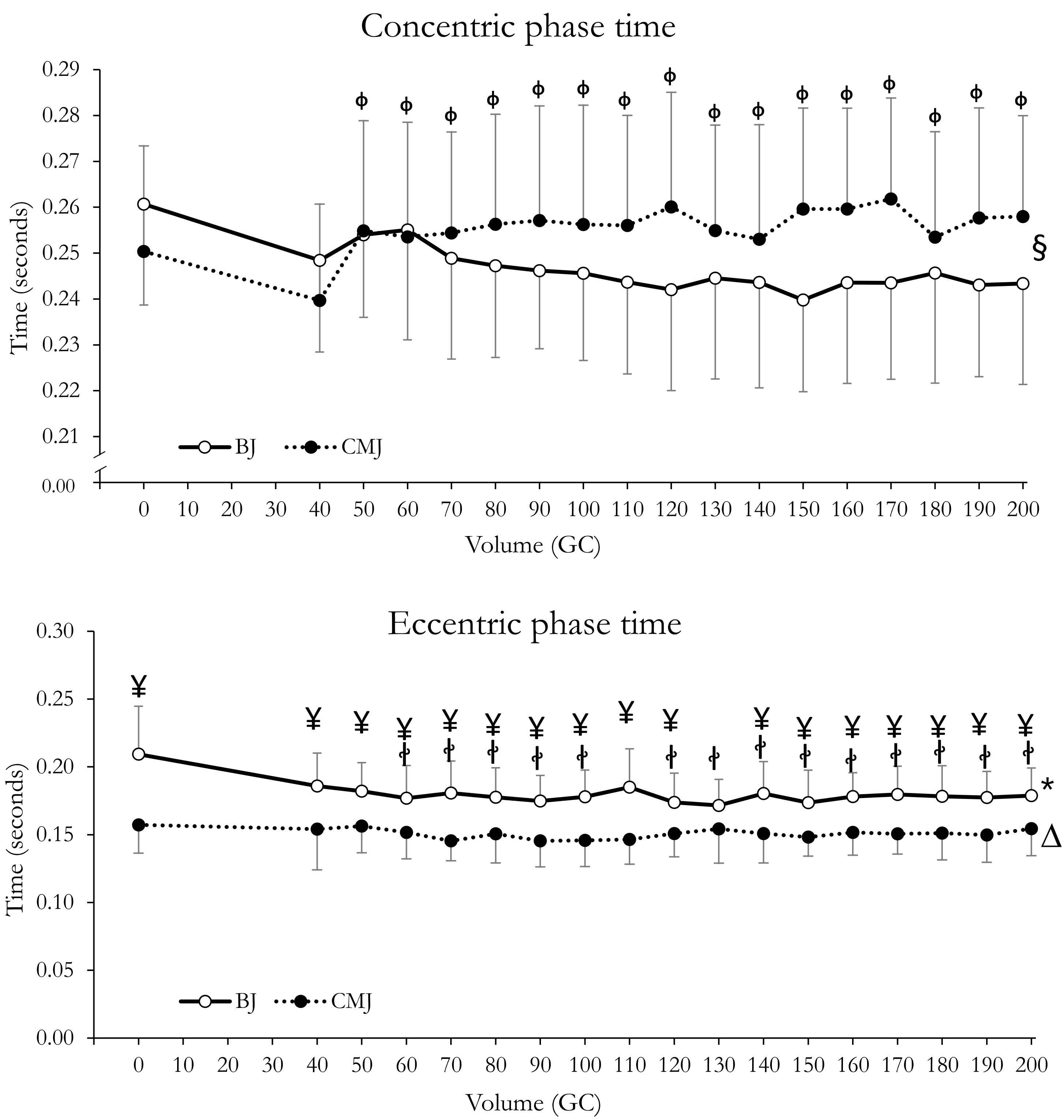


Figure 6.2. Concentric and eccentric phase time during vertical and horizontal assessments for PRE (0) and following progressively increased session volume (40, 50, 60…180,190, 200). Data presented as estimated means with 95% confidence intervals ($p < 0.05$). § = interaction between direction and volume; Δ = main effect for volume; * = main effect for direction; Φ = vertical time points significantly different to P-40; ƚ = horizontal time points significantly different to PRE-0; ¥ = significantly different between directions.

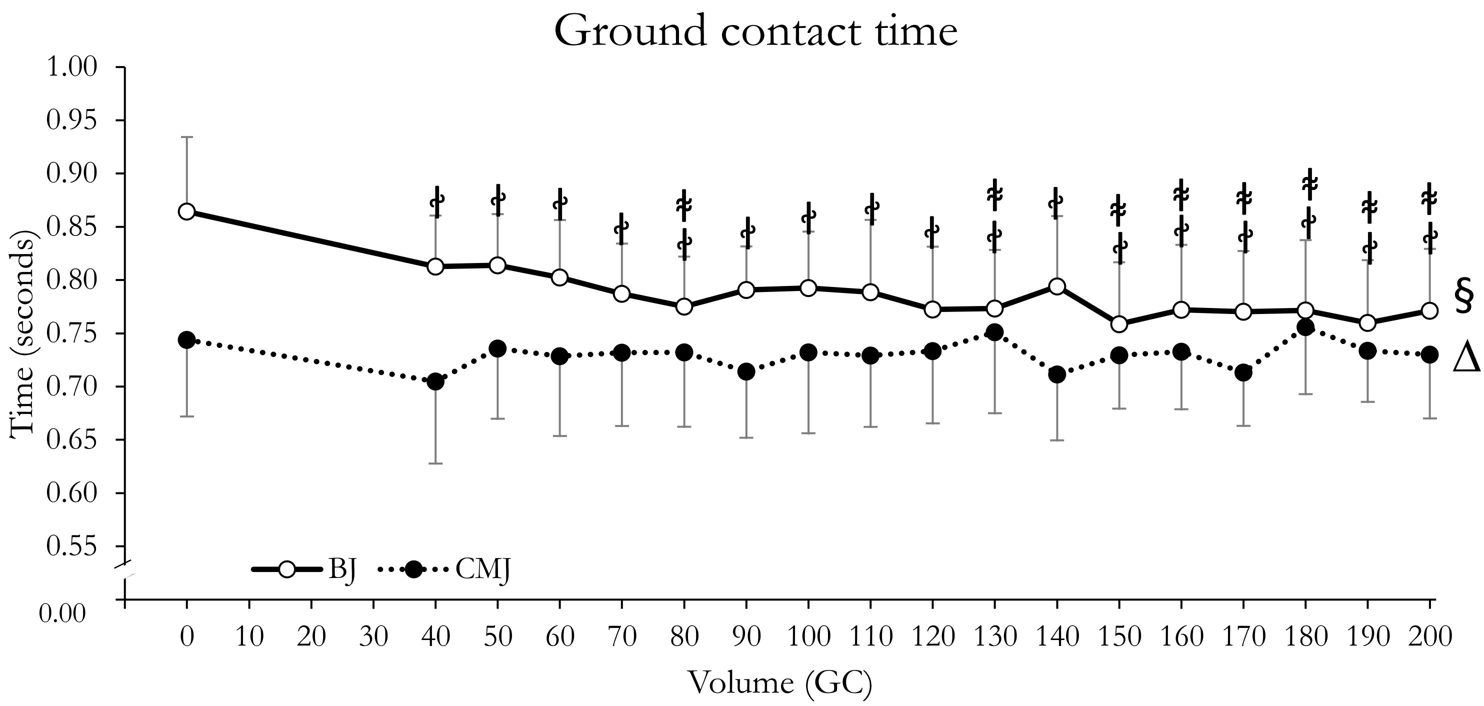


Figure 6.3. Ground contact time during vertical and horizontal assessments for PRE (0) and following progressively increased session volume, measured in ground contacts (GC) (40, 50, 60…180,190, 200). *Data presented as estimated means with 95% confidence intervals ($p < 0.05$). § = interaction between direction and volume; Δ = significant main effect for volume; Φ = vertical time points significantly different to P-40; ł = horizontal time points significantly different to PRE-0; ¥ = significantly different between directions.

6.3.3. Concentric and eccentric impulse

There was a significant direction by volume interaction for both eccentric ($p = 0.012$) and concentric impulse ($p < 0.001$; Figure 6.4). For concentric impulse, there was a main effect for direction, whereby vertical values were significantly greater than horizontal values ($p < 0.001$). For horizontal, BJ PRE-0 concentric impulse was significantly greater than all subsequent time points, while for vertical, CMJ PRE-0 was significantly greater than P-50, P-60, P-70, P-80, and P-160 (Figure 6.4). Similarly, BJ P-40 portrayed greater values than all subsequent time points, with many (P-100, P-110, P-140, P-160, P-170, P-190, P-200) approaching significance ($p = 0.06 – 0.09$).

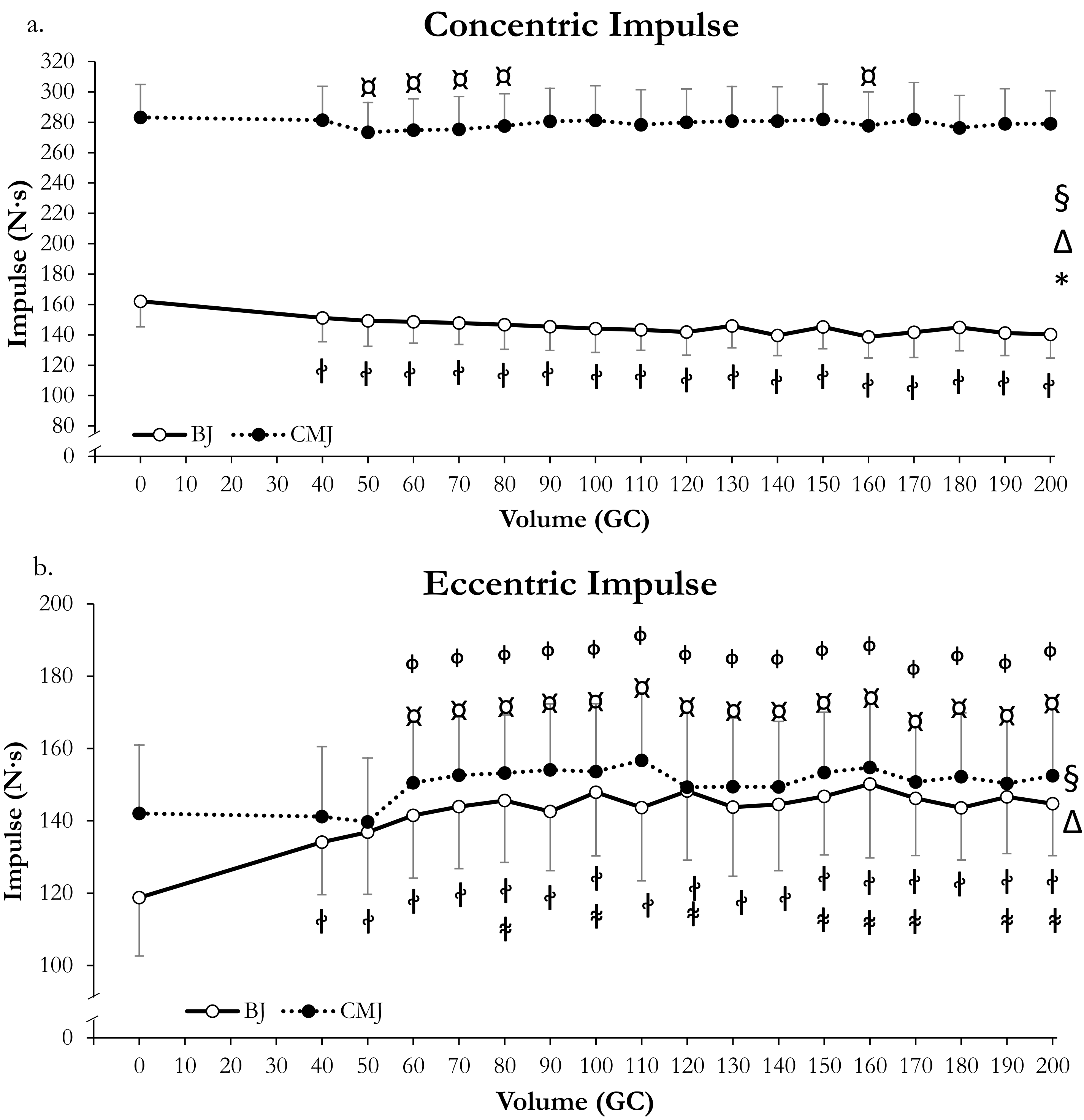


Figure 6.4. Concentric (a.) and eccentric (b.) impulse during vertical and horizontal assessments for PRE (0) and following (Post (P)) progressively increased session volume (P-40, 50, 60…180,190, 200). Data presented as estimated means and 95% confidence intervals. Symbols dictate significance ($p < 0.05$). § = interaction between direction and volume; Δ = main effect for volume; * = main effect for direction; ¤= vertical CMJ values different to PRE-0; ⸸ = horizontal BJ values different to PRE-0; ⸸ = horizontal BJ values different to P-40. *Note all CMJ concentric impulse values significantly greater than all corresponding BJ values.

6.3.4. Statistical parametric mapping

Time-normalised graphs for individual participants, group averages with standard deviation and SPM results with 95% confidence intervals for PRE-0 versus P-40 volumes is presented in Figure 6.5. There were no significant differences for this comparison.

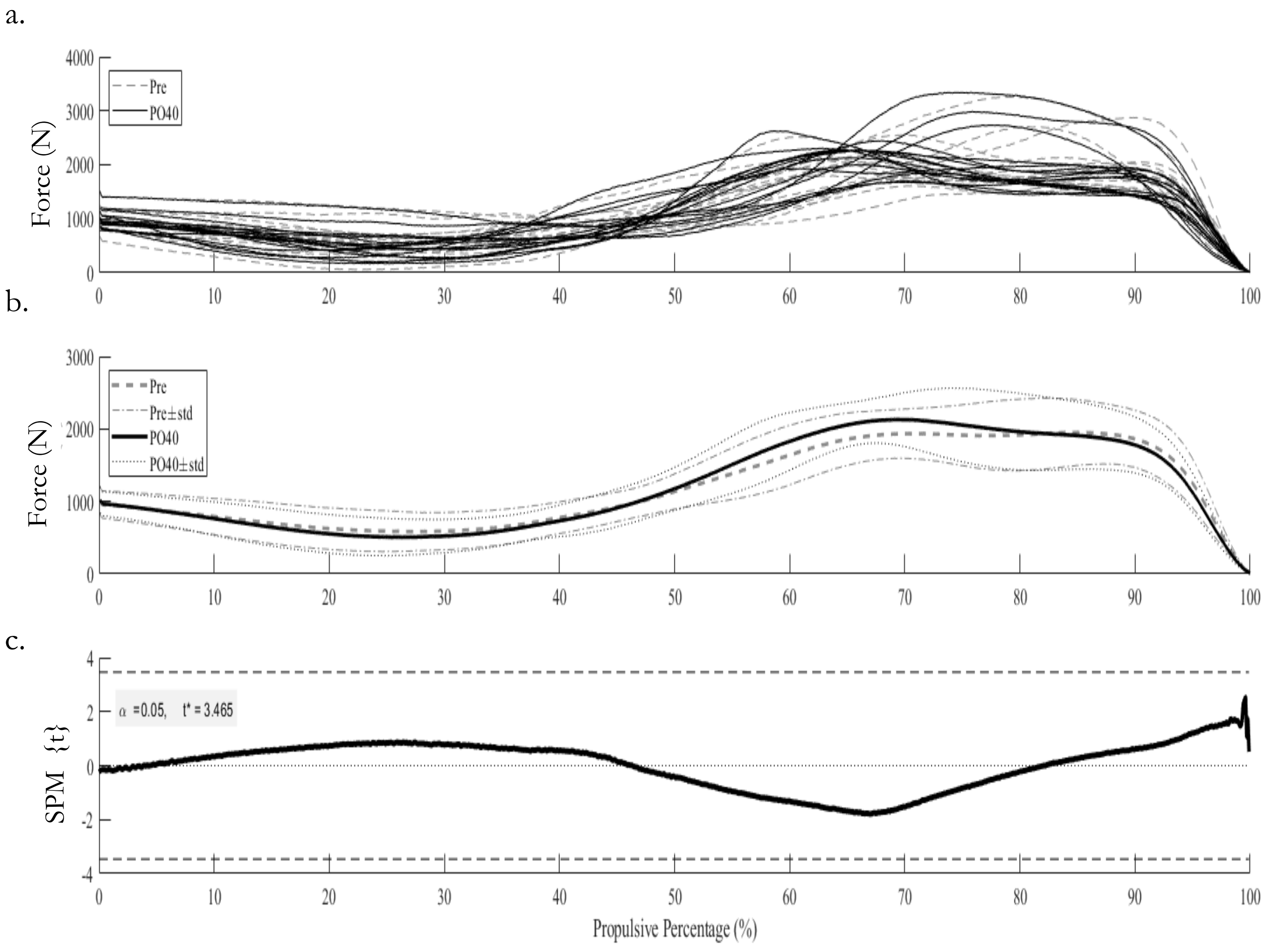


Figure 6.5. Time-normalised graphs for individuals (a); group averages (b); and statistical parametric mapping (SPM) graph (c) for PRE-0 and P-40 volumes. Group averages (b) presented with standard deviation; dashed lines (c) portray significance.

However, there were several significant comparisons for BJ performance with progressively increased volume (Figure 6.6 and Figure 6.7). Compared to PRE-0, P-100 (38.18 – 38.99%; $p < 0.05$), P-130 (98.3 – 99.33%; $p < 0.05$), P-150 (98.28 – 99.23%; $p < 0.05$), P-160 (97.73%; $p = 0.038$), P-170 (96.93 – 98.21%; $p < 0.05$), P-180 (96.09 – 96.33%; $p < 0.05$), and P-190 (96.43 – 99.05%; $p < 0.05$) portrayed significantly different periods (Figure 6.6 and Figure 6.7). The horizontal axis for the BJ also portrayed a significant comparison for PRE-0 versus P-150 (62.35 – 64.84%; $p < 0.05$). There were no other significant periods for horizontal axis, or for the vertical axis during CMJ propulsion, landing or stabilization ($p > 0.05$).

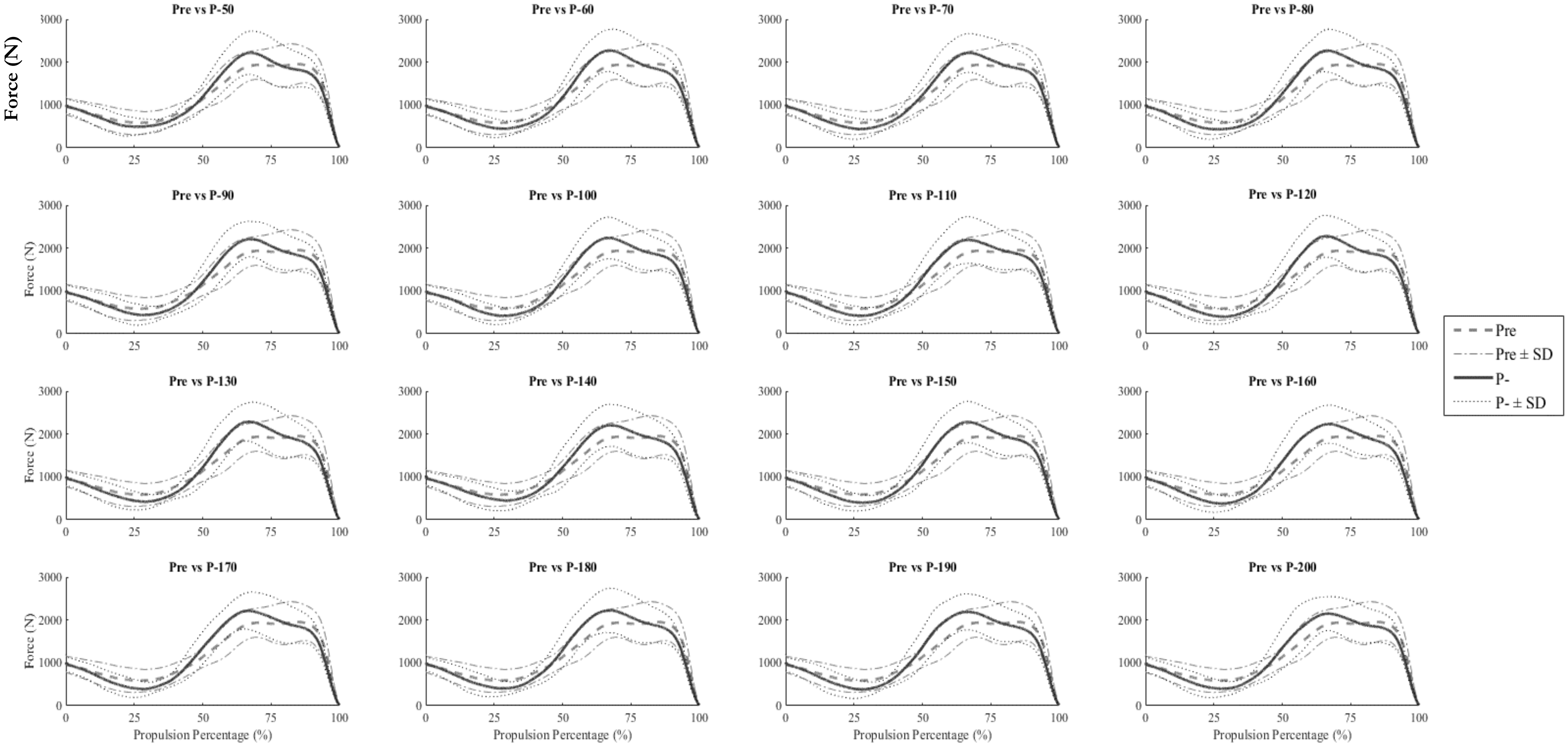


Figure 6.6. Group means and standard deviation (SD) for normalised-time graph comparisons Pre (dashed grey) vs. P-50 to P-200 (black line)

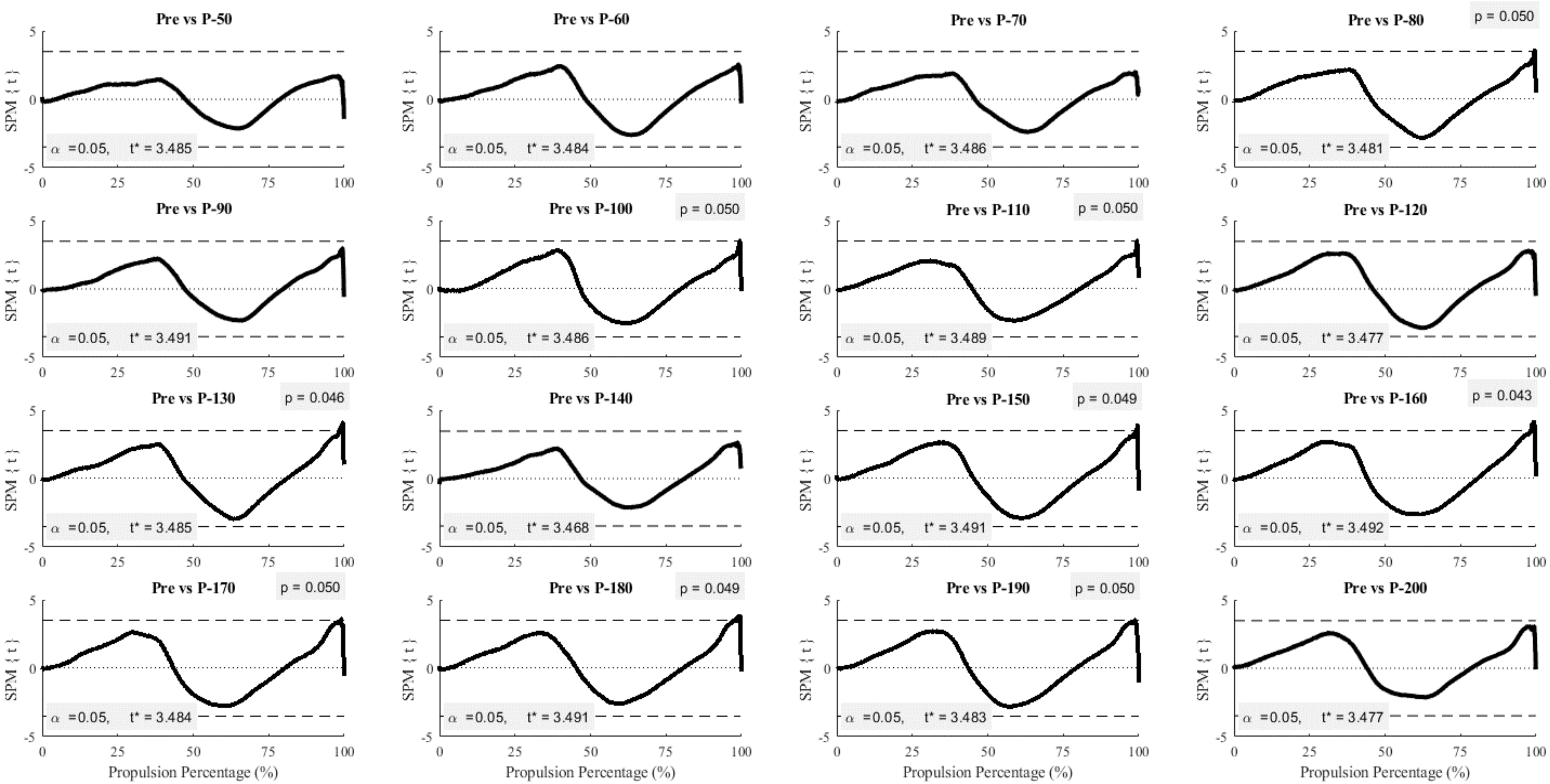


Figure 6.7. Statistical parametric mapping (SPM) results for Pre compared to P-50 to P-200. Dashed lines represent 95% confidence intervals and p-values represent periods of the propulsive period that are significantly different to Pre ($p < 0.05$).

6.4. Discussion

6.4.1. Main findings

The primary purpose of this investigation was to investigate the acute effect of low-volume (40 GC) plyometrics with progressively increased non-depth plyometric volume on kinetic performance. The secondary aim was to compare these dose-response effects during vertical and horizontal plyometric sessions. Accordingly, the main findings of this investigation were: i) the low-volume plyometric stimulus was sufficient in potentiating horizontal, but not vertical performance; ii) despite primarily maintained or improved performance, in-session fatigue altered kinetic performance during both sessions; iii) earlier and more consistent kinetic fluctuations in the horizontal sessions were associated with a shift in vertical force production strategy.

6.4.2. Low-volume plyometric stimuli

Somewhat in line with the hypotheses, the low-volume (40 GC) plyometric stimulus was effective in potentiating BJ, but not CMJ, performance. Moreover, the increase in BJ distance (~4 – 5%) was maintained throughout the entire high-volume session (200 GC). Conversely, although CMJ height was primarily maintained, small decrements in performance occurred early on (P-50 to P-80) (Figure 6.1). While research in potentiating protocols for horizontal jumps is limited, one study indicates haltere loading can augment kinematic and kinetic horizontal performance acutely (70). There is also evidence to suggest similar low-volume horizontal plyometrics (i.e., horizontal 25 cm SLDJ) can prompt significant adaptations in sprint performance and change of direction contact time acutely (-1.9%) and following a 10-week programme (-8.5%) (157,158). In contrast, resistance training protocols offer mixed results depending on the external load intensity, assessment exercise and strength of the participants

(330,331,343). This may be explained because transference is greater when the training exercise and assessment share more kinematic similarity (231). Body position, for example, heavily influences propulsive forces during acceleration (201). Thus, training in the horizontal direction, even acutely, may encourage a more horizontally oriented position during the BJ assessment thereby facilitating greater propulsion in the current study.

It is somewhat surprising that the vertical plyometric session did not elicit a similar potentiated response to the horizontal session. However, differences in exercise choice and MTU loading rates may be responsible. Previous low-volume plyometric programmes reporting improvements of 2 – 3 cm CMJ height in professional handball players and professional rugby players have used single-leg 25-cm DJ only, or a combination of ankle hops, hurdle hops (70 cm) and DJ (50 cm), respectively (158,372). In both instances, programmes are primarily rebound type exercises with large landing ground reaction forces, quick time frames (0.18 – 0.25 s) and significant tendon stretch loads resulting from depth-based plyometrics. In contrast, the vertical plyometric session in the current study was modified from above to include 30-cm DJ, power step-ups, single leg CMJ and ankle hops. The exercise intensity was conservatively adjusted for athletes with beginning plyometric experience, however, it is possible the power step-ups and SL CMJ were unable to impose sufficient MTU loads for strong athletes due to long GCT (> 0.43 s) and less intensive landing forces (262). Alternatively, vertical plyometrics compared to horizontally oriented exercises may be more difficult to self-monitor for performance due to the inability to visualize the distance travelled. In this respect, the addition of performance feedback (i.e., height achieved) may have beneficial to ensure maximal vertical projection during each repetition and assessment trial (291).

6.4.3. Kinetic performance

Despite primarily maintained or enhanced performance, some kinetic characteristics were altered in the presence of training-induced fatigue. Most prominently, eccentric impulse increased P-40 in BJ (+15.4 – 31.4 N·s) and P-60 in CMJ (+8.5 – 14.7 N·s), yet these increases were coupled with decreased or maintained concentric impulse in both BJ (-11.0 to -22.5 N·s) and CMJ (-1.3 to -9.8 N·s). These results suggest participants were achieving a greater negative velocity during the eccentric action owing to a greater eccentric internal load required for deceleration. Under normal conditions, the magnitude of eccentric loading, the speed of loading, and the time spent switching between eccentric and concentric motions dictate the concentric force output, take-off-velocity, impulse and resulting output (i.e., height or distance)(68,93,287). However, in the current study, the additional eccentric loading did not augment concentric force production as expected (105). This is typically the result of functional decrements to mental, muscular, neural, or proprioceptive factors. While verbal encouragement was given for every repetition, underlying mechanics are likely to go undetected by coaches (61). Small force enhancement windows (~20 ms) mean training-induced mental or neural fatigue can more easily prompt delays which affect energy transfer rates (105). Alternatively, it is very likely the skeletal muscle's metabolic homeostasis was disturbed during maximal effort SSC exercise (161,364). For example, low-frequency fatigue resulting from non-exhaustive jump training can cause fluctuations in intracellular calcium concentrations, subsequently affecting contraction dynamics and activation patterns (354,364). While not specifically measured, previous research frequently reports increases in muscle lactate concentration, creatine kinase activity, and decreased muscle phosphocreatine and pH following repeated ballistic exercise (37,150,364). Accordingly, these metabolic disturbances are typically associated with muscle damage and inflammation which are likely to inhibit stretch reflex stimulation or cause delays in sensitivity (19,364). This may partially explain why these alterations presented earlier and more consistently in horizontal BJ. While the two low-volume session exercises were matched for exercise characteristics and volume, horizontal jumps have previously demonstrated significantly greater landing forces in all directions (i.e., vertical, frontal and sagittal planes) (193), and may have therefore induced a greater load for the same volume. Anecdotally, when asked which session was more difficult, resoundingly all participants responded with the horizontal session, one player even remarking, "it was a solid ten" out of ten. As a result, practitioners may want to adopt a more cautious dosing strategy for horizontal plyometrics which may not require as much volume as vertical-oriented exercises due to greater landing forces, and earlier onset fatigue (P-40 vs. P-80).

6.4.4. Jump strategy

These kinetic fluctuations were met with a shift in vertical force production strategy during the BJ only (Figure 6.6). Differences most notably occurred during the final propulsive phase, indicating differences in take-off strategy and end-range kinematics. This period likely characterises differences in vertical velocity designed to maximize impulse and vertical projection, and in the current study horizontal distance (132). It is feasible this shift in jump strategy allowed participants to continue performing during the BJ in the presence of greater training-induced fatigue (119). There is a consistent trend, whereby the early volumes (P-40 and P-50) SPM graphs show minimal deviation from PRE-0 curves, but as volume is progressed, these deviations steadily increased in size during early (~30 – 40%), mid (~50 – 70%) and late (~88 – 99%) periods. Trends support kinetic alterations, by portraying greater eccentric load with steeper time-normalised graphs (~25 – 55%; Figure 6.6). However, lower forces and greater SPM deviations suggest participants may not be optimising SSC force enhancement during late eccentric and early concentric periods, resulting in shift to greater vertical force just before take-off in order to maintain performance.

This shift in waveform is similar to a previous study which reported that acute changes in jump strategy during non-fatigued states produced greater power outputs by using a short duration and large accelerations rather than large range-of-motions and displacements (174). Moreover, neural modulation of muscle-tendon unit control strategies has been shown to adapt following one plyometric session (140). Considering motor programmes and neurological stimulation adjust to task-specific parameters (358), it is possible that given the instructions to "jump as far as you can, attempting to reach your head to the wall in front of you" athletes were able to modify CNS motor programmes to facilitate optimal muscle-tendon interaction (140,358). While this may be considered a desirable training adaptation, practitioners are cautioned to understand the difference between training designed to elicit adaptations suitable to performing during fatigued states versus those beneficial to maximal power production under optimal conditions.

6.4.5. Limitations

While this study provides novel insight into kinetic differences during progressively increased volumes, there are some limitations. Unfortunately, due to the prioritization of the team's competitive agenda, we were unable to monitor the recovery process. Similarly, more complex analysis of specific muscular and neural fatigue-related decrements was not possible in their training facility, thus we can only speculate here on proposed mechanisms. Moreover, this study investigated low-volume plyometrics and progressively increased CMJ and BJ performance. Future research may look at sessions involving more intensive exercises with shorter GCT.

6.5. Practical Applications

The purpose of this study was to investigate the differences in kinetic performance between low-volume horizontal and vertical plyometric programmes with progressively increased in-session volume. The results suggest performance output is significantly related to training axis. The low-volume plyometric programme in the current study induced a potentiated response in BJ but not CMJ, and this performance enhancement was maintained throughout the sessions. Conversely, CMJ height realized small decrements during moderate volumes (P-50 to P-80) before recovering. While intensity was cautiously regulated, the power step-ups and single-leg CMJ in the vertical session may not have stressed the MTU system effectively, utilizing long GCT to generate power. Practitioners may consider exercises more targeted to load the tendon in trained athletes during low-volume sessions. Nevertheless, while performance in both sessions was mostly maintained, fatigue-related kinetic alterations were present. Most notably, increases in eccentric impulse with concomitant decreases in concentric impulse suggest the mechanisms underlying optimal performance augmentation were not functioning appropriately. These fluctuations presented earlier in BJ (P-40) compared to CMJ (P-80) were more consistent and associated with a shift in jump strategy. Practitioners may therefore want to consider using less volume during horizontal plyometric training due to greater landing forces and earlier onset kinetic fluctuations.

Section III – Plyometric training programme efficacy and implementation

Chapter 7 – The effect of low-volume preseason plyometric training on force-velocity sprint profiles in semi-professional rugby players.

Reference

Watkins, CM, Gill, ND, Maunder, E, Downes, P, Young, JD, McGuigan, MR, and Storey, AG. The effect of low-volume preseason plyometric training on force-velocity profiles in semiprofessional rugby union players. *J Strength Cond Res 35(3):* 604–615, 2021.

Author contribution

Watkins, CM, 80%, Gill, ND, 4%, Maunder, E, 4%, Downes, P, 2%, Young, JD, 2%, McGuigan, MR, 4%, Storey, AG, 4%.

7.0. Prelude

The results from the previous investigation (Chapter 6) provided novel insight to kinetic performance changes with progressively increased volumes. While trained athletes were able to complete high-volume sessions, underlying kinetic factors were altered in both sessions. Most notably, improvements in BJ distance were associated with longer GCT and decreased concentric impulse. Moreover, increased eccentric impulse in both directions, without augmented concentric performance, indicated fatigue-related decrements in neuromuscular performance were present early on (P-40 to P-80). These results further support the use of low-volume high-quality repetitions for eliciting performance changes, particularly as SSC adaptations depend on MTU loading rates (Section I). Interestingly, larger, and more consistent kinetic alterations and changes in jump strategy during the BJ sessions may help to explain lower horizontal volumes used by expert practitioners (Chapter 5). In light of these findings, this section aimed to apply those principles in real-world training programmes. Keeping in mind competitive priorities, the training programmes were designed to be efficient and easily implementable in a large team setting. Considering support for low-volume protocols in professional athletes (157) and reported efficacy from elite strength and conditioning practitioners (Chapter 5) (389), further research was required to investigate low-volume programmes in both vertical and horizontal directions on sprint-profiles.

7.1. Introduction

Rugby union is a physically demanding and complex team sport requiring athletes to maintain a multi-faceted athletic profile throughout the season. Analysis of game demands demonstrate professional rugby players travel ~4500 – 7500 m across an 80 min match, with ~1,100 – 1,800 m at or above 4 $m.s^{-1}$ which is defined as "running speed" (18,86). While sprinting represents ~25% of game-play for backs players, and only ~4% for forwards players, both positional groups reach speeds >90% of their respective maximal velocity in similar relative frequencies (~50% of sprint occurrences) during match play, suggesting all players should train acceleration and maximum velocity characteristics (82,83). Each athlete's horizontal FV profile, or individual ability to express force across a spectrum of velocities, plays a primary role in regulating maximal speed (264). Differing between positional groups, rugby codes, and performance levels, the expression of force across velocities and distances is a distinguishing factor in rugby union performance (73). However, limited training and recovery time between subsequent training sessions and/or matches means training efficiency is a top priority when considering different training stimuli to elicit the desired adaptations.

Plyometric training is one method that has been used to improve speed in as little as two weeks (231,236,274). Using a rapid eccentric-concentric coupling action, plyometrics employ the stretch-shortening cycle to efficiently transmit force, facilitate elastic recoil and enhance sprint performance (188). During the eccentric action, the muscle-tendon complex is rapidly stretched, and the stretch-shortening cycle facilitates fibre contraction mechanics, increases neural activity and activates stretch reflexes to augment concentric FV expression (188). Rarely do humans perform purely concentric actions; natural locomotion patterns including walking, sprinting, and jumping all inherently use the stretch-shortening cycle to absorb and recycle energy (163). Similar kinetic profiles and force-generating mechanisms make plyometric training an ideal method to transfer improvements garnered in the gym to functional on-field improvements in speed (138).

Still, the optimal dosage of plyometrics is up for debate. Published recommendations support a wide range of session volumes (60 – 400 GC) (78,96). However, volumes above 100 GC frequently cause large decrements (8 – 20%) in jump performance, increased muscle damage and soreness for up to five days post-training, consequently hindering competitive athletes performing on a weekly basis (57,151). Furthermore, plyometric volume analysis demonstrates similar acute stress (100, 200, and 300 GC) in adult rugby players and comparable chronic performance improvements in adolescent soccer players despite ~50% less volume (40 – 50 vs. 110 – 120 GC; 840 vs. 1,680 GC), suggesting additional volume may not be warranted (49,55,380). In fact, just one set of five DJ has shown to be a sufficient stimulus for acutely potentiating jump performance in adult athletes (20). The effectiveness of low-volume (40 – 60 $GC.session^{-1}$) high-intensity plyometric training is well supported in adolescent and untrained populations (38,315,380), and is quickly gaining credence in elite athletes (157,158,372). Such predominance further warrants the need to investigate the most efficient dose-response in semi-professional athletes for optimal speed and acceleration adaptation, with minimally incurred stress.

Granted, the changing proportion of horizontal and vertical forces during sprint performance influences the optimal manipulation of plyometrics for improving phase-specific performance. As running velocity increases from acceleration to maximal speed, vertical forces increase from ~1,200 – 2,300 N, while propulsive horizontal forces decrease from ~750 – 500 N as the rate of acceleration slows, indicating horizontal forces are a greater priority for accelerative phases as compared to maximum velocity sprinting (282). In fact, recent research suggests the orientation rather than the total sum of ground reaction forces has the greatest positive influence on accelerative performance (201). Functionally, directionally-specific plyometric training demonstrates superior athletic performance with respect to training axis in young (231,254,315) and more recently elite (157) athletes. When comparing uniaxial plyometric programmes, horizontally applied training tends to exhibit greater transference to sprint acceleration phases (0 – 10 m), change-of-direction ability and propulsive forces (157,231). In contrast, previous literature suggests vertically-applied programmes typically benefit transitional (10-20 m) and maximal speed phases as well as vertical jump performance by increasing ground reaction forces, reactive strength, leg stiffness, and decreasing GCT (157,231). Although, plyometric training programmes which have reported no sprint performance benefits tend to be void of horizontal stimulus and are generally associated with low-intensities (315,373). Thus, more clarity is needed to understand the loading parameters and specific adaptations with respect to training axis, especially as the majority of direction-based investigations are in young populations.

The aim of this investigation was to determine the effect of combined low-volume horizontal and vertical plyometric mesocycles on sprint performance in semi-professional rugby union players during a pre-season training period. The secondary objective was to determine if directionally specific plyometric training differentially affected the sprint performance and FV profiles. Given the number of variables measured with FV profiles, and the novelty of plyometric training direction on sprint mechanical performance, assessment of the second objective should be considered exploratory in nature. We hypothesised that horizontal and vertical plyometric training would improve sprint performance, but adaptations would occur through different phase specific FV qualities (Table 0.1). Specifically, previous research suggests horizontal plyometric training may preferentially benefit acceleration, while vertical plyometric training is more suited for transitional and maximal velocity where vertical forces are much greater (23,209,231).

7.2. Methods

7.2.1. Experimental approach to the problem

A mixed-model cross-over design was used to determine the effects of low-volume vertical and horizontal plyometric training on speed and FV profiles in semi-professional rugby union players. Participants were randomly allocated to one of two experimental training groups, which were matched for speed (30 m split time) and strength (maximum squat), or a control group (CON-0) that did not participate in any plyometric training (Table 7.1). All three groups continued with regular resistance training and sport practice twice weekly. The most recent one repetition maximum squat data (within one month of pre-tests) was obtained from the club to ensure groups were equally matched for strength and sprint performance. Both experimental groups performed two three-week horizontally- and vertically- directed plyometric training blocks. One experimental group (HV-1) performed horizontal plyometrics in their first block, and vertical in their second while the second experimental group (VH-2) performed the opposite. Training blocks were performed in succession with speed testing conducted before and after each mesocycle, and a short (12 days) wash-out. While this period is relatively short for a true washout of physiological adaptation, the duration was limited due to the season's preparatory period, keeping in context practicality and ecological validity. Previous wash-out periods of one- three weeks have been used for acute adaptation studies (49,234). In addition, while strength can be maintained for up to three weeks; sprint performance has been shown to significantly decreases (30m time: +0.07 s) in elite athletes following two weeks of detraining, highlighting the sensitivity of high-velocity actions (179). Auckland University of Technology ethics committee approved this research project. All participants were notified of the risks and benefits prior to volunteering, and all participants provided written informed consent.

7.2.2. Participants

Thirty-seven male semi-professional rugby union players volunteered for this study. Participants were all contracted members of the Auckland Rugby Union academy where they performed resistance exercise and rugby training twice weekly. To be included in the analyses, participants had to complete five out of six training sessions for each mesocycle and had to attend two successive testing sessions of one mesocycle. Five participants dropped out due to unrelated injuries obtained primarily during rugby training, or auxiliary commitments concerning team selection camps. Therefore, 32 participants were included in the final analyses presented as mean ± standard deviation (SD) (mass = 102.6 ±16.4 Kg; height = 183.9 ± 6.9 cm; age = 19.8 ± 2.2 y). All participants were over 18 years old (Table 7.1).

Table 7.1. Plyometric training group baseline characteristics.

Mean ± SD (range) for each group			
Variable	Con-0 (n=12)	HV-1 (n=8)	VH-2 (n=12)
Age (years)	20.4 ± 2.6 (18 – 25)	18.9 ± 1.5 (18 – 22)	19.8 ± 2.0 (18 – 25)
Height (cm)	183.1 ± 7.2 (174.5 – 198.7)	181.1 ± 5.7 (171.1 – 188.6)	186.5 ± 7.0 (175.8 – 196.6)
Mass (Kg)	102.2 ± 16.9 (78.7 – 130.0)	93.3 ± 16.0 (68.5 – 114.8)	109.3 ± 13.9 (93.2 – 140.9)
Yoyo	17.1 ± 1.5 (14.6 – 19.3)	17.5 ± 1.1 (16.3 – 19.2)	17.1 ± 1.3 (14.3 – 19.1)
Skinfold (mm)	103 ± 34 (50 – 166)	98 ± 50 (44 – 165)	112 ± 34 (74 – 197)
Squat 1RM (kg)	144 ± 22 (115 – 190)	138 ± 25 (100 – 180)	156 ± 28 (105 – 90)

Con-0= control group; HV-1= experimental group that performed horizontal, then vertical plyometric training; VH-2= experimental group that performed vertical, then horizontal plyometrics. 1RM = maximum weight athlete able to lift for 1 repetition.

7.2.3. Testing procedures

Participants underwent speed testing on four separate occasions as part of their pre-season athletic profiling. During the initial testing session, body composition and aerobic fitness were also measured. Speed tests were conducted prior to and following each training block, such that the first two timepoints correspond with pre- and post-testing for mesocycle one. The third and fourth timepoints occur after the wash-out and correspond with pre- and post-testing for the second mesocycle. All participants rested for 72 hours prior to testing. Testing sessions occurred at the same time of day on the Monday of each testing week. All testing sessions occurred at the same indoor 3G turf field to control for surface and weather conditions. Upon arrival for the first testing session, height and body mass were obtained. In addition, body composition was measured via skinfold (SF) assessment by a certified International Society for the Advancement of Kinanthropometry practitioner, using the standardised eight-site (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh, and medial calf) method in line with New Zealand Rugby protocols (77).

Sprint performance

After five minutes of individual preparation, participants completed a dynamic warm-up including single-leg bridges, hamstring walks, cross-over steps, high knees, walking lunges, and sprints of increasing intensity to target the lower body and core musculature. Sprint performance was measured via radar (Stalker ATS 5.0, Texas, USA) and dual-beam infrared timing gates (Swift Performance, Lismore, Australia). Spatiotemporal data obtained from the radar was then modelled using least square linear regression analysis to create individual FV and power-velocity curves for each athlete, according to previously validated methods (352). The average of two sprint assessments was used for analysis. The radar system was set up three metres behind the start line, with a tripod height of one metre, positioned approximately at the athlete's lumbosacral joint. Timing gate width was one metre apart at 10, 20, and 30 m from the first timing gate pair. Participants lined up in a two-point split stance 50 cm behind the first set of timing gates. Radar was initiated via a laptop prior to any movement and the participants were then instructed to sprint as fast as they can past the last timing gates before slowing down. Participants completed two successful trials with three minutes rest between-trials. Outcome measures were 10-, 20-, 30-, 10-20, 20-30 metre time, and FV profile characteristics (Table 0.1).

Aerobic fitness

Following speed testing, aerobic fitness was also determined via the Yoyo intermittent shuttle test. Cones were set out 20 m apart, with an additional five metre walk zone set at the start. Players were instructed to run at a set pace from the start to the 20-m line and back within the allotted time. Between levels, players were required to walk the five metres out and back to the start line as an active recovery. The required speed progressively increased every level, and players received one warning if they failed to make the line in time, left early, or cut the repetition distance short at the turnaround. Two judges determined if the players completed the full distance each repetition within the allotted time and called out when the player could no longer keep up with the test requirements. The testing procedures were in line with standard New Zealand Rugby protocols.

7.2.4. Training programme

A low-volume directionally specific plyometric programme was performed twice-weekly in the morning prior to their resistance training sessions during the pre-season training period (Table 7.2). All athletes were given a foundational low-intensity plyometric familiarisation programme to complete during their off-season prior to commencing the study. Participants performed two, three-week training blocks focused on either vertical or horizontal plyometrics with a one-week wash out between blocks.

Table 7.2. Plyometric training programme.

	Exercises	Week 1	Week 2	Week 3
Horizontal training	Horizontal Drop Jump (30 cm)	1x5	1x6	2x4
	Double-Leg Bounds	1x5	1x6	2x4
	Alternate Sprint Bounding	2x6 each	2x7 each	2x8 each
	Single-Leg Bounding	2x4 each	2x6 each	2x7 each
	Double-Leg Zig-Zag Cone Hops	2x5	2x6	2x7
Total session contacts		**40**	**50**	**60**
Vertical training	Exercises	Week 1	Week 2	Week 3
	Vertical Drop Jump (30 cm)	1x5	1x6	2x4
	Double-Leg Depth Jump (40-, 50-, 60- cm)	1x5	1x6	2x4
	Power Step Ups (40 cm)	2x6 each	2x7 each	2x8 each
	Single-Leg Countermovement Jump	2x4 each	2x6 each	2x7 each
	Double Leg Mini Hurdle Jumps	2x5	2x6	2x7
Total session contacts		**40**	**50**	**60**
Total weekly		**80**	**100**	**120**
Total Ground Contacts				**600**

The training programme was designed to increase lower-body power, rapid force transmission and stretch-shortening cycle efficiency. Previous literature has previously supported two-six week training blocks as sufficient stimulus to elicit such adaptations (222,236,315). Therefore, two three-week mesocycles were chosen to investigate the smallest necessary dose for improving sprint performance. Plyometric exercises (Figure 7.1) consisted of five directionally specific exercises including double- and single-leg movements of moderate-high intensity that have previously demonstrated beneficial effects (222,315,372,380). The DJ, depth jumps, sprint bounding, and hop varieties were specifically included to increase rapid force transmission and pre-activity of the muscle-tendon junction prior to and during short ground contact times (204,222,315). Conversely, double- and SL CMJ, and horizontal bounds were included to improve explosive power over longer ground contacts, and a larger range of motion to accommodate for different kinematic profiles in sprinting (226). Training sessions started with a standardised dynamic warm-up, targeting the trunk and lower body musculature. Additionally, participants completed directionally specific low-intensity plyometrics during their warm-up including stick and land and BJ for the horizontal group, or CMJ and ankle hops for the vertical group.

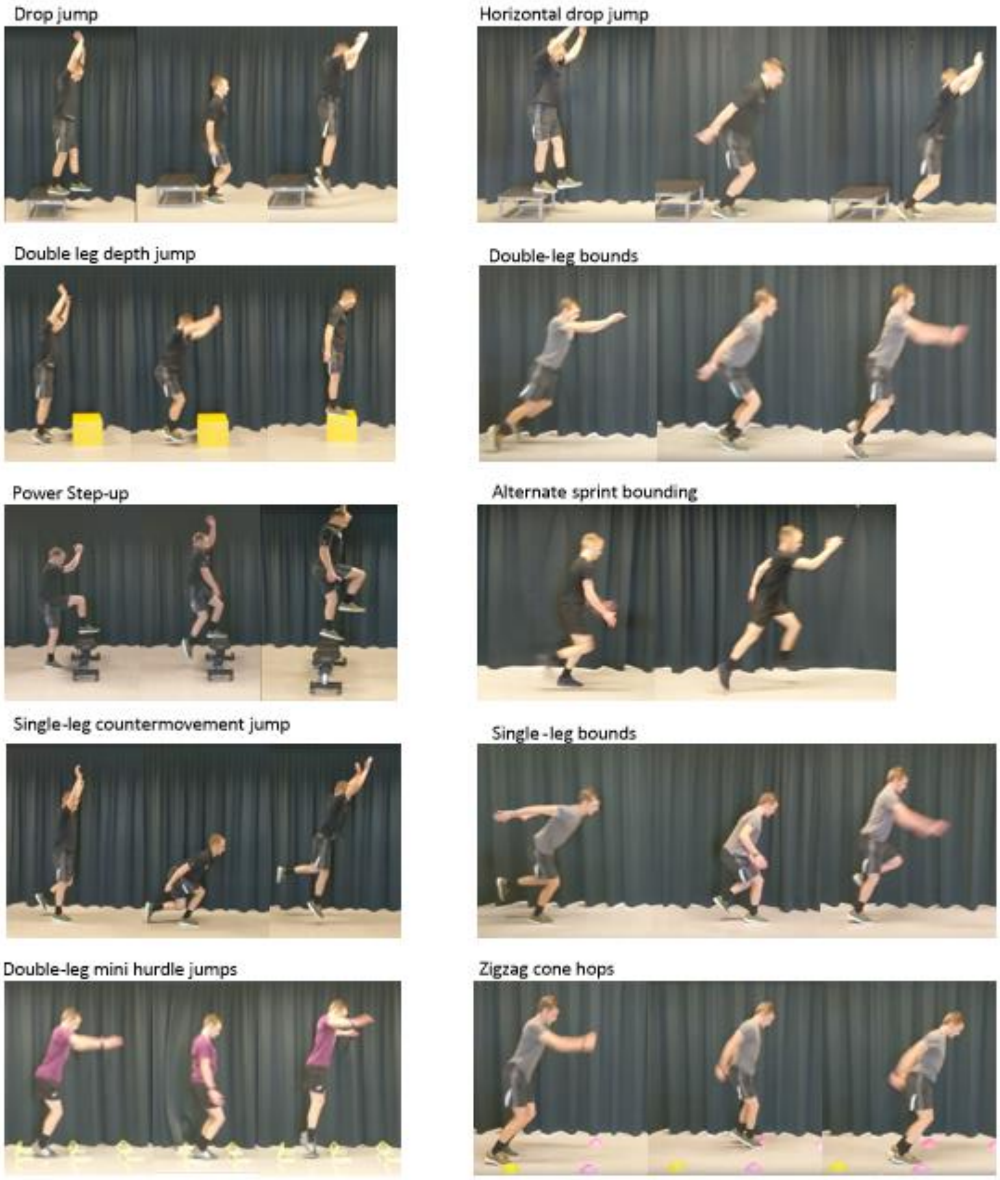


Figure 7.1. Vertical and horizontal plyometric exercises.

Vertical and horizontal DJ were executed from a 30 cm box (Figure 7.1). For the vertical training sessions, depth jumps drop (20-, 25-, or 30-cm) and box (40-, 50-, or 60-cm) height increased weekly (Table 7.2). Participants were instructed to minimise GCT during DJ and depth-jump exercises. An exercise including frontal plane motion was included for movement variety, considering previously noted adaptations in speed and agility performance benefit from frontal plane movement (254). Training sessions took approximately 15 – 20 minutes to complete. Total session volume (Table 7.2) was progressively increased by 10 contacts per week so both sessions in weeks one, two and three had 40-, 50-, and 60- contacts, respectively, resulting in a mesocycle total volume of 300 contacts, and a total training programme volume of 600 contacts. All plyometric training was performed on rubberised floor matting. Previous research has found 15 s rest to be sufficient for improving plyometric performance during single-rep exercises, and 30 – 120 s between multiple rep exercises (313). Therefore, shorter rest periods were prioritised, 15 s between single reps and one-minute between-sets.

7.2.5. Statistical analysis

Statistical analyses were performed using STATA 15 (StataCorp LLC, Texas, USA). Due to small training periods, small practically relevant adaptations, and a small sample size, significance was set at $p \leq 0.05$. Unfortunately, 14 participants missed one or two testing session because of sickness, alternate work priorities, or previous commitments. All results are expressed as means and SD. Normal distribution of data was tested using the Shapiro-Wilk test. Sphericity was verified using the Mauchly's test. Baseline characteristics were analysed with a one-way ANOVA. Intra-class correlations (ICC) and coefficient of variations (CV) were calculated on same day multiple-trial tests for reliability. Previously reported thresholds for interpreting ICC results are: 0.20 – 0.49, 0.50 – 0.74, 0.75 – 0.89, 0.90 – 0.98 and ≥0.99 for low, moderate, high, very high and extremely high, respectively (147). For CV, values of ≤ 10% were considered small (32).

Acceptability was determined for measures when ICC ≥ 0.75 and a CV ≤ 10%, moderate when ICC < 0.75 or CV > 10%, and unacceptable/poor when ICC < 0.75 and CV > 10%.

Mixed linear model analyses were used to compare differences between groups, time-points, training direction and intervention length. Models were ran again excluding the control to verify magnitude of difference between training groups and training direction. Effect sizes (ES) were determined according to Hedge's G, using only participants that attended all four testing sessions for appropriate comparison (n = 19). Magnitude of ES as followed: < 0.2 trivial, 0.2 – 0.4 small, 0.41 – 0.7 moderate, 0.7 – 1.9 large, and >2.0 very large, with -/+ denoting direction of change compared to baseline (62). Pearson correlations were used to assess programme change scores (30 m split time, ΔVmax, and ΔF0) with baseline attributes (SF, mass, Yoyo, F0, and V0). An effect-size sensitivity analysis was performed in G*Power using the bivariate normal correlation model (power = 80%, p = 0.05, tails = 2, n = 32) which revealed a correlation effect size of 0.47 (critical r = 0.34).

7.3. Results

No significant baseline differences (Table 7.1) existed between age, height, SF or Yoyo score (p> 0.20). No significant differences existed between baseline comparisons for any sprint times (p> 0.65) or FV variables (p>0.2). CVs and ICCs were 0.9-2.2% (90% CI: 0.7 – 2.5%) and 0.83 – 0.95 (90% CI: 0.70, 0.97) for all split times and 1.0 – 5.1% (90% CI: 0.8-6.6%) and 0.74 – 0.96 (90% CI: 0.56, 0.98) for all FV variables. Only S_{rel} was deemed moderate with ICC 0.74 (90% CI: 0.56, 0.85) and CV 5.1% (90% CI: 4.2 – 6.6%), while all others were deemed acceptable with high or very high reliability. Correlational analyses showed significant relationships between programme change scores (i.e., the magnitude of adaptation) and initial athlete characteristics including initial body composition, aerobic fitness, and strength (Table 7.3).

Table 7.3. Correlational matrix of initial athletic characteristics and 30 m time delta scores (n = 32).
*Note: SF= skinfold; F0 = initial theoretical maximal force production; V0 = initial theoretical maximal velocity; Vmax = highest velocity achieved in initial sprint; Δ M1&2 = change score for both mesocycles; Δ M1 = change score for mesocycle 1; Δ M2 = change score for mesocycle 2. **Bolded values*** indicate significant relationship ($p \leq 0.05$).

	Yoyo	SF	Mass	F0	V0	Δ30 M1&2	Δ30 M1	Δ30 M2	ΔV_{max} M1&2	ΔV_{max} M1	ΔV_{max} M2	ΔF0 M1&2	ΔF0 M1
Yoyo	1												
SF	**-0.667***	1											
Mass	**-0.777***	**0.792***	1										
F0	**-0.706***	**0.640***	**0.837***	1									
V0	0.225	**-0.416***	**-0.327***	-0.269	1								
Δ30 M1&2	-0.318	0.219	0.335	0.332	-0.08	1							
Δ30 M1	0.117	-0.075	-0.007	0.016	-0.019	**0.413***	1						
Δ30 M2	**-0.568***	**0.434***	**0.374***	0.329	0.092	**0.437***	-0.185	1					
ΔV_{max} M1&2	0.129	0.055	-0.249	-0.204	-0.201	**-0.625***	**-0.470***	-0.134	1				
ΔV_{max} M1	-0.028	0.052	-0.001	0.122	**-0.493***	-0.270	**-0.352***	-0.116	**0.505***	1			
ΔV_{max} M2	0.242	**-0.370***	-0.337	-0.291	0.073	**-0.372***	0.019	**-0.361***	**0.506***	-0.014	1		
ΔF0 M1&2	**0.515***	**-0.422***	-0.284	**-0.536***	-0.0821	-0.230	0.054	-0.243	0.044	0.190	0.192	1	
ΔF0 M1	0.278	-0.1589	-0.215	-0.268	0.2765	-0.013	**-0.359***	0.323	0.132	-0.203	-0.042	0.336	1
ΔF0 M2	**0.375***	-0.196	-0.141	-0.169	-0.263	-0.235	0.074	**-0.518***	0.161	0.284	-0.025	0.344	-0.320

7.3.2. Sprint times

There were no significant interactions between direction and intervention length for 10-, 20-, or 30- m sprint time (in all cases p > 0.3). However, there was a 10 – 20 m sprint time direction by intervention length interaction for vertical, but not horizontal, plyometrics when compared to the control group (vertical: Δ10-20 m sprint time: -0.01 s, ES: -0.28, 95% CI: -0.92, 0.36; horizontal: Δ10 – 20 m sprint time: <0.01 s, ES: -0.1, 95% CI: -0.78, 0.62; control: Δ10 – 20 m sprint time: <0.01 s, ES: 0.07, 95% CI: -0.74, 0.87; p = 0.035). For 10-20 m (p = 0.015) and 20-30 m time (p = 0.030) there were group by time interactions for HV-1 at time point four when compared to CON-0. There were group by time interactions for 10-, 20- and 30- m time (Figure 7.2).

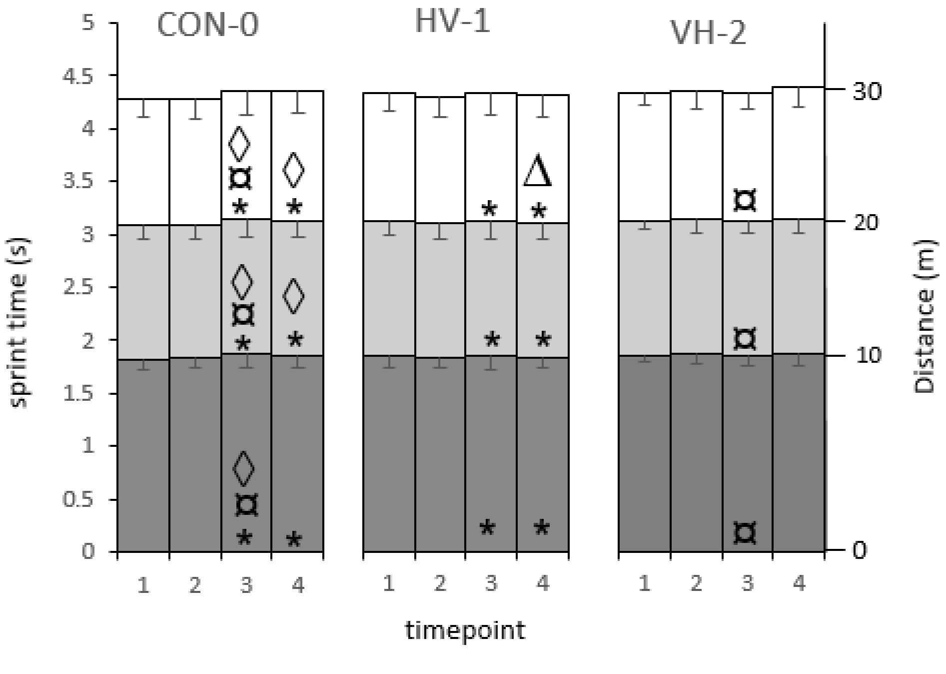


Figure 7.2. Sprint times by group for 10- (dark grey), 20- (light grey), and 30- (white) m distance split times.
*Note: T= timepoint with 1 and 3 corresponding to mesocycle pre-tests, and 2 and 4 corresponding to mesocycle post-tests; *= group x time interaction [10 m (T3: p= 0.043; T4: p= 0.06); 20 m (T3: p= 0.033; T4: p= 0.012); 30 m (T3: p= 0.037; T4: p= 0.004)]; ¤= group x time interaction [10 m (T3: p= 0.042); 20 m (T3: p= 0.028); 30 m (p= 0.029)]; Δ= significantly less than baseline [30 m (p= 0.038)]; ◊= significantly greater than baseline [10 m (T3: p= 0.005; 20 m (T3: p= 0.010; T4: p= 0.040); 30 m (T3: p= 0.026; T4: p= 0.019)].

7.3.3. Force-velocity profile changes

Significant FV profile changes occurred across all three groups (Figure 7.3 and Table 7.4). For V_o and V_{max}, there were no significant interactions for direction and intervention length. There were group by time point interactions for HV-1 at time point two (V_o: p = 0.050; V_{max}: p = 0.047), three (p<0.001 in both cases) and four (p < 0.001 in both cases). Group HV-1 significantly improved V_o and V_{max} at time points three (V_o: p = 0.004; V_{max}: p = 0.008) and four (V_o: p = 0.046; V_{max}: p = 0.036), while VH-2 displayed significantly less values for V_o (p = 0.003) and V_{max} (p = 0.007) at time point four. Additionally, CON-0 displayed significantly less values for V_o (p = 0.001) and V_{max} at time-point four (p = 0.001). Between-experimental groups, at time point three there was a group by time interaction for V_o (p = 0.028), but not V_{max} (p = 0.051), and group by time interactions for V_o and V_{max} at time point four (p < 0.001 in both cases).

For F_o and F_{rel}, there were no significant interactions for direction intervention when compared to CON-0 (Con F_o Δ: +8 N, ES: 0.17, 95% CI: -0.64, 0.97; F_{rel} Δ: +0.22 $N \cdot kg^{-1}$, ES: 0.26, 95% CI: -0.55, 1.06). However, when comparing only experimental groups, there was a direction by intervention length interaction for F_{rel}, but not F_o (F_o: VΔ: +80 N, ES: 0.43, 95% CI: -0.22, 1.07; HΔ: +10 N, ES: 0.14, 95% CI: -0.56, 0.84; p = 0.074; F_{rel}: VΔ: +0.53 $N \cdot kg^{-1}$, ES: 0.78, 95% CI: 0.11, 1.44; HΔ: +0.22 $N \cdot kg^{-1}$, ES: 0.35, 95% CI: -0.35, 1.05; p = 0.041). Similarly, there were no group by time interactions compared to CON-0, but comparing experimental groups only, there were significant group by time interactions at time point three for F_o and F_{rel} (in both cases; p<0.001). Group HV-1 decreased F_o (p<0.001) and F_{rel} (p = 0.002) at time point three, while VH-2 increased F_{rel} at time point two (F_{rel}: p = 0.009) and F_0 and F_{rel} at time point four (F_o: p = 0.044; F_{rel}: p = 0.005) compared to baseline. There was no significant difference for CON-0 across any time points compared to baseline.

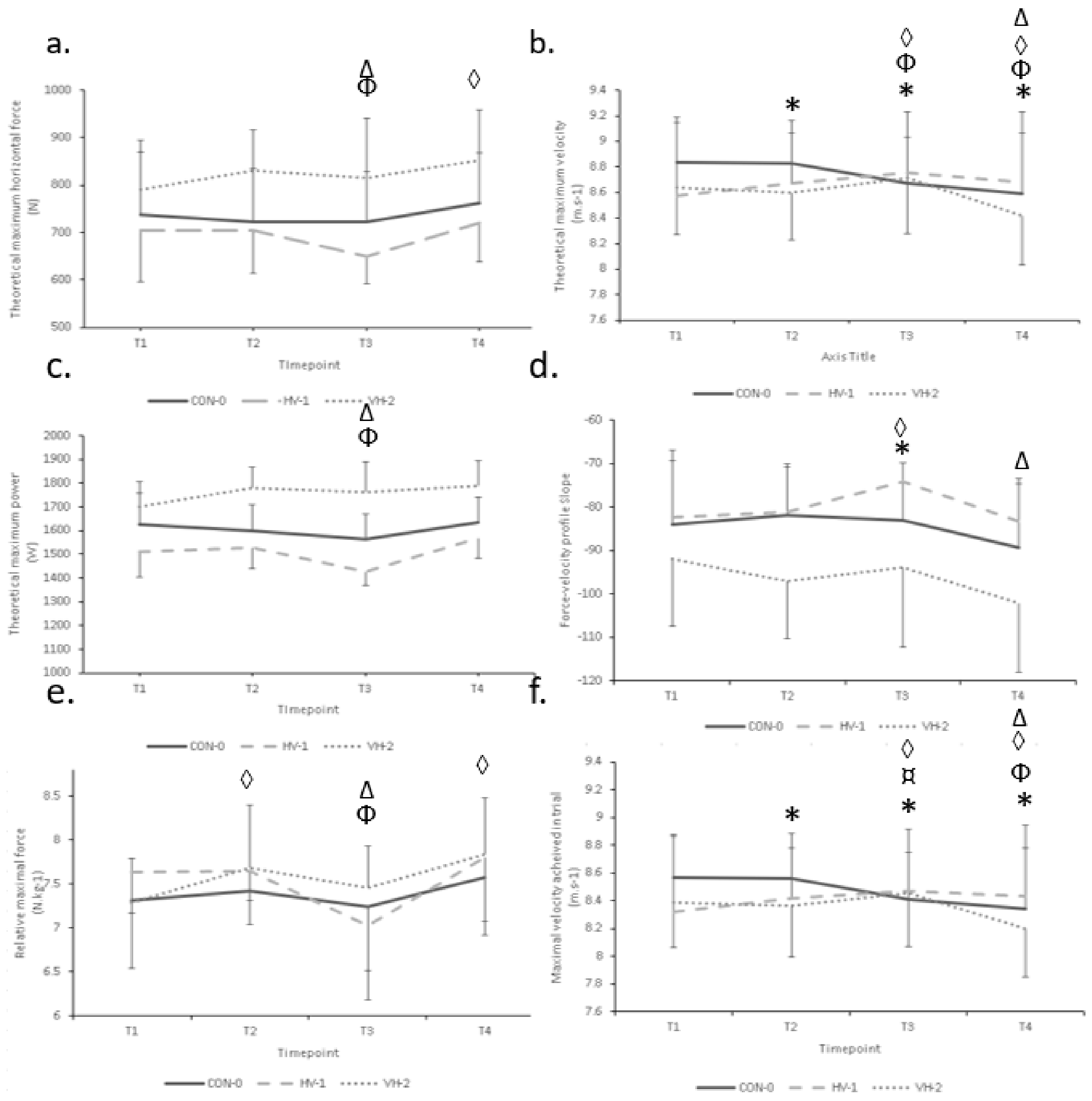


Figure 7.3. Force-velocity profile changes for the three groups [control group: CON-0, and two training groups: HV-1 (horizontal-vertical training) and VH-2 (vertical-horizontal training)] across four time points (T1, T2, T3, and T4).

*Note: T1 and T3 corresponding to mesocycle pre-tests, while T2 and T4 correspond to mesocycle post-tests. a. Theoretical maximal horizontal force (F0); b. Theoretical maximal velocity (V0); c. Theoretical maximal power (Pmax); d. Force-velocity slope (Sfv); e. Relative maximal force produced; f. Actual maximal velocity achieved in trial. All symbols denote significant relationship ($p < 0.05$). *= group (HV-1 and CON-0) by time interaction; ¤= group (VH-2 and CON-0) by time interaction; Φ= group (HV-1 and VH-2) by time interaction; Δ= significantly less than baseline (Fo: HV-1; Vo: VH-2 & CON-0; Pmax: HV-1; Sfv : VH-2; F0rel: HV-1; Vmax: VH-2 & CON-0) ◊= significantly greater than baseline (Fo: VH-2; Vo: HV-1; Sfv: HV-1; F0rel: VH-2; Vmax : HV-1).

For P_{rel}, there were direction by intervention length interactions for vertical plyometrics compared to the control condition, but not P_0 (P_0: ConΔ: +19 W, ES: 0.1, 95% CI: -0.71, 0.90; VΔ: +100 W, ES: 0.43, 95% CI: -0.22, 1.08; HΔ: +0 W, ES: 0.13, 95% CI: -0.57, 0.83; p=0.099; P_{rel}: ConΔ: +0.4 $W \cdot kg^{-1}$, ES: 0.17, 95% CI: -0.91, 1.25; VΔ: +1.08 $W \cdot kg^{-1}$, ES: 0.66, 95% CI: 0.00, 1.31; HΔ: +0.2 $W \cdot kg^{-1}$ ES: 0.23, 95% CI: -0.47, 0.93; p= 0.049). Between experimental groups only, there were again direction by intervention length interactions for vertical plyometrics compared to horizontal (P_0: p = 0.039; P_{rel}: p = 0.020). For P_0 and P_{rel}, there were no significant group by time interactions when compared to CON-0, but between groups there was a significant interaction at time point three (Table 7.4; P_0: p= 0.014; P_{rel}: p = 0.015). Compared to baseline, HV-1 significantly decreased P_0 at time point three (p = 0.011), and CON-0 did not significantly change at any time point. For P_{rel}, HV-1 significantly decreased performance at time point three (p = 0.042) while VH-2 increased P_{rel} at time point two (p = 0.008) and four (p = 0.043).

For S_{fv} and S_{rel}, there was no direction by intervention interactions (S_{fv}: ConΔ: -2.25, ES = -0.22, 95% CI: -1.03, 0.59 VΔ: -6.26, ES = -0.38, 95% CI: -1.03, 0.26; HΔ: -2.2, ES = -0.13, 95% CI: -0.83, 0.56; p > 0.2; S_{rel}: ConΔ: -0.028, ES = -0.26, 95% CI: -1.39, 0.97; VΔ: -0.066, ES = -0.72, 95% CI: -1.38, -0.05; HΔ: -0.034, ES = -0.36, 95% CI: -1.06, 0.34; p > 0.2), but there were group by time point interactions for HV-1 for S_{fv} (p = 0.026) and S_{rel} (p = 0.013) at time point three. Compared to baseline, HV-1 significantly increased (i.e., became less negative) at time point three (p < 0.001), whereas, VH-2 significantly decreased values (i.e., became more negative) for S_{rel} at time point two (p = 0.014) and both S_{fv} (p = 0.012) and S_{rel} (p = 0.001) at time point four.

Table 7.4. Sprint time and force-velocity values across all four (T1, T2, T3, T4) timepoints (n = 32), with effect sizes (ES) and 95% confidence intervals (CI) for paired data (n = 19). All symbols signify statistical significance ($p < 0.05$). *= group x time interaction (CON-0 & HV-1); ¤= group x time interaction (CON-0 & VH-2); Φ= group x time interaction (HV-1 & VH-2); Δ= significantly less than baseline; ◊= significantly greater than baseline.

Variable	G	D1	T1	T2	T2-T1 ES (CI)	D2	T3	T4	T3-T4 ES (CI)	T4-T1 ES (CI)
10 m (s)	CON-0	C	1.819 (0.102)	1.830 (0.091)	0.44(-0.63, 1.49)	C	1.866 (0.131)*¤◊	1.853(0.099)	-0.23(-1.28, 0.82)	0.37(-0.70, 1.41)
10 m (s)	HV-1	H	1.839 (0.066)	1.826 (0.077)	-0.07(-1.04, 0.91)	V	1.838 (0.065)*	1.826(0.067)	-0.17(-1.15, 0.81)	-0.28(-1.26, 0.72)
10 m (s)	VH-2	V	1.849 (0.068)	1.867 (0.100)	0.25 (-0.80, 1.30)	H	1.845 (0.089)¤	1.864(0.103)	-0.10(-1.13, 0.95)	0.03(-1.10, 1.16)
20 m (s)	CON-0	C	3.082 (0.136)	3.088 (0.141)	0.30(-0.76, 1.34)	C	3.144 (0.172)*¤◊	3.131 (0.148)*◊	-0.17(-1.21, 0.89)	0.31(-0.75, 1.35)
20 m (s)	HV-1	H	3.115 (0.100)	3.091 (0.113)	-0.16(-1.14, 0.82)	V	3.118 (0.109)*	3.096 (0.114)*	-0.18(-1.16, 0.81)	-0.28(-1.26, 0.71)
20 m (s)	VH-2	V	3.124 (0.093)	3.133 (0.130)	0.16(-0.89, 1.20)	H	3.117 (0.119)¤	3.147 (0.144)	-0.07(-1.11, 0.98)	0.04(-1.00, 1.08)
30 m (s)	CON-0	C	4.280 (0.172)	4.287 (0.191)	0.31 (-0.75,1.35)	C	4.355 (0.214)*¤◊	4.351 (0.198)*◊	-0.09(-1.13, 0.96)	0.36(-0.71, 1.40)
30 m (s)	HV-1	H	4.324 (0.168)	4.295 (0.157)	-0.14(-1.12, 0.84)	V	4.330 (0.159)*	4.304(0.172)*Δ	-0.15(-1.12, 0.84)	-0.23(-1.21, 0.76)
30 m (s)	VH-2	V	4.335 (0.116)	4.346 (0.164)	0.17(-0.88, 1.21)	H	4.322 (0.159)¤	4.384 (0.19)	0.01(-1.03, 1.05)	0.17(-0.88, 1.21)
10-20 m (s)	CON-0	C	1.264 (0.044)	1.258 (0.058) Δ	-0.03(-1.07, 1.01)	C	1.278 (0.049)	1.278 (0.059)*Δ	0.00(-1.04, 1.04)	0.17(-0.88, 1.20)
10-20 m (s)	HV-1	H	1.276 (0.061)	1.264 (0.045)	-0.22(-1.20, 0.77)	V	1.279 (0.049)	1.270 (0.051)*	-0.17(-1.15, 0.81)	-0.20(-1.18, 0.79)
10-20 m (s)	VH-2	V	1.275 (0.048)	1.265 (0.050)	-0.05(-1.09, 0.99)	H	1.272 (0.039)	1.283 (0.050)	0.00(-1.04, 1.04)	0.04(-1.05, 1.08)
20-30 m (s)	CON-0	C	1.197 (0.044)	1.199 (0.054)	0.32(-0.74, 1.36)	C	1.212 (0.047)	1.219 (0.057)* Δ	0.15(-0.90, 1.20)	0.47(-0.61, 1.52)
20-30 m (s)	HV-1	H	1.209 (0.077)	1.204 (0.051)	-0.08(-1.06, 0.90)	V	1.212 (0.055)	1.208 (0.06)*	-0.07(-1.05, 0.91)	-0.13(-1.11, 0.85)
20-30 m (s)	VH-2	V	1.211 (0.041)	1.214 (0.048)	0.16(-0.89, 1.20)	H	1.205 (0.049)	1.237 (0.054)	0.23(-0.82, 1.28)	0.48(-0.59, 1.54)
V_0 (m·s^{-1})	CON-0	C	8.84 (0.35)	8.83 (0.34)*	0.07(-0.98, 1.11)	C	8.67 (0.36)*	8.59 (0.48)*Δ	-0.13(-1.17, 0.92)	-0.36(-1.40, 0.76)
V_0 (m·s^{-1})	HV-1	H	8.57 (0.58)	8.68 (0.39)*	0.22(-0.77, 1.20)	V	8.75 (0.48)*Φ ◊	8.68 (0.55)*Φ ◊	-0.14(-1.11, 0.85)	0.29(-0.70, 1.27)
V_0 (m·s^{-1})	VH-2	V	8.64 (0.37)	8.60 (0.40)	0.09(-0.96, 1.13)	H	8.71 (0.43)Φ	8.42 (0.39)Φ Δ	-0.30(-1.34, 0.76)	-0.27(-1.31, 0.78)
V_{max} (m·s^{-1})	CON-0	C	8.57 (0.31)	8.56 (0.33)*	0.02(-1.02, 1.07)	C	8.41 (0.34)*¤	8.34 (0.44)*Δ	-0.10(-1.13, 0.95)	-0.35(-1.39, 0.72)
V_{max} (m·s^{-1})	HV-1	H	8.32 (0.54)	8.42 (0.36)*	0.21(-0.77, 1.19)	V	8.47 (0.45)*◊	8.43 (0.51)*Φ ◊	-0.08(-1.06, 0.90)	0.29(-0.70, 1.27)
V_{max} (m·s^{-1})	VH-2	V	8.39 (0.33)	8.36 (0.37)	0.08(-0.96, 1.13)	H	8.45 (0.39)¤	8.20 (0.35)Φ Δ	-0.28(-1.32, 0.78)	-0.26(-1.30, 0.79)
F_0 (N)	CON-0	C	738 (133)	723 (111)	-0.22(-1.26, 0.84)	C	722 (106)	763 (106)	0.30(-0.76, 1.34)	0.17(-0.88, 1.31)
F_0 (N)	HV-1	H	704 (108)	704 (89)	-0.04(-1.10, 1.00)	V	649 (57) Φ Δ	721 (82)	0.95(-0.11, 1.99)	0.09(-0.97, 1.12)
F_0 (N)	VH-2	V	790 (105)	830 (87)	-0.02(-1.06, 1.02)	H	815 (125)Φ	853 (105)◊	0.24(-0.81, 1.29)	0.23(-0.83, 1.27)
F_{0rel} (N·kg^{-1})	CON-0	C	7.32 (0.78)	7.42 (1.22)	-0.31(-1.35, 0.75)	C	7.24 (.73)	7.58 (0.66)	0.49(-0.59, 1.54)	0.40(-0.66, 1.45)

F_{rel} (N·kg^{-1})	HV-1	H	7.64 (0.47)	7.65 (0.60)	-0.08(-1.06, 0.91)	V	7.03 (0.85)ΦΔ	7.80 (0.73)	0.90(-0.16, 1.93)	0.27(-0.72, 1.25)
F_{rel} (N·kg^{-1})	VH-2	V	7.29 (0.49)	7.69 (0.71)◊	0.17(-0.88, 1.21)	H	7.46 (0.47)Φ	7.84 (0.64)◊	0.48(-0.59, 1.53)	0.45(-0.62, 1.50)
P_0 (W)	CON-0	C	1626 (262)	1599 (272)	-0.19(-1.23, 0.94)	C	1562 (225)	1635 (210)	0.24(-0.82, 1.28)	0.07(-0.98, 1.10)
P_0 (W))	HV-1	H	1512 (269)	1528 (217)	0.03(-0.96, 1.00)	V	1425 (190)ΦΔ	1568 (228)	0.64(-0.39, 1.64)	0.17(-0.15, 1.15)
P_0 (W)	VH-2	V	1699 (183)	1779 (166)	0.04(-1.00, 1.09)	H	1764 (218)Φ	1789 (178)	0.15(-0.90, 1.19)	0.12(-0.93, 1.16)
P_{rel} (W·kg^{-1})	CON-0	C	16.15 (1.77)	16.43 (3.20)	-0.24(-1.29, 0.81)	C	15.73 (1.97)	16.30 (2.01)	0.32(-0.74, 1.36)	0.15(-0.90, 1.20)
P_{rel} (W·kg^{-1})	HV-1	H	16.41 (1.90)	16.60 (1.69)	0.05(-0.93, 1.03)	V	15.37 (1.90)Φ Δ	16.92 (1.96)	0.75(-0.29, 1.76)	0.33(-0.66, 1.31)
P_{rel} (W·kg^{-1})	VH-2	V	15.74 (1.28)	16.54 (1.91)◊	0.17(-0.88, 1.21)	H	16.22 (1.30)Φ	16.50 (1.67)◊	0.24(-0.82, 1.28)	0.22(-0.83, 1.27)
S_{fv}	CON-0	C	-83.9 (17.1)	-81.9 (11.9)	0.24(-0.82, 1.28)	C	-83.4 (13.1)*	-89.4 (14.9)	-0.33(-1.43, 0.73)	-0.25(-1.30, 0.80)
S_{fv}	HV-1	H	-82.3 (12.9)	-81.2 (10.4)	0.14(-0.85, 1.12)	V	-74.2 (4.2)*◊	-83.3 (9.9)	-1.13(-2.19,-0.03)	0.05(-0.94, 1.02)
S_{fv}	VH-2	V	-92.0 (15.4)	-97.0 (13.2)	0.05(-1.00, 1.09)	H	-94.4 (18.3)	-101.8 (16.1)Δ	-0.27(-1.32, 0.78)	-0.26(-1.30, 1.80)
S_{rel}	CON-0	C	-0.855 (0.099)	-0.865 (0.121)	0.35(-0.12, 1.40)	C	-0.861 (0.073)*	-0.910 (0.071)	-0.60(-1.66, 0.49)	-0.56(-1.61, 0.52)
S_{rel}	HV-1	H	-0.919 (0.045)	-0.909 (0.067)	0.27(-0.72, 1.25)	V	-0.833 (0.117)*◊	-0.927 (0.096)	-0.82(-1.84, 0.22)	-0.06(-1.04, 0.93)
S_{rel}	VH-2	V	-0.871 (0.066)	-0.920 (0.081)Δ	-0.14(-1.19, 0.90)	H	-0.884 (0.067)	-0.956 (0.079)Δ	-0.65(-1.72, 0.45)	-0.62(-1.68, 0.47)
RFpeak (%)	CON-0	C	48.9 (2.8)	49.1 (4.6)	-0.30(-1.42, 0.86)	C	48.5 (3.0)	49.6 (2.5)	0.46(-0.61, 1.64)	0.32(-0.82, 1.46)
RFpeak (%)	HV-1	H	49.9 (2.3)	50.0 (2.4)	-0.01(-1.06, 1.04)	V	47.7 (3.3)Φ Δ	50.5 (2.6)	0.88(-0.18, 1.90)	0.29(-0.70, 1.27)
RFpeak (%)	VH-2	V	48.7 (1.9)	50.0 (2.9)◊	0.09(-0.96, 1.13)	H	49.4 (1.8)Φ	50.3 (2.4)◊	0.37(-0.69, 1.42)	0.32(-0.74, 1.37)
DRF (%)	CON-0	C	-7.5 (0.8)	-7.6 (0.9)	0.35(-0.72, 1.40)	C	-7.6 (0.6)*	-8.0 (0.6)Δ	-0.57(-1.63, 0.52)	-0.58(-1.64, 0.51)
DRF (%)	HV-1	H	-8.1 (0.4)	-8.0 (0.5)	0.27(-0.72, 1.25)	V	-7.4 (1.0)*Φ ◊	-8.1 (0.8)Φ	-0.79(-1.81,0.25)	0.01(-0.97, 0.99)
DRF (%)	VH-2	V	-7.7 (0.6)	-8.1 (0.6)Δ	-0.21(-1.34, 0.94)	H	-7.8 (0.6)Φ	-8.4 (0.6)Φ	-0.85(-2.01, 0.43)	-0.91(-2.12, 0.38)

Note: G= group; D= direction; C= control; V= vertical; H= horizontal; m= metre; V_0= theoretical maximal velocity; V_{max}= maximal velocity achieved in trial; F_0= theoretical maximal force; F_{rel}= theoretical maximal force production per kilogram of body mass; P_0= theoretical maximal power; Prel= maximum power per kilogram of body mass; Sfv= rate of decreasing horizontal force; Srel= relative decreasing horizontal force per kilogram; RFpeak= maximum ratio of forces; DRF= rate of decline in RFpeak; s=second; N= Newton; W= Watts.

7.3.3. Ratio of forces

For RFpeak, there was not a significant interaction for vertical plyometrics when compared to the control group (ConΔ: +0.6%, ES = 0.17, CI: -0.64, 0.98; VΔ: +2.8%, ES = 0.71, CI: 0.05, 1.37; HΔ: +0.6%, ES = 0.30, CI: -0.41, 0.99; $p = 0.068$). There were group by time interactions between experimental groups only at time point three (Table 5; $p = 0.002$). Individually, HV-1 decreased their RFpeak at time point one ($p= 0.002$), while VH-2 significantly increased RF at time points two ($p = 0.017$), and four ($p = 0.015$). CON-0 did not significantly change at any time point.

7.3.4. Decline in ratio of forces

For DRF, there were no significant interactions between directions (ConΔ: -0.23%, ES = -0.17, 95% CI: -1.30, 0.97; VΔ: -0.3%, ES = -0.69, 95% CI: -1.35, -0.03; HΔ: -0.3%, ES = -0.34, 95% CI: -1.04, 0.36; $p > 0.2$). There was a group by time point interaction for HV-1 at time point three (Table 5; $p = 0.008$) compared to CON-0. Between experimental groups, there were group by time point interactions three ($p = 0.001$), and four ($p=0.032$). Individually, HV-1 increased DRF at time point three ($p < 0.001$). While VH-2 significantly decreased DRF at time point two ($p = 0.016$), VH-2 decreased DRF at time point four ($p = 0.001$) and CON-1 did not significantly change ($p = 0.081$).

7.4. Discussion

7.4.1. Main findings

This purpose of this study was to determine the influence of implementing a low-volume plyometric training programme on sprint performance variables during a pre-season training period in semi-professional rugby union players. Additionally, the study investigated the specific

FV adaptations relating to training axis. The results indicated that adding short periods of low-volume plyometric training may be an effective strategy to stimulate small, but practically relevant improvements in sprint performance (split time: -0.02 to -0.05 s, ES = -0.23 to -0.28) and maximal velocity characteristics (V_0 and V_{max}: +0.11 m·s^{-1}, ES = 0.29 – 0.30), with minimally added stress. Alternatively, in lesser-trained individuals adding low-volume plyometric training may attenuate performance decrement for sprint performance (split time: +0.01 s – 0.04 s; ES = 0.03 – 0.17) and maximal velocity characteristics (V_0 and V_{max}: -0.09 to -0.11 m·s^{-1}, ES = -0.26 to -0.27) during periods of progressively increased total training volume. In contrast, rugby and resistance training only primarily resulted in sprint time (split time: +0.04 – 0.07, ES = 0.31 – 0.37) and maximal velocity (V_0 and V_{max}: -0.15 to -0.23 m·s^{-1}, ES = -0.35 to -0.36) decrements in CON-0. Interestingly, vertical plyometric training appears to have impacted several force-dominant FV profile characteristics to a greater extent than horizontally applied training. Moreover, changes in sprint performance were paired with FV profile shifts in both experimental groups, while CON-0 was able to maintain maximal force characteristics. These fluctuations in mechanical and functional performance over short durations support the high pliability of velocity-based characteristics.

7.4.2. Force-velocity profile changes

The sprint performances in this study are similar to what has previously been reported in University-level rugby players (386) and other New Zealand provincial players (356). During the seven-week study, HV-1 portrayed improved sprint performance, while VH-2 maintained performance initially, but demonstrated decrements in V_0 and V_{max} during the final testing session. In contrast, CON-0 continually trended downward, demonstrating the greatest performance decrement in split times and maximal velocity across the seven-week study. These results support previous research indicating high-velocity characteristics are highly susceptible to fatigue (166). Mechanistically, accrued neural fatigue and muscle damage from progressive loading can inhibit muscle activation, firing rates and dampen the elastic recoil response (151). These are areas where plyometric training may have been able to make appreciable changes by offsetting fatigue-induced neural inhibition (151,188). Interestingly, VH-2 showed greater acute performance decrements during the second mesocycle when compared to CON-0, but lesser total decrements across the entire study. Thus, the results indicated that the low plyometric volumes used in the current study were enough to provide an initial adaptation response, most likely via improved neural input and eccentric energy storage (345). Moreover, HV-1 and VH-2 demonstrated their best performance relative to CON-0 at the third time point suggesting that acute fatigue may have affected immediate performance.

Interestingly, correlations reveal initial body composition and aerobic fitness across all groups were related to both velocity- and force-centric profile changes throughout the whole seven-week programme (Table 7.2). These relationships were particularly evident in the latter mesocycle ($r = 0.434$ to -0.568), suggesting accumulated fatigue and total combined volume load may have diminished results in lesser trained individuals. Although not statistically significant, VH-2 and CON-0 had participants with lower aerobic fitness compared to HV-1 (Table 7.1) as evidenced by lower mean (VH-2 = 17.1 ± 1.3 , CON-0 = 17.1 ± 1.5 vs. HV-1= 17.5 ± 1.1) and minimum range (VH-2 = 14.3 – 19.1, CON-0 = 14.4 – 19.3 vs. HV-1 = 16.3 – 19.2) yoyo test scores and higher skinfold measurements (VH-2 = 112 ± 34, CON-0 = 103 ± 34 vs. HV-1 = 98 ± 50 mm). While speculative, this may partially explain the discrepancy in training group response. Indeed, athletic characteristics like prior strength levels, adipose tissue, and somatotype have shown to directly affect the magnitude and rate of adaptation for ballistic performance in strong (i.e., 1.2 – 2.0 kg·BM^{-1} squat) males, and youth populations alike (168). Participants were randomly allocated and matched for speed (30 m split time) and strength to control for the capacity for adaptation based on prior athletic ability, but not aerobic fitness or body composition. Sprinting performance is highly regulated by the ability to produce force, and as such, 30 m time and max strength directly affect the bandwidth for adaptation in sprinting performance (168,264). Therefore, these qualities were seen to take precedence over aerobic fitness and anthropometric measures for group allocations.

7.4.3. Programme length and adaptation rates

Few studies have investigated short (three week) plyometric training mesocycles, nevertheless sprint time and maximal velocity characteristic adaptations from this study can be compared to other plyometric training studies using similar periods (231,236,322). Using longer duration programmes (i.e., 8 – 12 weeks), some plyometric training studies have previously reported greater improvements in running velocity, across a variety of distances (10 – 40 m) (157,224,231). Results herein indicate short mesocycle lengths with low volumes offer some limited availability for adaptation in velocity-based qualities, particularly in trained team sport athletes (166). Pienaar et al. (2013) reported similarly maintained 10 m, but greater improvements in 20 m split time (Δ: -0.11 vs. -0.03) than the current study, following one month of high-volume (120 $GC.session^{-1}$, 3x weekly) vertical and horizontal plyometrics, resistance training and rugby conditioning in South African U-19 players (304). It is possible that differences in sport and aerobic training load between studies contributed to differences in sprint performance adaptation beyond a simple plyometric dose-response (1440 GC vs. 600 GC) (304). Although it is true that more volume is likely to provide more of a training stimulus, increased volume may additionally fatigue athletes, thus hindering their neuromuscular ability in subsequent sport training sessions. While much less, the current study wanted to investigate the lowest necessary volume for improving performance and provided evidence to suggest short periods of low-volume plyometrics can stimulate a small improvement (ES = -0.2 to 0.33) for sprint performance. Low volumes (i.e., 30

– 40 GC) have previously demonstrated greater jump kinetics and sprint performance in collegiate and professional athletes (157,372).

From a practitioner's perspective, training efficiency is critical when managing load from multiple daily workouts and rugby sessions during the season. Seeing as bouts of 70 – 100+ DJ have commonly been used to examine exhaustive stretch-shortening cycle mechanisms immediately, 2-, and 4- days post-exercise (150,151), the added benefit from higher volumes may be muted if the fatigue dampens an athlete's performance during sport-specific training and competition. Interestingly, Mäckała et al. (236) reported a similar split time improvement (flying - 20 m: -0.05 s vs. standing 30 m: -0.03 s) in trained sprinters using four to five times the sessional volume of the current study over two weeks suggesting excessive volume may not always be preferential. On the other hand, trained sprinters are generally accustomed to much greater plyometric volumes due to the direct transfer to linear performance. These athletes may need higher volumes to elicit even the smallest of performance gains, whereas for team sport athletes, low volumes may be just as beneficial. Other authors have reported equivocal benefits from lesser volumes or frequencies, indicating intensity, neural input and movement velocity may be more critical to performance than increases in volume (49,157,317). Further research is necessary to understand the complexity of dose-response and fatigue management for improving sprint performance in team-sport athletes.

7.4.4. Training axis

In contrast to our hypothesis, only vertical plyometrics significantly affected sprint performance more than rugby and resistance training alone. Due to the short wash-out period and mesocycle lengths, we cannot completely discount an interaction between horizontal and vertical stimuli, or the possibility of a delayed adaptation supercompensation effect entirely. More research is needed to determine the isolated adaptations following directionally specific plyometric training blocks for a true mechanistic understanding. In the current study vertical plyometric training impacted 10 – 20 m split time (ES = -0.28), as well as several force-dominant profile characteristics (ES = -0.38 to 0.72) to a greater degree than horizontal training (ES = 0.13 – 0.35) or no plyometric training (ES < 0.3) consistent with previous literature on uniaxial plyometric training (157,231). Specifically, Loturco et al. (231) similarly reported improved 10 – 20 m performance following vertical, but not horizontal training. Practically speaking, transitioning from lower velocities to near maximal requires a shift in force ratios and an exponential increase in vertical force production as the trunk becomes more upright (209). On the other hand, horizontal plyometrics did not conjointly alter sprint performance. Vertical and horizontal stimuli might require different refractory periods for recovery. Hip and trunk joint torques have been reportedly higher in horizontally-applied jumping, due to the addition of pelvic control in the transverse and frontal planes (180). As such, stress placed on the muscle and tendinous structures of the lower leg may outweigh those applied vertically and could result in longer session-to-session recovery requirements. Thus, practitioners may want to implement additional later testing sessions to capture any delayed or lag effects given progressively increased sport and resistance training volume.

7.4.5. Mechanical parameters and sprint performance

The results from this study highlighted the interconnected nature of FV characteristics to functional speed performance. Specifically, HV-1 demonstrated faster split times, lower maximal force characteristics and a less negative S_{fv} at time point three following horizontal plyometrics, while VH-2 portrayed a more negative slope, and better maintained force-centric improvements at time point four following vertical plyometrics. With no directionally specific training, CON-0 was able to maintain maximal force characteristics across the study. Previous literature suggests force characteristics are not as sensitive to fatigue or decay as velocity-based adaptations are (166). Interestingly, both training groups demonstrated acute larger F_0, F_{rel}, P_0 and P_{rel} scores following vertical plyometrics. Loturco et al. (231) and Della Iacono et al. (157) reported similar directionally-oriented jump kinetic improvements following vertical (% change = 8.9 – 10.3%) and horizontal (% change = 7.8 – 12.6%) jumps. Surprisingly, in the current study even horizontal forces trended to increase more following vertical, compared to horizontal plyometrics, which is in contrast to other uniaxial investigations (157,231). In fact, for HV-1, F_o did not acutely change at all following horizontal training. Instead, athletes were able to reach greater maximal velocities while maintaining the ability to produce force, and the shape of their profile. This may have been because the horizontal exercises were instructed predominantly to reach maximal distance while minimizing ground contact time in the sprint bounding, single-leg horizontal jumps, and skater jump exercises, potentially altering neural input, and shifting force production to earlier in the stance phase. A growing body of literature has reported substantial differential effects based on instructions. These should be carefully considered so that they elicit desired outcomes (183). Alternatively, Della Iacono et al. (157) demonstrated greater stride length during the first four steps following horizontal DJ, noting a more optimal horizontal-to-vertical force ratio was contributing to performance improvements.

7.4.6. Limitations

The primary aim was to investigate low-volume plyometric training in a practical setting in order to understand necessary dosing strategies. This was an exploratory investigation to better understand how directionally specific plyometric training may alter specific FV profile attributes. Results herein warrant further investigations in FV adaptations resulting from vertical and horizontal plyometric training. In an ideal world, multiple volumes would have been investigated (i.e., 800, 1200, 1600 total volumes); however, this was not possible given the competitive demands, population size and time frame of the semi-professional rugby players in the current study. Due to prioritizing competitive agendas of the participating rugby union, and the wellbeing of their athletes, a large number of participants dropped out, thus affecting the statistical power. Several athletes missed one or two testing sessions to attend recruitment camps, manage alternate work commitments, or address injuries procured from rugby specific training and/or matches. Furthermore, a longer familiarization and the inclusion of a taper period for horizontal plyometrics may have increased programme efficacy, considering the short mesocycle length and novelty of horizontal stimulus. Both the mesocycle and washout durations were shortened given the constraints of the preparatory period. Future investigations may want to increase both the duration and washout periods to get a more detailed understanding of direction-specific adaptation.

7.5. Practical Applications

Integrating low-dose vertical plyometrics during pre-season training programmes appears to be a useful intervention for improving sprint performance in rugby union players. Moreover, in athletes with high skinfold and low aerobic scores, low dose plyometrics may help to attenuate decrements from high-volume combined training loads. Vertical plyometrics in particular may preferentially improve transitional velocities (10 – 20 m split time), and force-centric FV profile characteristics. However, a delayed beneficial effect from horizontal plyometrics cannot be discounted from the current model. Practitioners may want to ensure athletes are familiarized and given a sufficient taper to realise the most benefit from plyometric training.

Chapter 8 – How low do you go? Dose response of horizontal single-leg drop jumps on sprinting profiles

Reference

Manuscript in preparation for journal submission.

Authorship

Watkins, CM, 80%, Gill, ND, 4%, McGuigan, MR, 4%, Downes, P, 4%, Storey, AG, 8%

8.0. Prelude

While this thesis has provided support for low volume plyometrics, there was still a gap involving least critical dosing strategies. Reports suggest expert practitioners implement volumes less than 20 GC per session (Chapter 5), while literary support for very-low (< 25 GC) volumes were mixed. Furthermore, following initial analysis of training axis related adaptations, there were still some questions surrounding how best to implement horizontal plyometrics. Short mesocycle (three weeks) and wash-out periods may have inhibited adaptation rates in Chapter 7, particularly in horizontal plyometrics. This may be due to the greater landing forces incurred during horizontally oriented exercises, or the lack of familiarity with these exercises compared to vertical ones which affected the programme's efficacy. Earlier in-session increases in eccentric impulse and concomitant decreases in concentric impulse from horizontal, as compared to vertical, plyometrics could indicate less volume may be more advantageous to prevent in-session fatigue (Chapter 6). In this respect, a second horizontal-only investigation was implemented over four weeks to better determine if programme length or dose response possibly affected adaptation. Accordingly, only one exercise was used in an attempt to reduce any learning effects associated with a short-term multiple-exercise programmes (Chapter 7). Exercise choice was determined in part from the results from Chapter 3 which supported SLDJ as an effective method for improving short-distance sprint performance. Similarly, this exercise was more frequently reported for those practitioners (Chapter 5). Thus, dosing strategies were investigated in the following chapter using only SLDJ performed horizontally twice weekly for four weeks.

8.1. Introduction

Sprinting and acceleration are critical factors for success in rugby union, impacting attacking strategies, line breaks, and pressure defence (144). While outside and inside backs sprint more frequently and for greater distances, as well as reach higher peak speeds than forwards players, all positional groups reach near-maximal relative velocities (>90% Vmax) during 50% of all sprints performed (90,178). Furthermore, for well-trained athletes competing in professional and semi-professional leagues, speed and accelerative performance can be an important determinant for comparing athletes following a training programme, regardless of positions or playing standards (135,356). As in many other team sports, competitive rugby players are also required to be strong, powerful, mechanically efficient, aerobically fit, agile and resilient (356). Maintaining this varied athletic profile year-round is a challenge for many strength and conditioning coaches who work with large groups of athletes. Due to additional team practices, travel demands and possible work commitments, team-sport athletes require a high level of training efficiency. This requirement places an emphasis on determining the lowest effective training stimulus.

Plyometric training is an effective form of ballistic training used to improve athletic performance by integrating the stretch-shortening cycle and facilitating optimal neuromuscular contraction dynamics (248). Published research provides substantial evidence that plyometric training can beneficially affect jumping, speed and acceleration in as little as two weeks (157,236). However, contrasting recommendations between published research and practitioner prescription result in a lack of clarity surrounding optimal dosing strategies for trained athletes. Published recommendations suggest wide sessional volume ranges of 60 – 400 GC depending on an individual's training status (78,96). Similarly, most experimental studies using elite athletes report significant adaptations in jumping and sprinting performance using high-volume protocols (120 – 220 GC) (232,236,304). Yet, there is increasing support for low-volume (40 – 60 GC) plyometric training in youth, amateur athletes and, more recently, professional athletes (157,159,372). Interestingly, some elite (i.e., Olympic and international-level) strength and conditioning coaches have reported frequently using ultra-low sessional volumes <20 GC (Chapter 5) (389). Comparable performance gains from reduced (50%) volume programmes do suggest the existence of an adaptation threshold, after which more volume may cause merely unwanted stress (380). However, more research is needed to understand the lowest effective dosing strategies.

While session volumes are hotly debated, there is strong agreement surrounding the benefit of high-intensity plyometrics on sprint performance (24,377). For example, DJ and especially the SLDJ variety, provide an effective method for improving stretch-shortening cycle efficiency, neuromuscular ability, running economy, sprinting, and change-of-direction performance (157,340). For these reasons, international-level strength and conditioning coaches more often reported using SLDJ than practitioners working in lower-level competitions (389). Furthermore, there is some evidence to suggest SLDJ performed horizontally may prompt superior sprint gains (-8.5% vs. -4.0%), greater increases in step length, and concomitant decreases in change-of-direction ground contact time, than vertical varieties (157). Similarly, kinetic analysis demonstrates that horizontal DJ and SLDJ had significantly lower peak forces (~five times), but greater relationships to sprinting speed than vertical varieties (84). Additionally, these authors reported larger correlations with sprinting speed and velocity measures during single-leg as opposed to double-leg jump varieties (84). Altogether, these results suggest that horizontally applied SLDJ may be an effective strategy to improve sprint performance.

Therefore, the purpose of this investigation was to compare the use of moderately-low (MLV) and ultra-low (ULV) volume dosing strategies using horizontal SLDJ for improving sprint performance in trained rugby union players.

8.2. Methods

8.2.1. Experimental approach to the problem

The current study employed a parallel group, repeated measures experimental design with random group allocation and pre/post assessments. Accordingly, participants were pair-matched by position and randomly allocated to one of two experimental groups that trained with MLV or ULV protocols in addition to their regular rugby training and resistance exercise programmes. While we considered a non-plyometric control group, the ULV group underwent a minimal dosing approach, with their experimental volume significantly reduced (~50%) compared to the MLV group. Considering competitive schedules, limited player pools from the same rugby club and previous studies employing a two-experimental group method (157,380), we decided that a limited training control approach was necessary. Plyometric training was conducted in the preparatory period prior to the start of season (January – February). Concurrent resistance training was performed twice-weekly with the intent to increase athlete strength (i.e., four exercises performed at 70 – 90% relative maximum strength for 4 – 8 sets of 1 –5 reps) and hypertrophy. Specific rugby training and skills work was also completed twice weekly. The study lasted six weeks with testing performed the week prior to and following a four-week block of twice-weekly training. Tests included CMJ, DJ, and a maximal sprint assessment to assess vertical and horizontal ballistic performance. The Auckland University of Technology Ethics committee approved this project and all participants provided written consent prior to volunteering.

8.2.2. Participants

Sample size estimation was calculated from a similar study reporting η_p^2 of 0.629 for 10 m sprint performance (157). Using these results in an ANOVA interaction model with within-between interactions, a power threshold of 0.80 and an alpha of 0.05, the estimated sample size was six.

To account for shorter programme lengths and greater expected drop-out, 26 male high-level club- and semi-professional rugby union players were recruited for this study. However, four participants (MLV = 2, ULV = 2) dropped out due to conflicting schedules, travel and work commitments. Therefore, 22 participants completed this study (MLV: n = 11; 94.9 ± 13.4 kg; 185.9 ± 7.3 cm; 20.4 ± 2.2 years; ULV: n = 11; 102.8 ± 10.9 kg; 184.0 ± 7.3 cm; 20.4 ± 2.4 years). All participants belonged to the same rugby union organisation, participating in rugby technical and tactical practice two days per week, rugby ball skills two days per week and strength training two days per week. All participants had been involved in club rugby for >10 years and had been consistently training with the identified club between six months and four years (1RM back squat = 1.2 – 2+ x body mass). To be eligible for study participation, subjects were required to be: male, 18 years or older, not currently taken or have ever taken anabolic steroids, free of any musculoskeletal injuries and cleared for training by the team's sport doctor, and currently participating in the Auckland Rugby contenders programme for Mitre 10 rugby team selection. All participants were either already contracted to the semi-professional team or selected as potential candidates contending for spots in the upcoming season. The Auckland University of Technology Ethics committee approved this project and all participants provided written consent prior to volunteering.

8.2.3. Procedures

One week before training, all participants completed jump and sprint assessments as part of their pre-season profile. Pre- and post-assessments were completed during two sessions in the same order. Participants completed both sessions at the same time of day, on Monday and Tuesday mornings within a three-hour window (5:00 AM – 8:00 AM). Sprint and aerobic testing always took place in the same indoor testing location, which had a 3G turf field that minimized diurnal and environmental effects. Similarly, jump testing was always performed the following day in the gym, prior to resistance training. Upon arrival at the indoor field for the initial testing session, height and body mass measurements were taken using a portable stadiometer (SECA model 213, Germany) and scale (SECA, model 277, Germany). Athletes were given five minutes of individual warm-up time to foam roll, stretch, or carry out individual routines. After this, a targeted warm-up, focusing on core and lower-body musculature, was conducted by the primary supervisor. The warm-up was performed over a distance of 15 m followed previous suggestions designed to increase muscle and core temperature, activate neuromuscular pathways, move the body through full range of motion, and finally potentiate performance (172). Dynamic squats, lunges, shuffling drills, bridges, core exercises and plyometrics were used in this process, lasting ~10 minutes. Warm-ups finished with three progressively increased stride outs at approximately 50, 70, and 80% maximal effort for 20, 30, and 35 m respectively. An additional one or two stride-outs were performed ≥90% Vmax, per protocol for the following maximal assessment.

8.2.4. Sprint assessment

Sprint performance was measured via radar (Stalker ATS II Pro, Texas, USA) and dual-beam infrared timing gates (Swift Performance, Lismore, Australia). Split times were recorded directly from timing gates, while maximal force and velocity characteristics were obtained from radar files to provide a more comprehensive analysis of sprint performance (388). The radar gun was situated three metres directly behind the start line, which was a further 50 cm behind the first set of timing gates. Subsequent gates were set at 10-, 20-, and 30-m from the first timing pair, at a width and height of one metre. Cones were placed five metres behind the last timing pair to discourage pre-mature deceleration. Three minutes rest were given between all maximal trials (135,388). The radar was initiated by laptop and all participants were set up in a two-point stance. To allow for a more natural run, participants initiated their own start once the radar was recording. Instructions were to stand as still as they could for at least one second to obtain a clear start point, then run as fast as they could all the way past the cones before slowing down. Split times were automatically recorded when the laser line was broken. Spatiotemporal data was collected from the radar and horizontal force-velocity profiles were calculated using least-square linear regression analysis as previously validated (352). As a result, V_0 and F_0 were calculated as the intercepts of the linear force-velocity relationship and P_0 as half the distance between V_0 and F_0 multiplied, or $(F_0*V_0)/4$ (Table 0.1). Then, P_0 was divided by body mass in kg to compare Prel between rugby players (Table 0.1). The average of two sprint trials was used for analysis, with dependent variables V_0, F_0, and Prel.

8.2.5. Jump assessments

To minimize arm sway differences between sessions, hands were placed on the hips for all jump assessments. In line with the rugby team's standard protocols, maximal CMJ and DJ performance were measured using dual portable uniaxial Pasport force plates (PASCO, California, USA), sampling at 1,000 Hz each (351). Both force plates (each 35 x 35 cm) were fitted securely into a larger platform. The force plates were connected via laptop and initiated by commercially available Forcedecks analysis software (Vald Performance Pty Ltd, QLD, Australia). Following a standardized warm-up, CMJ assessments were completed first. Participants were asked to step onto force plates and remain completely still (~1 second) until their body weight was registered. Starting in full stance position, athletes dipped straight down to a self-selected depth before rapidly extending their ankles, knees, and hips to jump as high as possible vertically. Force-time trace and visual checks were completed to ensure no pre-vertical movement was conducted prior to the initial dip in order to obtain greater jump heights. For the DJ exercise, participants were instructed to step off a 30 cm box with one foot, "like they're walking the plank, land with two feet and attack the ground; as quickly as possible, jump as high as they can." This height was chosen to determine changes in reactive strength and stretch-shortening cycle performance (48). The RSI is a measure of jump performance with respect to time and is calculated by dividing contact time from jump height (297). Jump height is then derived from the flight time method, using the equation:

$$\text{Jump height} = \frac{1}{2}\, g(FT/2)^2$$

Where $g = 9.81\ m{\cdot}s^{-2}$ and FT = the flight time (270).

8.2.6. Training programme

Following the initial testing session, participants were pair-matched by position and randomly allocated to either the MLV or ULV group. Plyometric training was performed at the beginning of rugby training, directly following the warm-up and prior to any exercise. Technical and tactical training during rugby sport practice involved moderate running volumes, typically 3,800 – 7,100 m daily. The warm-up consisted of five repetitions of bird-dog, single-leg bridges, lunges, and single-leg deadlifts, followed by 20 repetitions of high knees, and 10 ankle POGO jumps. Plyometric training consisted of performing alternating horizontal SLDJ from a 30-cm box. Similar to the vertical assessment, athletes were instructed to step-off and attack the ground, but with one leg, jumping as far horizontally as they could and sticking the second landing. The training volume was progressed each week for three weeks, with a 30% reduction the last week. DJ height and training volume was based on previous research (157). Training programme volumes for each group are listed in Table 8.1.

Table 8.1. Programme volume for moderately-low (MLV) and ultra-low (ULV) volume groups.
*Note: 2 x (3 x 5) = two sessions of three sets of five alternate horizontal drop jump each leg (SLDJ) or 15 ground contacts (GC) each leg for MLV week 1, session 1 & session 2.

Alternating horizontal SLDJ programme for both groups		
Schedule	MLV	ULV
Week 1 **total**	2 x (3x5) **30 each leg**	2 x (1x5) **10 each leg**
Week 2 **total**	2 x (5x5) **50 each leg**	2 x (1x7) **14 each leg**
Week 3 **total**	2 x (7x5) **70 each leg**	2 x (2x7) **28 each leg**
Week 4 total	2 x (4x5) **40 each leg**	2 x (2x4) **16 each leg**
Total Volume	**190 each leg; 380 combined GC**	**68 each leg; 136 GCT total**

8.2.7. Statistical analysis

All statistical analyses were performed using SPSS (version 26), and statistical significance was set at $p \leq 0.05$. A one-way ANOVA was used to analyse baseline anthropometric measurements. Subsequently, 2 x 2 (group x time) mixed factor repeated-measures ANOVA was used to analyse within- and between-subject performances for jumping and sprinting assessments. Following which, simple main effects were analysed and, due to group sample sizes below 20, Hedge's G ES and 90% CI were calculated for within-group pre to post intervention changes in sprint profile, CMJ and DJ scores (Table 8.2). For test-retest reliability, ICC and 90% CI were calculated for between-trials on the same day for jump and sprint variables. Previously reported thresholds for interpreting ICC results are: 0.20 – 0.49, 0.50 – 0.74, 0.75 – 0.89, 0.90 – 0.98 and ≥ 0.99 for low, moderate, high, very high and extremely high, respectively (147). For CV, values of ≤ 10% were considered small (32). Acceptability was determined for measures when ICC ≥ 0.75 and a CV ≤ 10%, moderate when ICC < 0.75 or CV > 10%, and unacceptable/poor when ICC < 0.75 and CV > 10%.

8.3. Results

8.3.1. Sprint times

All variables were deemed acceptable with sprint times (ICC: 0.91 – 0.98, 90% CL: 0.83 – 0.99; CV: 0.7 – 1.4%, 90% CL: 0.6 – 1.8%), FV profile (ICC: 0.80 – 0.94, 90% CL: 0.62 – 0.97; CV: 1.3 – 5.8%, 90% CL: 1.0 – 7.9%), and jump (ICC: 0.84 – 0.93, 90% CL: 0.66 – 0.97; CV: 5.9 – 9.4%, 90% CL: 4.7 – 13.5%) variables exhibiting high to very high reliability**.** Both groups were statistically similar for all variables at baseline ($p > 0.05$). There was a significant interaction (group x time) for 0 – 10 m ($p = 0.031$), and 0 – 30 m split time ($p = 0.033$; Figure 8.1).

There was no interaction for 0 – 20 m time ($p = 0.053$), but there was a main effect for time ($p = 0.032$). Simple effects analysis revealed the MLV group significantly decreased 0 – 20 m time ($p = 0.028$), whereas there was no change in the ULV ($p = 0.817$). There were no significant interaction or main effects for 10 – 20 m time or 20 – 30 m time, however simple effect analysis revealed MLV significantly decreased 20 – 30 m time ($p = 0.007$), while ULV did not change ($p = 0.898$; Figure 8.1).

8.3.2. Force-velocity profile

For the FV profile, there were no significant interactions (group x time) for Vmax, Frel or Prel (Table 8.2). For Vmax, there was no significant main effect for group ($p = 0.372$) time ($p = 0.202$), nor simple main effects for pre- to post-intervention for ULV ($p = 0.053$) or MLV ($p = 0.829$). For Frel and Prel, there were significant main effects for time ($p < 0.001$ in both cases). Simple effects reveal both groups significantly improved Frel (ULV: $p = 0.012$; MLV: $p < 0.01$) and Prel (ULV: $p = 0.038$; MLV: $p < 0.01$).

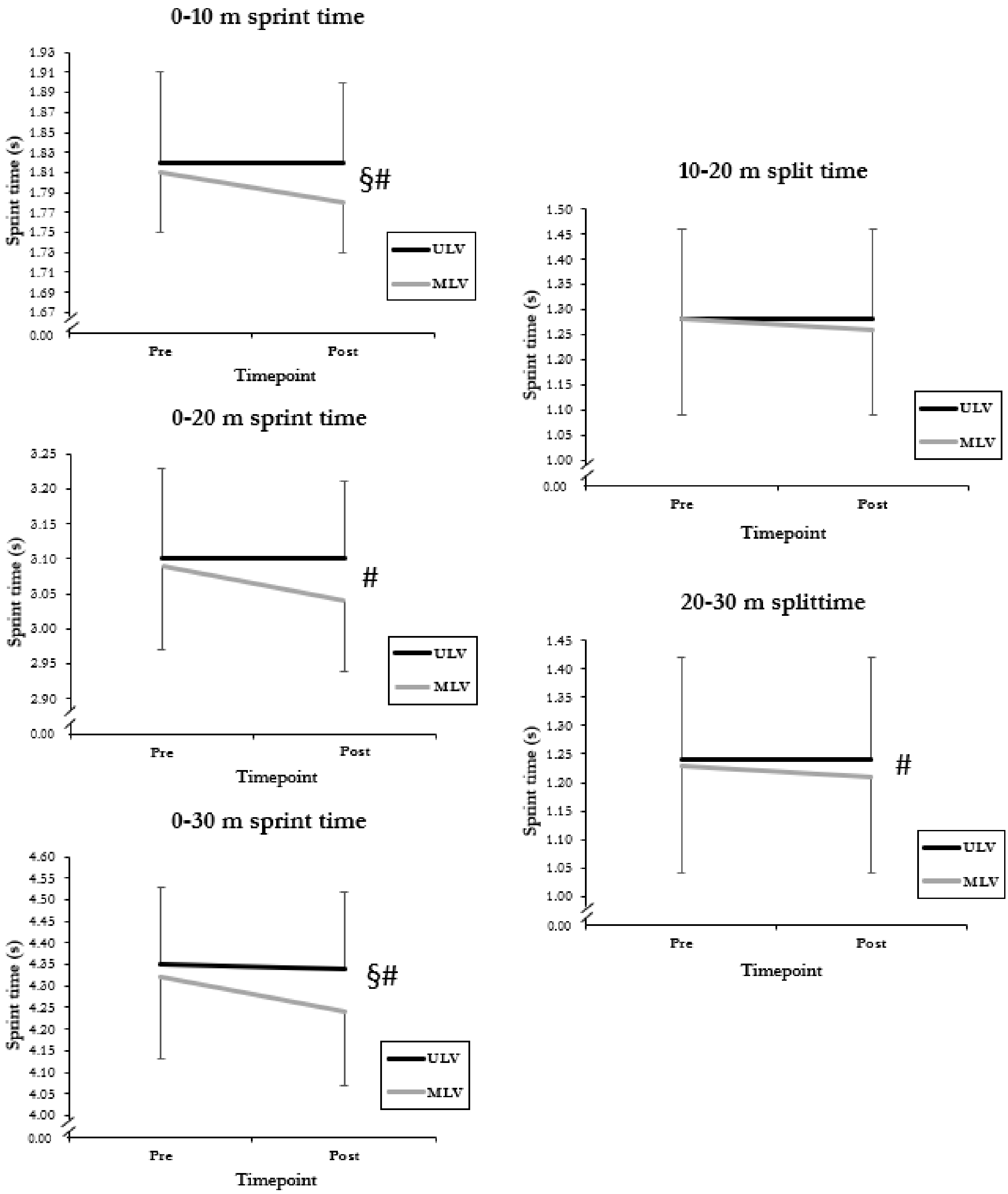


Figure 8.1. Sprint times for ultra-low (ULV) and moderately-low (MLV) volume groups pre- and post-intervention. Data presented as estimated means and 95% confidence intervals. Significance set at $p < 0.05$; § = interaction between groups; #= significant decrease for MLV.

8.3.3. Vertical jump performance

There were no interactions for any CMJ or DJ variables, but there were significant main effects for time in CMJ height, DJ height, DJ GCT and DJ RSI (Table 8.2; $p < 0.01$). Simple effect analysis reveals both groups significantly improved CMJ height pre- to post-intervention ($p < 0.02$).

Table 8.2. Force-velocity profile and vertical jump pre- and post-intervention assessment scores for moderately-low (MLV) and ultra-low (ULV) volume groups.

	ULV		Hedge's G	MLV		Hedge's G
	Pre	Post	ES (90% CI)	Pre	Post	ES (90% CI)
V_0 (m.s^{-1})	8.52 ± 0.4	8.37 ± 0.48#	-0.33 (-1.07, 0.41)	8.65 ± 0.5	8.64 ± 0.5	-0.02 (-0.75, 0.72)
F_{rel} (N.kg^{-1})	7.5 ± 0.3	8.0 ± 0.7*	0.93 (0.15, 1.71)	7.2 ± 0.6	8.0 ± 0.9*	0.92 (0.14, 1.70)
P_{rel} (W.kg^{-1})	16.0 ± 1.1	16.8 ± 1.5*	0.58 (-0.17, 1.34)	15.8 ± 1.9	17.5 ± 2.1*	0.80 (0.03, 1.57)
H_{CMJ} (cm)	30.7 ± 4.2	35.2 ± 4.3*	1.02 (0.23, 1.81)	31.2 ± 4.7	35.9 ±7.3*	0.74 (-0.03, 1.50)
H_{DJ} (cm)	29.5 ± 3.6	32.8 ± 4.2*	0.81 (0.04, 1.58)	29.4 ± 5.7	33.3 ± 5.4*	0.68 (-0.08, 1.44)
GCT_{DJ} (s)	0.33 ±0.08	0.28 ±0.06*	-0.68 (-1.44, 0.08)	0.32 ± 0.10	0.26 ±0.07*	-0.67 (-1.43, 0.09)
RSI_{DJ}	0.94 ±0.24	1.25 ±0.33*	1.02 (0.24, 1.83)	0.99 ±0.30	1.37 ± 0.35*	1.12 (0.32, 1.92)

*Note: Values presented as means ± standard deviation, with Hedge's G effect sizes (ES) and 90% confidence intervals (CI). V0 = theoretical maximum velocity; Frel= theoretical maximum force relative to body mass derived from linear sprint; Prel= peak power relative to body mass; CMJ= countermovement jump; DJ= drop jump; H= jump height; GCT = ground contact time; RSI= reactive strength index; *denotes significant within-subjects improvement and # denotes significant within-subjects decrease ($p < 0.05$).

8.4. Discussion

8.4.1. Main findings

The primary purpose of this investigation was to compare MLV and ULV dosing strategies on sprinting and vertical jumping performance in trained club rugby union players. There were three main findings: 1) Horizontal SLDJ training with MLV, but not ULV dosing strategies were effective at improving short-distance sprint performance, most prominently in the first 10 metres. 2) MLV strategies may help attenuate small decrements in maximal velocity attributes. 3)

In contrast, both dosing strategies in conjunction with rugby and resistance training were similarly effective for provoking CMJ and DJ performance improvements.

8.4.2. Moderately-low volume sprint performance

In accordance with our hypothesis, the MLV horizontal SLDJ protocol resulted in significant improvements in sprint performance. Low volume (40 – 70 GC.session^{-1}) plyometric training has been rapidly gaining credence for positively affecting acute (159,372) and chronic (157,230,231) sprint performance in trained athletes. While the average decrease in sprint time (-1.53 to -1.74%) in the MLV group was considerably less than previously reported sprint decrements (-3.7 to -8.6%) realised in professional handball athletes (157), the plyometric programme was implemented for only four as compared to ten weeks, giving support for the efficacy of MLV strategies during short periods. Similar to previous research including horizontal plyometrics, the results of our investigation confirm that this type of stimulus can provoke substantial improvements across the first 10 m (157,224,231). Improvements in short-distance (<10 m) acceleration are often a result of greater step-length (157,224). While not measured in the current study, increases in step length suggest a superior ability to generate large horizontal forces, a primary determinant of initial acceleration and propulsive power (282). Consistent with previous research, horizontally oriented plyometrics did not improve 10 – 20 m time in either group (231,388) There is increasing support that improvements during this transitional phase are a result of vertically oriented stimulus as the body moves towards a more upright position, directing the resultant force more vertically (201,231). While horizontal SLDJ involve a small vertical component, this was not the focus.

8.4.3. Ultra-low volume sprint performance

While the MLV strategy improved sprint performance, the ULV programme did not result in a change suggesting these volumes are an inadequate stimulus in trained athletes. Using similar volumes (12 – 32 GC.session^{-1}) to the ULV group, authors have reported some ballistic improvements in novice (336), relatively weak males (69), recreationally trained populations (38), trained long jumpers (100) and college soccer athletes over chronic (8 – 10 week) durations. Whereas, competitive team sport and professional soccer athletes have shown trivially small improvements in sprint performance from moderate intensity very-low (25 – 36 GC.sessions^{-1}) programmes (27,44,326). Notably, young elite Portuguese soccer players had greater improvements following one session per week, compared to two sessions, using constant very-low (20 GC.session-1) dosing strategies of skips, CMJ, and high-depth (60 cm) DJ over a six week period, suggesting more eccentric load is necessary (2). Interestingly, session volume rather than total volume may also be culpable. Comparing equal-volume high-intensities programmes, Váczi et al. (2013) reported that a once-weekly high-volume session (120 – 176 GC.session^{-1}) produced superior results in contrast to twice-weekly low to moderate volume sessions (36 – 108 GC.session^{-1}) programmes for provoking short-term sprint decrements (377). Using a once weekly strategy may allow a true overload, with sufficient rest in order to adequately adapt to high-intensity stimuli.

8.4.4. Maximal velocity characteristics

Interestingly, the ULV group slightly decreased maximal sprint velocity, while the MLV dosing strategy was able to mitigate these decrements. This phenomenon is supported by previous research and may be in part due to enhanced neuromuscular ability resulting from four to eight weeks of plyometric training (29,30,266,394). As a result, these adaptations positively alter neuromuscular control strategies during fatigued states, allowing athletes to better manage sport workloads (41,140). Specifically, previous literature reports horizontal SLDJ training prompts substantial improvements in change-of-direction time in part due to superior eccentric force absorption (157). While not measured in the current study, enhancements to eccentric force absorption would work to reduce strain during frequent change-of-direction actions in practice, in turn preserving energy and serving to mitigate these fatigue-related neuromuscular decrements (148,150). Afterall, small decrements in maximal speed are not uncommon during heavy periods of training (267). Fatigue from high-volume SSC actions (i.e., moderate running volumes) have been shown to suppress neuromuscular efficiency and modulate firing rates, shortening speeds and stretching reflexes, particularly during high-velocity actions requiring maximal muscular contraction (148,149). In any case, previous literature indicates short-contact DJ (i.e., 20 – 30 cm) may be suited for enhancing SSC performance due to high tensile energy restitution and myotatic reflex initiation (162,358).

8.4.5. Vertical jump performance

In contrast to sprint times, performing more volume was no more effective for improving vertical jump performance (Table 8.2). However, while vertical performance was not the primary focus, both groups yielded substantial improvements to CMJ height (+14.7 – 15.0%; ES = 0.74 – 1.02), DJ height (+11.2 – 13.2%; ES = 0.68 – 0.81), DJ GCT (-15.2 to -18.8%; ES = -0.67 to -0.68) and DJ RSI (+33.0 – 38.4%; ES = 1.02 – 1.12), respectively. These are well within previously reported ranges for vertical jump improvements following plyometric training (4 – 27%) (122,157,394). This may reflect the available bandwidth for horizontal SLDJ exercises to improve vertical performance following a training cessation. Typically, neural enhancements are credited for initial programme improvements in ballistic performance, while morphological changes often stem from more chronic interventions (29). On the other hand, improvements cannot be attributed solely to the current plyometric intervention; it is widely known that rugby training in conjunction with strength training has been shown to increase ballistic performance (10). As the majority of their resistance training is traditionally performed vertically, both groups may have been able to improve vertical production similarly. Notably, the rate and magnitude of improvement will depend on many factors including training experience, concurrent training, load tolerance and specific yearly training phase (92).

8.4.6. Limitations

While the study was completed as intended, there are always limitations to discuss. To prioritize the competitive agenda of the organisation and work within the practical limits of the available sample size, no control group was included. While ULV was investigating very little stimulus, an idealist research scenario might have included multiple volume comparisons, along with a true non-plyometric training group. Another limitation is the lack of more complex kinematic analysis or neuromuscular assessments, because of this we can only presume the underlying adaptations underpinning greater performance. However, as with many investigations in trained athletes, the current study was limited by the availability and competitive schedule of the participants.

8.5. Practical Applications

These results indicate short periods (four weeks) of twice-weekly plyometric training using MLV (40 – 70 GC.session^{-1}), but not ULV (10 – 28 GC.session^{-1}) is effective for improving sprint performance in trained club rugby union players. Performance improvements from horizontal SLDJ were most prevalent in the initial 0 – 10 m phase, but still prompted small decreases in 20 – 30 m time and better mitigated fatigue-related decrements to maximal velocity characteristics. In contrast, SLDJ performed horizontally did not affect secondary acceleration (10 – 20 m) time, nor did it prompt further improvement to CMJ and DJ than ULV protocols. Therefore, practitioners should consider implementing 40 – 60 GC of alternate horizontal SLDJ (30 cm) protocols prior to rugby training for practical improvements in sprint performance. Accordingly, while all rugby positions would benefit from implementing an alternate horizontal SLDJ programme, practitioners may especially consider this programme for tight-5 and loose forward positional groups whose priority is rapid short-distance acceleration.

Section IV – Discussion and Conclusions

Chapter 9 – Summary, Practical Application, Limitations and Future Research Directions

9.1. General Summary

The primary question for this thesis was "what is the optimal dose and manipulation of plyometric training for improving sprint performance in rugby players?" The foundation for this thesis stems from a void in literary knowledge surrounding plyometric training variables, despite substantial evidence that plyometrics can improve sprint performance by facilitating contraction dynamics under similar kinetic constraints. To investigate this question, a series of literature reviews, experimental investigations and training interventions were conducted. Thus, the thesis consists of: Section 1) Systematic and narrative literature reviews; Section 2) Acute analysis of primary plyometric determinants and in-session adaptive responses; Section 3) Plyometric training programme efficacy and implementation. A summary of thesis chapters and findings are presented below in Table 9.1

Table 9.1. Thesis chapter summary.

Training dose manipulation to optimise speed profiles in rugby union athletes		
Chapter	Chapter title	Chapter outline
1	Chapter 1: Introduction and rationale	**Purpose:** To introduce thesis topic, present background information, rationale, structure, and provide significance
Section 1: Literature review		
2	Chapter 2: Plyometric training to increase speed in rugby union players. Physiological adaptations following stretch-shortening cycle activity.	**Purpose:** Review relevant literature on stretch-shortening cycle mechanisms, adaptations and practically analyse their function relating to rugby union players.

<table>
<tr><td></td><td></td><td>Rationale:
Speed is important to all rugby players and can be expressed differently to accommodate position-specific roles. A comprehensive understanding of physiological mechanisms is vital to optimally programme for optimal speed acceleration profiles across all positions.

Design:
Narrative review

Findings:
Plyometric training is effective at increasing speed through the integration of neural, structural, and elastic properties.
Of particular interest is the influence of plyometrics on neuromuscular efficiency and fatigue maintenance during a rugby match.
Eccentric fatigue is a major determinant of the inability to maintain muscular performance throughout later stages of play.
The rate and magnitude of muscle-tendon loading will determine the resulting adaptation.
For practitioners, ground contact times during different activities will provide guidance on movement-specific force demands.
Novel contribution:
This review is the first to analyse stretch-shortening cycle behaviour in relation to position-specific demands for rugby players. The chapter provided important adaptive considerations and rationale for manipulating plyometric training to benefit all positions, in contrast to traditional approaches.</td></tr>
<tr><td>↕</td><td colspan="2">Prelude to Chapter III:
Having reviewed important physiological factors relevant to rugby positions, and athletic traits necessary for optimal speed and accelerative performance, a literary gap was identified in the proper dose and manipulation of plyometric training for performance in well-trained athletes. Therefore, a systematic review was conducted to comprehensively analyse and provide recommendations on plyometric training characteristics relating to speed and acceleration performance in rugby union players.</td></tr>
<tr><td>3</td><td>Chapter 3:
Critical plyometric training variable manipulation for optimal speed profiles: A systematic review.</td><td>Purpose:
Review relevant literature on plyometric training programmes, including variable manipulation, dosage, and periodisation strategy. Provide practical recommendations for including plyometric training for position-specific demands.</td></tr>
</table>

Rationale:
Rugby union players are required to maintain a multi-faceted athletic profile, endure lengthy seasons with comprehensive team training demands. Strength, speed, acceleration, power, resilience, aerobic endurance and structural integrity are just a few of the athletic qualities rugby union players must maintain to be successful. Therefore, training efficiency is of utmost importance to practitioners working with rugby players. Having practical recommendations regarding the minimally effective training dose and the proper manipulation of plyometric training variables can prove essential for maintaining optimal performance during short training periods.

Design:
Systematic review

Findings:

- Adaptation is fundamentally related to the MTU stretch and rate of loading determined by the exercise intensity. High-intensity programmes resulted in superior improvements to sprinting profiles and jump performance.
- However, athlete characteristics strongly influence the results.
- The necessary volumes required for adaptation are much lower than previous recommendations, as long as load is carefully monitored.
- Optimal exercise may differ by target distance

Novel contribution:
This review provides critical information to improve speed and acceleration training efficiency.

Prelude to Section II:
Following the extensive literature review, inadequate evidence existed investigating plyometric training in well-trained rugby populations. Most of the available literature focused on amateur or pubescent populations. Strength, biological and training age, structural capability, and sport experience will affect the mechanical stress an athlete is able to handle. However, there was no consensus on primary determinants or how best to manipulate plyometric training variables for improving speed. Moreover, distinct differences exist across rugby positions in their ability to express force and velocity, but more clarity is required to better understand the magnitude of these differences and to better inform training practices. As such, further studies investigating performance determinants, force-velocity profiles, and physiological adaptation are required.

Section II: Acute analysis of performance determinants, force-velocity profiles, adaptation rates, and physiological characteristics

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<td>4</td>
<td>Chapter 4:
Force-velocity profiles of rugby union players: a competition-level and position-specific analysis.</td>
<td>Purpose:
Investigate the differences in speed expression across competition-levels and positions.

Rationale:
Speed is essential to all rugby union players, although to differing degrees. Previous literature has identified significant differences in running profiles, work output and athletic qualities between forwards and backs. However, there was still insufficient information regarding positional demands in relation to force-velocity expression. Determining a player’s force-velocity profile helps identify their specific strengths and weaknesses, which could result in a more optimized training approach.

Design:
Cross-sectional study

Findings:
Sprint split times and mechanical variables demonstrated significant differences between competition levels and positional groups within a competition.
International and professional players demonstrated faster split times and a more forceful FV profile than club players, with the biggest discrepancy across the first 10 m.
International players had greater 0-10 m performance, while professional players portrayed faster 10-20 m split times, greater Vmax and a more force-dominant FV profile.
Split times and maximal velocity characteristics demonstrated a linear trend corresponding with positional number.
Loose forwards portrayed the most forceful profile, and slower split times than all backs positional groups, but similar maximal velocity characteristics to inside backs.
Novel contribution:
This study was the first to investigate sprint mechanical variables in such a large cohort of rugby players. Additionally, there were no previous studies, which investigated positional group differences in FV profiles.</td>
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<td colspan="2">Prelude to Chapter 5:
While the earlier chapters provided important performance determinants and position-specific characteristics from the literature, there was still a need to acknowledge expert opinion when developing recommendations for best practice. By better understanding practical applications</td>
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	and analysing programme details within the context of literary evidence, we intended to create a more comprehensive understanding of optimal plyometric training practices. Specifically, this thesis aimed to provide evidence-based recommendations that are ecologically valid.	
5	Chapter 5: Implementation and efficacy of plyometric training: Bridging the gap between practice and research.	**Purpose:** Obtain a greater understanding of the practitioner's perspective on the implementation and efficacy of plyometric training. A secondary purpose was to identify any trends in training practice across competition levels, sport or training axis. **Rationale:** There appeared to be a disconnect between current literary recommendations and the anecdotal evidence of plyometric training practices. This conjecture led to a gap in understanding on best practice and effective dosing strategies. **Design:** Online globally distributed survey **Findings:** • Several competition-level distinctions exist between international, professional, and semi-professional/ amateur practitioners. Specifically, reported limitations, volumes, intensities, and exercise selection highlights unique characteristics between competitions. • Specific differences were identified across sports highlighting competition characteristics training priorities, and available resources. • Reported volumes differed drastically from current literary recommendations suggesting added volume may hinder results in real-world settings. • Significant differences occurred for the volumes and intensities used for vertical and horizontal training practices. • Practitioners were more likely to programme bilateral exercises vertically and single-leg varieties horizontally **Novel contribution:** This investigation is the first to critically identify key training and monitoring variables from a practitioner's point of view. This understanding allows researchers to investigate reported claims and create a more unified stance on what is considered best practice.
	Prelude to Chapter 6: Analysis of literary evidence and practically applied practitioner plyometric programmes has allowed for a comprehensive understanding of critical programming components including	

	volume, intensities and exercise choice. Previous recommendations supported high-volume sessions, proposing 140-400 GC per session in some cases. Conversely, anecdotal reports from expert practitioners proposed much lower volume loads. As such, there was still literary gaps in the understanding of acute physiological stress, the effect of high-volume sessions on subsequent athletic performance and whether increased volume is warranted. Furthermore, more clarity is required on the specific influence of training axis on structural fatigue and force production throughout high jump volumes.	
6	Chapter 6: Acute investigation of vertical and horizontal plyometric volumes	**Purpose:** Investigate the acute stress, performance and fatigue throughout a plyometric session involving recommended ground contact volume ranges. The secondary purpose was to compare vertical and horizontal-axis jumping and identify trends in force production and stretch-shortening cycle behaviour with increasing fatigue. **Rationale:** Both the CMJ and BJ are common exercises in assessment and training protocols. Previous recommendations support the use of high-volume sessions of 140 – 400 GC. However, these recommendations have often lacked context, and may not be valid in competitive athletes working to maintain a demanding athletic profile. Additionally, much of the available literature has investigated high volumes as one large stimulus, without understanding the acute effect of progressively increasing volume in session. **Design:** Acute cross-over design **Findings:** • Horizontal jump distance was acutely potentiated after 40 GC and this potentiation was maintained throughout the session. • In contrast, the low-volume vertical plyometric session was not sufficient in acutely potentiating CMJ height. • In fact, CMJ height realised small decrements following 50 – 80 GC but was able to recover to pre-session values. • There were still underlying kinetic fluctuations present including altered GCT, increased eccentric impulse with decreased on only maintained concentric impulse. • SPM revealed progressively increased horizontal volume provoked changes to kinetic

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<tr><td></td><td></td><td>jump strategy, most prominently just before take-off.
Novel contribution:
This study provides support for the use of low-volume plyometrics to potentiate BJ performance. Additionally, this is the first to investigate vertical and horizontal kinetic performance during progressively increased volume in-session. Additionally, scarce literature has previously investigated MTU capacity in rugby union players.</td></tr>
<tr><td></td><td colspan="2">Prelude to Chapter 7:
With a comprehensive understanding of plyometric training components, acute jump volumes and the associated stress, this section aimed to apply those principles in real-world training programmes. Keeping in mind competitive priorities, the training programmes were designed to be efficient and easily implementable in a large team setting.</td></tr>
<tr><td colspan="3">Section III: Plyometric training programme efficacy and implementation</td></tr>
<tr><td>7</td><td>Chapter 7:
Low-volume plyometric training improves athletic performance</td><td>Purpose:
To investigate the use of low-volume plyometric training on sprint performance in semi-professional rugby union players. The secondary purpose was to compare vertical and horizontal jumping protocols on sprint performance.

Rationale:
Initial evidence proposes low plyometric session volumes are a sufficient stimulus for improving performance. However, most of the investigations have been conducted acutely, or in pubescent populations. Trained adult athletes will differ in their mechanical capability and stress tolerance, and therefore require further inquiries. Additionally, evidence surrounding sprint performance and phase-specific indices suggest the direction of force application is an important consideration. Some authors have theorised that exercises performed horizontally preferentially benefit initial acceleration where the required horizontal forces are much greater to overcome inertia, while vertically-performed exercises will primarily benefit maximal velocity.

Design:
Crossover experimental design.

Findings:
Low-volume plyometrics significantly improved sprint performance in HV-1, which performed the horizontal plyometric training block prior to the vertical plyometric training block. In comparison, VH-2, which performed vertical</td></tr>
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<td>than horizontal plyometrics, maintained their performance. The control group who performed no plyometrics significantly declined their performance.
• Maximal velocity, 30-m time, and many force-centric variables improved following vertical plyometrics.
• Horizontal plyometrics did not collectively affect sprint performance, but we cannot completely rule out a delayed super compensation period.
• Performance gains were stunted in lesser-trained athletes across all groups suggesting accumulated fatigue may have affected results.

Novel contribution:
Collectively, the findings suggest low volumes of plyometrics provide a sufficient stimulus to improve or maintain speed profiles during short high-volume training periods in rugby union players. Additionally, this investigation provides initial support for vertically oriented training to improve maximal velocity sprint performance.</td>
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<td colspan="2">Prelude to Chapter 8:
While there has been support for the prescription of low plyometric volumes, there was still a gap between most appropriate dosing strategies. Reports suggested expert practitioners implement volumes less than 20 GC per session, while literary evidence for very – low plyometric volumes (< 25 GC) is mixed. Furthermore, there are still some questions surrounding how best to implement horizontal plyometrics. Considering horizontal SLDJ has previously demonstrated literary support for improving plyometrics and this exercise was more frequently reported for those practitioners, we sought to investigate dosing strategies for this exercise.</td>
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<td>8</td>
<td>Chapter 8:
How low do you go? Dose response of horizontal plyometric training volume in semi-professional rugby players.</td>
<td>Purpose:
To investigate low and ultra-low horizontal SLDJ volumes in club rugby union players.

Rationale:
Plyometric programmes using 40-60 GC per session have demonstrated improvements in sprint performance in trained cohorts. Furthermore, some very high literary sessional recommendations (140 – 400 GC) are in stark contrast to what some practitioners are reportedly prescribing to well-trained individuals (i.e. <20 GC in a session). As practitioners are often looking for the most efficient training dose strategy, the purpose of this investigation is to determine the effectiveness of an ultra-low volume, plyometric training programming (i.e. <20 GC in a session).</td>
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		Design: Experimental design **Findings:** • Ultra-low volumes were not sufficient in improving sprint profiles in club rugby union players. • In contrast, low volumes (40 – 60 GC) improved sprint performance after four weeks of twice weekly training. • However, both strategies were equally effective at improving vertical jump performance. **Novel contribution:** This is the first study to investigate ultra-low plyometric training in attempts to understand minimally effective dosing strategies.
9	Chapter 9: Conclusion and practical applications	**Purpose:** To collectively analyse thesis, present key findings, limitations and recommendations.

9.2. Key findings

9.2.1. Section 1

While broad support exists for the use of plyometrics, most of the literature has previously been targeted towards adolescent and untrained populations. Therefore, a narrative review of SSC interaction and plyometric adaptations pertaining to rugby players (Chapter 2) and a systematic review on plyometric dose response in trained athletes (Chapter 3) were executed. Chapter 2 revealed several important considerations for improving SSC efficiency including MTU interaction, stretch rate and magnitude, spinal and supra-spinal stimulatory pathways (91,239,392). As discussed throughout this thesis, effective SSC, muscle activation and rapid force transmission capabilities are vital for reaching top speeds (54,209). The foundation of the SSC hinges on the ability of the athlete to absorb large amounts of energy during eccentric movements, in turn recycling that energy for greater concentric movement. As an added benefit this energy restitution, in concert with CNS and myotatic-induced increases in muscle activation, reduces the metabolic work performed and assists in mitigating fatigue-related neuromuscular decrements (148,150). This has particularly interesting implications for modulating neuromuscular control and dynamic finesse during later periods of match-play in rugby union players. During competitive matches, a powerful offensive manoeuvre, quick defensive repositioning, or the ability to repeatedly achieve high speeds during the 60 – 70 and 70 – 80 min periods may dictate the game results. Moreover, the SSC, elastic and neuromuscular structures are constantly contributing positive work during acceleration and slower speeds, as well as jumping, running economy and other rugby related tasks, indicating all positions may benefit from plyometric training (163).

An important theme resulting from this thesis is that adaptation is based on the magnitude and rate of loading (165,358). In that respect, task-specific dynamic properties will dictate the extent and functional application of the adaptive response (91). Published literature has deemed the optimal conditions for SSC behaviour typically require a large external force which provides sufficient MTU load, a quick and timely pre-activation of muscle and a short amortisation time to facilitate energy restitution (188,287). Plyometric exercises requiring large rapid stretch rates may preferentially target tendon adaptations through braking phase kinetics (358). In comparison, drills involving small repetitive stretching may prompt positive changes to muscle activation, fibre elasticity and myotatic reflex stimulation (91). The results from Chapter 3 affirm the practical significance of moderate – high intensity plyometrics for improving sprint performance in trained athletes, while the effect of volume was less clear. Many studies reported moderate – very large effect sizes using low volume protocols, suggesting more volume is not always necessary (58,60,157). Moreover, optimal exercise choice appeared to have the greatest impact when kinetic and kinematic characteristics were most similar to the target distance.

Specifically exercises with high stretch rates and fast GCT like DJ and hurdles were most effective at improving maximal speed phases when vertical forces are greatest. In contrast, moderate intensity, longer GCT exercises like CMJ, SJ, and BJ were more effective for improving accelerative performance (Chapter 3). Interestingly, assisted varieties offer promising results across multiple sprint phases (65,230).

9.2.2. Section 2

Section 2 consisted of three chapters which investigated sprint profiles, current plyometric practice, and dose response in rugby union players. Collectively, this section has provided novel insight into the physical ability of trained rugby union players. While previous literature has investigated FV profiles in backs and forwards (45), this thesis conducted FV profile analysis in a large (n = 176) cohort of rugby union players, with specific attention to competition and position-specific demands. Notably, athletes competing at the international and professional levels were significantly faster than club competition players, irrespective of position. These results echo previously reported competition differences and small (~1.6 – 2.2%) decreases in sprint time as rugby union players elevated from Super Rugby to international status mid-year (356). Collectively, these findings have highlighted the need for all rugby players to train speed and acceleration. Furthermore, differences between force-dominant and velocity-dominant positions across all competitions revealed insight pertaining to training demands. Specifically, sprint performance demonstrated a linear trend with position, whereby tight forwards were the slowest and outside backs were the fastest. While this is not particularly novel in isolation, differences in SM0-10, but not SM10-20 or SM20-30 between tight-5 and loose forwards has provided insight to specific exercise prescription. Non-depth plyometrics including SJ, CMJ, BJ and SLDJ (20 – 30 cm), particularly those varieties performed horizontally or resisted, may be beneficial for tight-5 forwards in order to improve their "active state" through enhanced elastic and neuromuscular effectiveness during slow GCTs. Subsequently these exercises have shown to improve propulsive power and increase step length for more rapid multidirectional acceleration (157). While these exercises are similarly important to loose forwards, an increased attention to transitional acceleration (10 – 20 m) phases indicate CMJ, SLDJ (30 cm), DJ and assisted SJ or CMJ varieties, performed vertically may provide additional benefits (228,230,231,388). Interestingly, while all backs groups portrayed faster 10, 20, and 30 m split times than both tight and loose forwards, inside backs shared similar maximal velocities to loose forwards. Greater percentage of distance spent in moderate speeds and utility movements repositioning for inside backs supports these results (83,90,309). Accordingly, exercises which improve spinal and stretch reflex stimulation may provide specific benefit (91). Additionally, mid and outside backs wanting to be successful in competitive leagues should demonstrate maximal velocities approaching 9 $m \cdot s^{-1}$ across a maximal 30 m sprint. To achieve this, exercises emphasising greater RF for outside backs may be particularly important (278).

Interestingly, both practitioner reports (Chapter 5) and acute analysis of dose response (Chapter 6) established reasonable justification for low volume dosing strategies with specific attention to training axis. Key findings from Chapter 6 suggest that while trained athletes can primarily maintain jump outputs during high-volume sessions, underlying kinetic characteristics may start to decline much earlier in both vertical and horizontal sessions. Furthermore, an internationally conducted survey (Chapter 5) in elite strength and conditioning practitioners revealed several disparities between current "best practice" reports and published recommendations, most prominently concerning volume loads and exercise choice. For instance, practitioners working in international and national competitions were more likely to report lower session volumes, selective exercise choice, fewer training limitations, and greater use of horizontal plyometric programming than practitioners in lower-level competitions. However, analysis of all survey respondents highlighted a ~10% greater percentage of vertical compared to horizontal programming, and a greater propensity to programme horizontal exercises unilaterally, but vertical exercises bilaterally. While it is difficult to say conclusively, this may have been related to greater landing forces realised during horizontal jumps, subsequently causing greater acute fatigue (193). Greater eccentric forces may also partially explain the kinetic fluctuations following low volumes in horizontal jump performance which resulted in a change in jump strategy (Chapter 6). Considering eccentric fatigue typically modulates the effectiveness of the SSC system, even low volumes may have required altered motor programmes or a change in kinetic strategy to better manage horizontal braking forces and maintain jump performance (80). However, this performance was concomitant with decreases in concentric impulse, suggesting some SSC-related methods of force enhancement were hindered. While not specifically investigated, disruptions in muscle metabolic homeostasis, excitation-contraction coupling, or increased muscle damage could weaken neuromuscular and SSC performance (79,124,150,151,203). Therefore, caution is advised when programming moderate – high non-depth plyometric volumes to elicit SSC related adaptations.

The difference in eccentric stress may also help to explain why the low-volume (40 GC) horizontal stimulus was sufficient to acutely potentiate and maintain potentiated performance in BJ, but not CMJ (Chapter 6). While similar kinematic exercises were implemented, vertical exercises may not have provided a sufficient MTU load in the low-volume plyometric stimulus. While CMJ has demonstrated greater efficacy in improving jump height over DJ (332), low volumes of slow exercises like power step-ups and SL CMJ in trained rugby union players may not have provided optimal SSC loading conditions to potentiate acute performance (171). One study suggests adding an approach “run up” to vertical exercises to increase pre-activation muscle activity and eccentric phase neuromuscular performance (329). Alternatively, this difference may be attributed to the addition of augmented feedback during horizontal exercises (182).

9.2.3. Section 3

Section 3 examined plyometric training implementation through two short-term longitudinal studies. Chapter 7 implemented a cross-over design to investigate training-axis related adaptations and the application of low-volume plyometric training in academy and semi-professional rugby players. As a result, low-volume plyometric training prompted positive adaptations in sprint performance compared to rugby and resistance training only. Moreover, vertical plyometric training may preferentially benefit many force-centric variables and the transitional acceleration (10 – 20 m) phase more so than horizontally applied plyometrics, in line with previous literature (231). Conversely, the effects of horizontal training were unclear. Short three-week mesocycles may not have been long enough to overcome learning effects or eccentric-induced acute fatigue. Thus, a second training study isolating the dose response of horizontal SLDJ was implemented (Chapter 8). The results revealed moderately-low (40 – 60 GC), but not ultra-low (<30 GC) dosing strategies were effective for decreasing short-distance sprint times. Similarly, MLV strategies better maintained maximal velocity characteristics compared to ULV. In contrast, both protocols in conjunction with rugby and resistance training were similarly effective at improving jump performance, highlighting specific consideration required to improve sprint performance.

9.3. Moving Forward

9.3.1. Practical applications

The extensive literature review (Section I), acute investigations (Section II) and short-term longitudinal studies (Section III) collectively provide evidence for applying low-volume plyometric training for improving sprint performance, with specific reference in rugby union players. This thesis aimed to provide considerations for dosing effectiveness, adaptation rates and appropriate exercise prescription. A primary finding discussed throughout this thesis is the magnitude and rate of loading will dictate the adaptive response (358). In this respect, appropriate exercise prescription may depend on positional demands and athlete characteristics (251). For instance, non-depth exercises like SJ, BJ, and CMJ with longer GCT may be more effective for initial acceleration (228). Similarly, this thesis supports previous literature presenting SLDJ performed horizontally as an effective method for improving short-distance sprint performance (157). As such tight-5 forwards may benefit most from including these. In contrast, vertical exercises may be more effective for improving force-centric variables during secondary acceleration (10 – 20 m) (388). Moreover, repetitive exercises with short (~0.10 – 0.25) GCT and quick MTU stretch rates may be preferential for mid and outside backs looking to improve maximal velocity phases (7,58). Exercises may include “POGO” hops, SL repeated hops, bounding, hurdles, and DJ. For stronger athletes, practitioners may need to use greater drop heights during the DJ to load the MTU sufficiently (251). However, excessive drop heights may influence CNS protective and dampening strategies, thus dramatic increases in GCT or decreases in jump height should be carefully monitored when progressing to greater heights.

Another primary conclusion from this thesis was the effectiveness of low-volume dosing strategies. While published literature supports both low and high-volume programmes (Chapter 2 and Chapter 3), key findings suggest even low – moderate volumes may start to cause fatigue and attenuate SSC performance (Chapter 6). Low-volume plyometric training was shown to be effective in acutely potentiating BJ performance, as well as improving sprint performance with both training axis (Chapter 7) and dosing (Chapter 8) considerations. Importantly, while some experts report using very-low volumes (up to 20 GC; Chapter 5), four weeks of ULV strategies did not improve sprint performance (Chapter 8). Thus, practitioners may want to consider longer duration programme lengths or implement MLV strategies (40 – 70 GC) of SLDJ performed horizontally.

9.3.2. Future research

Whilst this thesis has provided preliminary support for the use of plyometric training in rugby union players, there are numerous considerations for future research to expand upon the results discussed throughout. The survey presented several findings which differed from previous literature recommendations; however, it was not possible to investigate all these reported disparities. For instance, more clarity is required surrounding accurate monitoring and regulating of plyometric exercises to better understand programme efficacy. From the results of this thesis, future researchers and practitioners should carefully consider in-session performance metrics, and multiple sprint distances, when determining the efficacy of varied dosing strategies to optimise SSC function. Moreover, further investigation for dosing strategies in high-intensity depth plyometrics is warranted considering their positive impact on sprint performance. This thesis has provided evidence supporting appropriate exercise prescription, however, the range of plyometric exercises available highlights the need for further research to investigate these specifically. Furthermore, the most appropriate dosing strategies, exercise prescription and plyometric periodisation across multiple phases of competition is still unclear. Similarly, this thesis primarily focused on adaptations to rugby union players FV profile, but potentially of additional interest is the proposed benefits to fatigue management and running economy. This thesis has provided original insight to the acute stress resulting from vertical and horizontal plyometrics; however, more research is needed to better understand this stress in the context of weekly preparation.

9.3.3. Limitations

- While substantial support exists for plyometric training, this thesis is the first to examine plyometric training manipulation in rugby union players. Due to complexity of factors included in the thesis, the prioritisation of competitive agendas, and use of high-profile athletes, several limitations and future directions exist.
- While this thesis was the first to describe practitioner reports of current practice in terms of plyometrics, the breadth of reported findings suggest more research is necessary to comprehensively understand differences between practitioner reports and published recommendations.
- Similarly, while positional-group sprint profiles were initially determined, future studies should consider addressing specific movement demands via individualised plyometric training programmes.
- Additionally, rather than one “optimal” drop height for all, future research is advised to better characterise individualised intensity progressions based on athletic profile attributes and measurable variables (i.e. GCT and velocities).
- Training durations and availability of semi-professional and professional athletes were limited; thus, most of this thesis was acute and with short-term programme lengths. Future research should consider investigating plyometric variables during longer programme durations to better understand adaptation efficacy.
- Additionally, the chronic use of periodised low-volume plyometric training during specific competition phases should be investigated.
- Similarly, further experimental studies investigating the neuromuscular, tendon and sprint phase-specific adaptations to different plyometric programmes in trained athletes should be examined.

- ❖ While kinetic and kinematic alterations in low-volume plyometric sessions and progressively increased BJ and CMJ were investigated, more research is needed to understand these interactions in high-intensity exercises like DJ and hurdles.
- ❖ Moreover, chronic analysis of high-intensity exercise dosing strategies in trained athletes is necessary for optimal plyometric training prescription for improving sprint performance.

9.4. Conclusions

This thesis presented novel information on MTU interaction, adaptation and sprint performance in rugby union players. Additionally, critical variables for plyometric training programme efficacy in trained athletes were identified. It is believed that both researchers and strength and conditioning practitioners will benefit from the information provided in this thesis. Researchers may better understand important training considerations through a practitioner's lens and practitioners may gain insight surrounding the implementation and efficacy of plyometric training for improving sprint performance. Specifically, this thesis adds insight to current practice, rugby position-specific movement demands, dosing strategies of plyometrics, and intensity- and exercise-specific considerations and adaptations. Moreover, this thesis provides substantial support for the use of low-volume plyometric training for improving sprint performance during short durations. This information paves the way for future research to better understand chronic applications and alternate programming manipulation.

Section V – References and Appendices

Chapter 10 – References

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Chapter 11 – Appendices

Appendix 1. Ethical Approval for Chapters 4, 6 and 7.

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

5 December 2017

Adam Storey
Faculty of Health and Environmental Sciences

Dear Adam

Ethics Application: 17/422 **Methods of improving speed and power in semi-professional and professional rugby union players**

I wish to advise you that the Auckland University of Technology Ethics Committee (AUTEC) has **approved** your ethics application at its meeting of 4 December 2017.

This approval is for three years, expiring 4 December 2020.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Non-Standard Conditions of Approval

1. Given the professional involvement the supervisors have with the players/teams being recruited, AUTEC seeks an assurance that the supervisors will only have access to de identified data;
2. AUTEC suggests that the Information Sheet could be edited for repetition.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: cwatkins025@gmail.com; Nic Gill

Appendix 2. Ethical Approval for Amendments to Chapter 5 – 8.

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

11 October 2018

Adam Storey
Faculty of Health and Environmental Sciences

Dear Adam

Re Ethics Application: **17/422 Methods of improving speed and power in semi-professional and professional rugby union players**

Training dose manipulation to optimise speed and acceleration profiles in rugby union athletes (studies 2,3,4, and 5)

Thank you for providing evidence as requested.

The amendment to the recruitment (additional players) and data collection protocols (more tests and a survey for coaches) is approved

Non-Standard Conditions of Approval

1. Amend the Information Sheet as follows:
   a. Complete the title - the word 'professional' is missing.
   b. b. The long paragraph explaining what will happened is very hard to follow. Please consider formatting in a table and/or a flow chart.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation, then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: cwatkins025@gmail.com; Nic Gill

Appendix 3. Ethical Approval for Amendments to Chapter 4.

AUT

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

15 July 2019

Adam Storey
Faculty of Health and Environmental Sciences

Dear Adam

Re: Ethics Application: **17/422 Methods of improving speed and power in semi-professional and professional rugby union players**

Thank you for your request for approval of an amendment to your ethics application.

The amendment to the eligibility criteria (to include international athletes and non-rugby resistance trained males) is approved.

I remind you of the **Standard Conditions of Approval**.

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: cwatkins025@gmail.com; Nic Gill

Appendix 4. Participant Information Sheet for Chapters 4 – 8.

Participant Information Sheet

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Date Information Sheet Produced:

15th November 2017

Project Title

Methods of improving speed and power in semi-professional and professional rugby union players.

An Invitation

Hello, my name is Casey Watkins and I am a Doctoral student at the Auckland University of Technology (AUT). I would like to personally invite you to assist me with my research project that aims to determine the most efficient methodology for improving speed and power in rugby union players. Upon the completion and grading of this research project I will be awarded a Doctorate of Philosophy degree concentrated in Sport and Exercise science.

Participation in this project is entirely voluntary, and will not affect your standing on any team you participate in. During the study, if you decide you no longer want to participate you are free to withdraw yourself and any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. If you do choose to participate in this research, your position on the team you play for will not be affected by your results. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of this research?

Speed and power are integral to the competitive success of both professional and non-professional rugby union, and are congruently utilised in many game-specific tasks including sprinting, defending, line braking, and most importantly scoring tries. Yearly periodization is used to manipulate force-velocity characteristics associated with improved performance on the field. Therefore, understanding which training methods best transfer the force-velocity characteristics specific to each movement profile, and each training method's most efficient application, are crucial to implementing a successful season-long training regimen. The execution of the proposed training schedule will result in improved speed and power performance individually, as well as offer new insight into training protocols for the coaching staff, encouraging long term success for the team, and informing the strength and conditioning community at large. Therefore, the purpose of this thesis is to investigate the most efficient methods for increasing speed and power in professional and semi-professional rugby union players.

How was I identified and why am I being invited to participate in this research?

You have either seen an advertisement about this research project around your training facility, have been presented the research details during a team presentation, or via face-to-face meeting with the primary researcher. Your contact details should be provided by you to the primary researcher if you are interested in participating in this research allowing communication to take place regarding this research.

You are eligible to participate in this research if you are:

1) A male

2) Of an age >16 years old

3) Currently have a position on a Super Rugby team, Mitre 10 Cup team, or a development team for one of these competitions

4) Free of any acute or chronic injury that may affect your ability to participate in this research

5) Not currently using, nor have ever used anabolic steroids.

How do I agree to participate in this research?

If you are interested in participating in this research project please feel free to contact the primary researcher, Casey Watkins. You will be emailed an AUT consent to participate form which will you will need to fill out and sign, then return to the primary researcher either by email or in person. You will then be given a copy of your signed consent form which you will need to keep for future reference.

Your participation in this research is entirely voluntary and the decision to participate will neither advantage nor disadvantage your standing on the team. Participation in this research will take no more time or energy than what is regularly required of you. Furthermore, if you decide you no longer want to participate, you can withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible, but your specific data will not be identifiable as such.

What will happen in this research?

Once you have agreed to participate in this research, you will be required to take part in resistance training sessions three times weekly. These sessions will occur as part of your normal training whether, or not, you decide to participate. A general strength and hypertrophy block will be first to give every participant a foundation from which to build on. A force-velocity profile will occur on the third week including maximal strength tests, 30 metre sprint test, and a series of jump tests: countermovement jump, static jump, and drop jump across various loads. Testing will commence on multiple days as to avoid the accumulation of fatigue, prior to testing. A general warm-up will be performed prior to all testing to warm-up musculature, and prepare athletes for maximal exertion. All exercises will be demonstrated and explained thoroughly. Maximal strength tests will find your one repetition maximum (1RM) for fundamental exercises including squat, deadlift, and bench. Lifters will perform the exercise prior to 1RM attempt at various sub-maximal loads, and be given complete rest between all sets. Lifters will have three attempts for their 1RM per exercise. Sprint test will include a field warm-up and practice sprints increasing in intensity. Once warmed up, participants will be required to perform three maximal 30-m sprints, with time recorded via timing gates, and radar system. Complete rest will be given between attempts. Force-velocity profiles will also include maximal jump tests. Participants will set up on an AMTI force plate as instructed, and jump as high as they can; force and velocity data will be recorded for each trial. There will be three recorded jumps per condition. You will then be assigned to an intervention group, or for certain studies including semi-professional teams, an intervention or a control group. All intervention groups will be required to partake three resistance training sessions each week for the duration of the season (30 weeks), included in your normal regular training plan. Training occurs throughout the season and is intended for the optimization and maintenance of speed. Training blocks will each last three to five weeks, and emphasize a certain training style, pursuant to the time of year and priority of team. Yearly training will start with general fitness and trending toward more speed and power specific training throughout the season. The training sessions will last approximately one hour, including a warm up and cool down. Following each training intervention, all groups will once again be required to perform the same tests that were used in the baseline testing session. Again, this session will last approximately four hours, split over two days.

What are the discomforts and risks?

The testing and training sessions will require you to perform maximal physical efforts which may cause you to experience some temporary discomfort. This level of discomfort should not be any different to what you feel during your regular training and competition.

How will these discomforts and risks be alleviated?

Being an experienced athlete that regularly competes and trains at high intensities, the testing and training sessions will be similar to what you are familiar with during your week to week competition and training programs. Although you may be familiar with this type of training intensity, you are encouraged to inform the researcher if you are experiencing any discomfort at any time so that the problem can be addressed in the best possible way. If you have any questions regarding the risks or discomfort involved in this research, please feel free to bring these concerns to the attention of the researcher so that you feel comfortable throughout each stage of this process.

What are the benefits?

The participant will gain personal knowledge about their own speed and power capabilities, having the opportunity to improve upon those abilities throughout the season through training. The primary researcher will gain valuable practical experience working within a research setting with high level rugby athletes. The primary researcher may also be awarded a Doctorate of Philosophy in Sport and Exercise Science degree upon submission and grading of this research. Coaches will benefit from new insight about speed and power capabilities of their team, regardless of anonymity, from which they can improve training in future years. Practitioners and researchers alike will be provided with new knowledge on the effects of current training methods on speed and power characteristics. This could lead to the development of new exercise prescription techniques for rugby union athletes, and an increase in the quality of rugby at all levels.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Your privacy will be protected by data being de-identified (coded numbers i.e. ID 123 instead of your name to be used throughout), and the researcher will not disclose anyone's participation in this study. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. However, your name will remain coded and anonymous. Your privacy and anonymity will be of primary concern when handling the data.

What are the costs of participating in this research?

The only financial cost to the participant will be money spent on petrol to get to the testing and training facilities, which would normally be required to participate at the facility. Each testing session will take approximately two hours and each training session will last approximately one hour, including a warm up and cool down.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within four weeks whether or not you are able to participate in this research. After consideration you may withdraw your participation at any time.

Will I receive feedback on the results of this research?

Yes, each participant will receive a personalised athletic assessment of their performance in each speed and power test, as well as comparisons of performance in the different training blocks, and theoretical explanations following the completion of the data collection. It is your choice whether you share this information with your coach or other people.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Dr. Adam Storey, adam.storey@theblues.co.nz, as well as the primary researcher, Ms. Casey Watkins, cwatkins025@gmail.com.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Casey Watkins, cwatkins025@gmail.com

Project Supervisor Contact Details:

Dr. Adam Storey, adam.storey@theblues.co.nz

Approved by the Auckland University of Technology Ethics Committee on *11 October 2018*, AUTEC Reference number *17/422*.

Appendix 5. Informed Consent for Chapters 4, 6, 7, and 8.

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: ***Methods of improving speed and power in semi-professional and professional rugby union players.***

Project Supervisor: ***Dr. Adam Storey***

Researcher: ***Ms. Casey Watkins***

- I have read and understood the information provided about this research project in the Information Sheet dated 15 /11/ 2017.
- I understand that any data used for publication will be anonymous and presented as group averages.
- I have had an opportunity to ask questions and to have them answered.
- I understand that performance tests and training sessions require maximal physical efforts which may induce muscle soreness for up to 48 hours following training. No other embarrassment or discomfort is likely to occur that is outside the scope of the participant's normal training and physical testing requirements as semi-professional and professional rugby players.
- I understand that taking part in this study is voluntary (my choice) and that no accolades or punishments will result from my participation. I also understand 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 data that is identifiable as belonging to me removed or allowing it to continue to be used. Although, all data will be presented anonymously, only as group averages for comparison. However, once the findings have been produced, removal of my data from group analysis may not be possible.
- 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):

Email :..

Phone : ....

Other : ....

Date:

Approved by the Auckland University of Technology Ethics Committee on 30 October 2018 AUTEC Reference number 17/422

Note: The Participant should retain a copy of this form.

2 July 2015 page 1 of 2 This version was last edited in June 2016

Appendix 6. Participant Advertisement for Chapter 4.

REQUEST FOR STUDY PARTICIPANTS

Project Title:

"Methods for improving speed and power in semi-professional and professional rugby players."

Qualifications:

1. Currently participating in any of NZ top rugby union competitions or an affiliated development rugby union team (Super Rugby, Mitre 10 cup, and/or associated Academy Squads).
2. Male older than 16 years of age
3. Free form acute or chronic injury
4. Not using any performance enhancing or banned substances (World Anti-Doping Agency 2017)

Purpose of the study:

Speed is an integral component in rugby union, and a strong determinant in several other performance predictors associated with successful play. Plyometric and eccentric-style training has demonstrated effective at improving power and speed derivatives, but dosage and proper integration of training styles in elite athletes is still largely unknown. Therefore, the purpose of this study is to determine the most efficient training methods for increasing and maintaining speed, and acceleration throughout the season, specific to different movement profiles in semi-professional and professional rugby union players.

What is involved:

Testing

Prior to the start of the study, you will be required to complete an exercise familiarisation, a force-velocity profile and maximal (1RM) strength tests for back squat, bench, weighted chin-up and power clean as required by your Rugby union franchise as a part of your preseason athletic profile. In addition, your 30m sprint will be tested twice. Total approximate time= 1 hour

Training

Training will be within the scope of your regular team requirements. You will not have to participate in training outside your normal team training sessions. Training interventions will be periodized longitudinally and build off each other to produce favourable adaptations throughout the year, holistically intended for the optimization of speed and power.

Benefits of the study:

You will benefit from the proposed training schedule, and potentially increase individual force-velocity characteristics. You will also benefit from gaining personal knowledge about your own speed and power capabilities as it pertains to your position. The primary researcher will gain practical knowledge about testing and training semi-professional and professional rugby athletes.

Whom do I contact for further information about this research?

Researcher **Casey Watkins** PH: 0277890780 E: Cwatkins025@gmail.com
Project supervisor **Dr. Adam Storey PH:** 021 2124200 E: adam.storey@aut.ac.nz

Appendix 7. Participant Information Sheet for Chapter 5.

Participant Information Sheet

Strength and Conditioning Coaches of international, national, professional or provincial sport teams

Date Information Sheet Produced:

09/10/18

Project Title

Training dose manipulation to optimise speed and acceleration profiles in rugby union athletes

An Invitation

Kia Ora!

Thank you for taking the time to consider my survey. My name is Casey Watkins. I'm a PhD candidate at Auckland University of Technology (AUT) in New Zealand, supervised by Dr. Adam Storey, Professor Mike McGuigan and Associate Professor Nic Gill. I would like to personally invite you to assist me with my research project that aims to determine the most efficient methodology for improving sprinting in rugby athletes. Upon the completion and grading of this research project I will be awarded a Doctor of Philosophy degree concentrated in Sport and Exercise science.

Specifically, the purpose this investigation is to determine the optimal dose of plyometrics for increasing speed in rugby union athletes. To successfully accomplish this, we need to better understand the current use of plyometrics in elite sport. Therefore, the results of this study will direct our subsequent studies to help optimise future training protocols. Presently, there seems to be a disconnect between literary recommendations and real-world prescription for plyometric training. In this study our aim is to understand the purpose, programming and efficacy of plyometrics used in a variety of elite sports, countries and organizations to make future research more practically applicable worldwide.

Participation in this project is entirely voluntary, and the decision will not affect your standing on any team you participate in. Your consent to use the information you provide in the survey will be indicated by your participation. Completion of the survey indicates you have read and understood this information sheet, have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT. Thank you again for your consideration and I really appreciate your time!

What will happen in this research?

This mixed methods survey is comprised of mainly multiple choice and Likert scale questions, along with a few short answer questions. Please be assured your answers will be totally anonymous. In total, this should take approximately 15 minutes. If you have any questions or would like a short report of our findings, please don't hesitate to email me at caseywat@aut.ac.nz.

How will my privacy be protected?

No personal information will be released. Your answers will be completely anonymous.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, *Dr. Adam Storey, adam.storey@aut.ac.nz*, 64 9 921 9999 ext 6687

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Casey Watkins, caseywat@aut.ac.nz, + 64 9 921 9999 ext 6687

Project Supervisor Contact Details:

Dr. Adam Storey, adam.storey@aut.ac.nz, 64 9 921 9999 ext 6687

Approved by the Auckland University of Technology Ethics Committee on *type the date final ethics approval was granted*, AUTEC Reference number *17/422*.

5 February 2021 page 1 of 2 This version was edited in April 2018

Appendix 8. Participant Cover Letter for Chapter 5.

AUT SPORTS PERFORMANCE
RESEARCH INSTITUTE NEW ZEALAND

5 February 2021

Kia Ora!

Thank you for taking the time to consider my survey. My name is Casey Watkins. I'm a PhD candidate at Auckland University of Technology (AUT) in New Zealand, supervised by Dr. Adam Storey, Professor Mike McGuigan and Associate Professor Nic Gill. The purpose of my thesis is this investigation is to determine the dose response of plyometrics to improve the force velocity and sprinting profiles in rugby athletes. To successfully accomplish this, we need to better understand the current use of plyometrics in elite sport. Therefore, the results of this study will direct our subsequent studies to help optimise future training protocols.

Presently, there seems to be a disconnect between literary recommendations and real-world prescription for plyometric training. In this study our aim is to understand the purpose, programming and efficacy of plyometrics used in a variety of elite sports, countries and organizations to make future research more practically applicable worldwide.

This mixed methods survey is comprised of mainly multiple choice and Likert scale questions, along with a few short answer questions. Please be assured your answers will be totally anonymous. In total, this should take approximately 15 minutes. If you have any questions or would like a short report of our findings, please don't hesitate to email me at caseywat@aut.ac.nz. Thank you again for your consideration and I really appreciate your time!

Kind regards

Casey Watkins, PhD Candidate

AUT
RESEARCH & INNOVATION

Appendix 9. Competition- and Position-Specific Split Times (Chapter 4).

Specific group values for sprint split times for each position by competition level
Mean ± Standard Deviation (SD) (95% CI)

International (n = 53)		0-10 m (s)	0-20 m (s)	0-30 m (s)	10-20 m (s)	20-30 m (s)
Mean (SD) 95% CI	**Tight 5**	**1.82** ± 0.07 (1.79, 1.85)	**3.17** ± 0.12 (3.11, 3.23)	**4.46** ± 0.13 (4.35, 4.57)	**1.35** ± 0.06 (1.32, 1.38)	**1.27** ± 0.04 (1.24, 1.30)
Mean (SD) 95% CI	**Loose Forwards**	**1.72** ± 0.05 (1.69, 1.76)	**2.98** ± 0.09 (2.91, 3.05)	**4.15** ± 0.12 (4.06, 4.25)	**1.26** ± 0.04 (1.22, 1.29)	**1.17** ± 0.04 (1.15, 1.20)
Mean (SD) 95% CI	**Inside Backs**	**1.70** ± 0.06 (1.66, 1.74)	**2.95** ± 0.09 (2.88, 3.03)	**4.12** ± 0.14 (4.00, 4.23)	**1.25** ± 0.04 (1.22, 1.29)	**1.17** ± 0.06 (1.12, 1.21)
Mean (SD) 95% CI	**Mid Backs**	**1.67** ± 0.05 (1.63, 1.72)	**2.90** ± 0.05 (2.86, 2.94)	**4.04** ± 0.06 (3.98, 4.09)	**1.23** ± 0.03 (1.20, 1.25)	**1.14** ± 0.03 (1.11, 1.16)
Mean (SD) 95% CI	**Outside Backs**	**1.65** ± 0.05 (1.61, 1.68)	**2.85** ± 0.08 (2.79, 2.91)	**3.96** ± 0.12 (3.87, 4.05)	**1.21** ± 0.04 (1.18, 1.24)	**1.11** ± 0.04 (1.07, 1.14)
Professional (n = 47)		**0-10 m (s)**	**0-20 m (s)**	**0-30 m (s)**	**10-20 m (s)**	**20-30 m (s)**
Mean (SD) 95% CI	**Tight 5**	**1.82** ± 0.05 (1.80, 1.84)	**3.12** ± 0.09 (3.08, 3.17)	**4.34** ± 0.12 (4.29, 4.39)	**1.31** ± 0.04 (1.29, 1.32)	**1.23** ± 0.05 (1.20, 1.25)
Mean (SD) 95% CI	**Loose Forwards**	**1.77** ± 0.05 (1.73, 1.81)	**3.01** ± 0.10 (2.93, 3.10)	**4.22** ± 0.14 (4.10, 4.33)	**1.24** ± 0.06 (1.19, 1.29)	**1.20** ± 0.04 (1.17, 1.24)
Mean (SD) 95% CI	**Inside Backs**	**1.71** ± 0.02 (1.69, 1.72)	**2.93** ± 0.05 (2.88, 2.98)	**4.12** ± 0.14 (4.00, 4.23)	**1.25** ± 0.04 (1.22, 1.29)	**1.17** ± 0.06 (1.12, 1.21)
Mean (SD) 95% CI	**Mid Backs**	**1.69** ± 0.02 (1.66, 1.72)	**2.90** ± 0.04 (2.86, 2.95)	**4.04** ± 0.06 (3.98, 4.09)	**1.23** ± 0.03 (1.20, 1.25)	**1.14** ± 0.03 (1.11, 1.16)
Mean (SD) 95% CI	**Outside Backs**	**1.72** ± 0.04 (1.68, 1.76)	**2.93** ± 0.05 (2.87, 2.98)	**3.96** ± 0.12 (3.87, 4.05)	**1.21** ± 0.04 (1.18, 1.24)	**1.11** ± 0.04 (1.07, 1.14)
Club (n = 76)		**0-10 m (s)**	**0-20 m (s)**	**0-30 m (s)**	**10-20 m (s)**	**20-30 m (s)**
Mean (SD) 95% CI	**Tight 5**	**1.84** ± 0.06 (1.82, 1.87)	**3.16** ± 0.09 (3.12, 3.20)	**4.41** ± 0.14 (4.35, 4.47)	**1.32** ± 0.04 (1.30, 1.34)	**1.25** ± 0.06 (1.22, 1.27)
Mean (SD) 95% CI	**Loose Forwards**	**1.83** ± 0.06 (1.80, 1.86)	**3.10** ± 0.10 (3.06, 3.16)	**4.32** ± 0.14 (4.25, 4.39)	**1.28** ± 0.05 (1.25, 1.30)	**1.21** ± 0.05 (1.19, 1.24)
Mean (SD) 95% CI	**Inside Backs**	**1.82** ± 0.08 (1.77, 1.86)	**3.06** ± 0.10 (3.00, 3.12)	**4.25** ± 0.12 (4.18, 4.32)	**1.24** ± 0.04 (1.22, 1.26)	**1.19** ± 0.03 (1.17, 1.21)
Mean (SD) 95% CI	**Mid Backs**	**1.77** ± 0.05 (1.73, 1.81)	**3.00** ± 0.08 (2.94, 3.05)	**4.18** ± 0.11 (4.10, 4.25)	**1.23** ± 0.04 (1.20, 1.26)	**1.18** ± 0.03 (1.16, 1.20)
Mean (SD) 95% CI	**Outside Backs**	**1.73** ± 0.05 (1.70, 1.77)	**2.96** ± 0.08 (2.91, 3.01)	**4.11** ± 0.11 (4.05, 4.18)	**1.22** ± 0.05 (1.25, 1.27)	**1.16** ± 0.04 (1.13, 1.18)

*Please note group values reported here will differ slightly from the manuscript reporting competition and positional grand mean estimates.

Appendix 10. Competition- and Position-Specific FV Variables (Chapter 4).

Specific group values for force-velocity profile variables for each position by competition
Mean ± Standard Deviation (SD) (95% CI)

International (n = 53)		**V_0 (m·s^{-1})**	**F_0 (N)**	**P_0 (W)**	**Sfv**	**V_{max} (m·s^{-1})**	**RFpeak (%)**	**$F0_{rel}$ (N·kg^{-1})**	**$P0_{rel}$ (W·kg^{-1})**
Mean (SD)	**Tight**	**7.94** ± 0.50	**935** ± 138	**1847** ± 234	**-118.8** ± 22.6	**7.76** ± 0.46	**49.2** ± 3.0	**7.8** ± 1.0	**15.4** ± 1.9
95% CI	**5**	(7.70, 8.18)	(869, 1002)	(1734, 1960)	(-129.7, -108.0)	(7.54, 7.98)	(47.8, 50.7)	(7.3, 8.3)	(14.5, 16.3)
Mean (SD)	**Loose**	**8.81** ± 0.32	**921** ± 202	**2030** ± 455	**-104.6** ± 22.9	**8.57** ± 0.30	**52.4** ± 4.8	**8.5** ± 1.8	**18.7** ± 4.1
95% CI	**Forwards**	(8.57, 9.05)	(766, 1076)	(1680, 2379)	(-122.2, -87.0)	(8.34, 8.80)	(48.7, 56.1)	(7.1, 8.8)	(15.5, 21.9)
Mean (SD)	**Inside**	**8.81** ± 0.29	**718** ± 47	**1580** ± 130	**-81.7** ± 5.17	**8.55** ± 0.27	**51.9** ± 2.4	**8.2**± 0.7	**18.0** ± 1.8
95% CI	**Backs**	(8.58, 9.02)	(682, 754)	(1480, 1681)	(-85.6, -77.7)	(8.34, 8.75)	(50.0, 53.8)	(7.7, 8.7)	(16.7, 19.4)
Mean (SD)	**Mid**	**9.05** ± 0.23	**830** ± 95	**1871** ± 172	**-92.2** ± 12.8	**8.79** ± 0.19	**53.0** ± 3.4	**8.5** ± 1.2	**19.1** ± 2.4
95% CI	**Backs**	(8.83, 9.26)	(742, 918)	(1711, 2030)	(-104.0, -80.4)	(8.61, 8.97)	(49.8, 56.1)	(7.4, 9.6)	(16.9, 21.4)
Mean (SD)	**Outside**	**9.49** ± 0.43	**824** ± 115	**1955** ± 299	**-87.1** ± 12.9	**9.19** ± 0.40	**52.3** ± 3.1	**8.1** ± 0.9	**19.2** ± 2.9
95% CI	**Backs**	(9.16, 9.82)	(735, 913)	(1771, 1937)	(-97.0, -77.1)	(8.88, 9.49)	(50.0, 52.2)	(7.4, 8.8)	(17.2, 21.1)
Professional (n = 47)		**V_0 (m·s^{-1})**	**F_0 (N)**	**P_0 (W)**	**Sfv**	**V_{max} (m·s^{-1})**	**RFpeak (%)**	**$F0_{rel}$ (N·kg^{-1})**	**$P0_{rel}$ (W·kg^{-1})**
Mean (SD)	**Tight**	**8.40** ± 0.38	**985** ± 237	**2059** ± 470	**-118.0** ± 31.0	**8.20** ± 0.34	**51.7** ± 5.4	**8.6** ± 2.0	**17.9** ± 4.1
95% CI	**5**	(8.23, 8.56)	(880, 1090)	(1850, 2268)	(-131.8, -104.3)	(8.04, 8.25)	(49.3, 54.1)	(7.7, 9.5)	(16.1, 19.7)
Mean (SD)	**Loose**	**8.82** ± 0.23	**1140** ± 333	**2508** ± 723	**-129.6**± 38.8	**8.61** ± 0.23	**56.6** ± 8.6	**10.4** ± 2.9	**23.0** ± 6.4
95% CI	**Forwards**	(8.62, 9.01)	(862, 1418)	(1903, 3113)	(-162.1, -97.2)	(8.42, 8.80)	(49.4, 63.8)	(8.0, 12.9)	(17.6, 28.3)
Mean (SD)	**Inside**	**9.10** ± 0.41	**937** ± 205	**2117** ± 403	**-103.7** ± 25.8	**8.86** ± 0.34	**57.6** ± 5.2	**10.3** ± 2.1	**23.4** ± 4.2
95% CI	**Backs**	(8.67, 9.53)	(722, 1152)	(1694, 2540)	(-130.8, -76.7)	(8.50, 9.22)	(52.1, 63.1)	(8.1, 13.5)	(18.9, 17.8)
Mean (SD)	**Mid**	**9.30** ± 0.51	**927** ± 378	**2136** ± 819	**-100.8** ± 44.3	**9.02** ± 0.42	**54.6** ± 7.7	**9.4** ± 3.3	**21.7** ± 6.8
95% CI	**Backs**	(8.67, 9.93)	(455, 1398)	(1119, 3153)	(-155.8, -45.9)	(8.51, 9.54)	(45.1, 64.1)	(5.4, 13.5)	(15.3, 30.1)
Mean (SD)	**Outside**	**9.23** ± 0.36	**945** ± 250	**2174** ± 557	**-102.9** ± 28.8	**8.97** ± 0.32	**55.2** ± 6.5	**9.3** ± 2.7	**21.8** ± 5.8
95% CI	**Backs**	(8.85, 9.61)	(683, 1207)	(1590, 2758)	(-133.1, -73.7)	(8.64, 9.30)	(48.3, 62.0)	(6.6, 12.3)	(16.0, 27.8)
Club (n = 76)		**V_0 (m·s^{-1})**	**F_0 (N)**	**P_0 (W)**	**Sfv**	**V_{max} (m·s^{-1})**	**RFpeak (%)**	**$F0_{rel}$ (N·kg^{-1})**	**$P0_{rel}$ (W·kg^{-1})**
Mean (SD)	**Tight**	**8.32** ± 0.41	**836** ± 156	**1734** ± 311	**-101.0** ± 20.1	**8.10** ± 0.37	**48.0** ± 3.9	**7.3** ± 1.3	**15.2** ± 2.6
95% CI	**5**	(8.14, 8.50)	(776, 905)	(1596, 1872)	(-110.1, -91.8)	(7.94, 8.27)	(46.3, 49.7)	(6.7, 7.9)	(14.1, 16.3)
Mean (SD)	**Loose**	**8.57** ± 0.36	**806** ± 70	**1726** ± 159	**-94.3**± 9.6	**8.33** ± 0.33	**49.2** ± 2.3	**7.5** ± 0.6	**16.0** ± 1.6
95% CI	**Forwards**	(8.39, 8.75)	(771, 841)	(1647, 1805)	(-99.1, -89.5)	(8.17, 8.49)	(48.0, 50.4)	(7.2, 7.8)	(15.2, 16.8)
Mean (SD)	**Inside**	**8.80** ± 0.44	**659** ± 82	**1453** ± 211	**-75.0** ± 8.9	**8.52** ± 0.40	**50.0** ± 2.0	**7.6** ± 0.6	**16.7** ± 1.3
95% CI	**Backs**	(8.54, 9.05)	(612, 707)	(1331, 1575)	(-80.2, -69.9)	(8.29, 8.75)	(48.8, 51.1)	(7.3, 8.0)	(15.9, 17.5)

Mean (SD) 95% CI	**Mid Backs**	**8.91** ± 0.32 (8.68, 9.14)	**743** ± 62 (699, 787)	**1653** ± 136 (1557, 1750)	**-83.5** ± 8.3 (-89.4, -77.5)	**8.64** ± 0.29 (8.43, 9.85)	**50.0** ± 1.4 (48.8, 50.8)	**7.5** ± 0.3 (7.3, 7.7)	**16.7** ± 1.2 (15.9, 17.5)
Mean (SD) 95% CI	**Outside Backs**	**9.03** ± 0.28 (8.86, 9.21)	**724** ± 153 (626, 821)	**1626** ± 296 (1438, 1814)	**-80.6** ± 19.8 (-93.2, -85.0)	**8.75** ± 0.23 (8.60, 8.89)	**51.5** ± 3.2 (49.5, 53.6)	**8.0** ± 1.2 (7.3, 7.8)	**18.1** ± 2.3 (16.6, 19.6)

*Please note group values reported here will differ slightly from the manuscript reporting competition and positional grand mean estimates. Additionally, a subset (n = 8) of international rugby players were instructed by team personnel to only run 20 m, and thus was not included in V_0 and Vmax averages.

Appendix 11. Google Forms Survey (Chapter 5).

6/27/2020 Current Plyometric Practices for Sport Performance

Current Plyometric Practices for Sport Performance

Hello Strength and Conditioning Coaches of international, national, professional, provincial or collegiate sport teams!
Date Information Sheet Produced: 09/10/18
Project Title
Training dose manipulation to optimise speed and acceleration profiles in rugby union athletes
An Invitation
Kia Ora!
Thank you for taking the time to consider my survey. My name is Casey Watkins. I'm a PhD candidate at Auckland University of Technology (AUT) in New Zealand, supervised by Dr. Adam Storey, Professor Mike McGuigan and Associate Professor Nic Gill. I would like to personally invite you to assist me with my research project that aims to determine the most efficient methodology for improving sprinting in rugby athletes. Upon the completion and grading of this research project I will be awarded a Doctor of Philosophy degree concentrated in Sport and Exercise science.
Specifically, the purpose this investigation is to determine the optimal dose of plyometrics for increasing speed in rugby union athletes. To successfully accomplish this, we need to better understand the current use of lower body plyometrics in elite sport. Plyometrics are defined as any ballistic exercise using the stretch-shortening cycle designed to improve performance, or in other words eccentric-concentric muscle action with a short transition phase.

Therefore, the results of this study will direct our subsequent studies to help optimise future training protocols. Presently, there seems to be a disconnect between literary recommendations and real-world prescription for plyometric training. In this study our aim is to understand the purpose, programming and efficacy of plyometrics used in a variety of elite sports, countries and organizations to make future research more practically applicable worldwide.
Participation in this project is entirely voluntary, and the decision will not affect your standing on any team you participate in. Your consent to use the information you provide in the survey will be indicated by your participation. Completion of the survey indicates you have read and understood this information sheet, have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT. Thank you again for your consideration and I really appreciate your time!

What will happen in this research?
This mixed methods survey is comprised of mainly multiple choice and Likert scale questions, along with a few short answer questions. Please be assured your answers will be totally anonymous. In total, this should take approximately 15 minutes. If you have any questions, concerns, or would like a short report of our findings, please don't hesitate to email me, the primary researcher, at casey.watkins@aut.ac.nz or my primary supervisor Adam Storey, adam.storey@aut.ac.nz, 64 9 921 9999 ext 6687

How will my privacy be protected?
No personal information will be released. Your answers will be completely anonymous.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz , 921 9999 ext 6038.

Approved by the Auckland University of Technology Ethics Committee on type the date final ethics approval was granted, AUTEC Reference number 17/422.
* Required

Sport, Coaching, and Athlete Background

1. What is your primary job title and associated organization? (Please answer all questions for your primary occupation) *

Mark only one oval.

- Head S & C Coach
- Assit. S & C Coach
- Head Sport Coach
- Assit. Sport Coach
- Other: ______

2. What country do you train in?

______

3. Have you previously worked professionally with... *

Check all that apply.

- Individual sport athletes
- Field team sport athletes
- Non-field team sports (e.g. court, rink, etc.)
- Track and Field specific
- Other: ______

4. What level of competition do your athletes compete at? *

Check all that apply.

- Representative
- College
- Provincial
- Professional
- National
- International
- Olympics
- Other: ______

5. For your primary job, what level do your athletes compete at? Please answer all following questions for your primary job. *

Mark only one oval.

- Representative
- College
- Provincial
- Professional
- National
- International
- Olympics
- Other: ______

6. What sport do your athletes compete in?

7. How long have you worked with this team/athlete? *

Check all that apply.

- [ ] < 1 year
- [ ] 1-3 years
- [ ] 4-7 years
- [ ] 8-10 years
- [ ] 10+ years

8. How long have you coached professionally *

Mark only one oval.

- ◯ < 1 year
- ◯ 1-3 years
- ◯ 4-9 years
- ◯ 9+

9. How many years have you been using plyometric training for sport performance *

Mark only one oval.

- ◯ <1 year
- ◯ 1-3 years
- ◯ 4-6 years
- ◯ 7-9 years
- ◯ 9+ years
- ◯ N/a

10. To what extent do you use plyometrics in your regular programming?
As a specific focus, not including warm-up, etc.

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
0%	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	100%

11. Where does your plyometric knowledge primarily come from? *

Mark only one oval.

- ◯ Empirically-based research
- ◯ Anecdotal evidence (i.e. other people, media, blogs, etc.)
- ◯ Education (i.e. university, verified clinics/conferences, etc.)
- ◯ Personal experience
- ◯ Invented/ made up personally
- ◯ Other: ______________

12. How confident are you in your plyometric programming? *

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
Not confident at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely confident

13. What is the average resistance training age of the majority of athletes you train? *

Mark only one oval.

- ◯ < 1 year
- ◯ 1-3 years
- ◯ 4-6 years
- ◯ 7-9 years
- ◯ 9+ years

14. What is the average sport training age of the majority of athletes you train? *

Mark only one oval.

- ◯ < 1 year
- ◯ 1-3 years
- ◯ 4-6 years
- ◯ 7-9 years
- ◯ 9+ years

15. Do you use plyometrics with all your athletes? (not including injured or otherwise special cases) *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Other: ______________

16. What is the minimum resistance/ sport training age on average your athletes have when you start using plyometrics with them? *

As in criteria set by you prior to starting them on plyometric training

Mark only one oval per row.

	No requirement	< 1 year	1-3 years	4-6 years	7-9 years	9 + years
Resistance training	⬭	⬭	⬭	⬭	⬭	⬭
Sport training	⬭	⬭	⬭	⬭	⬭	⬭

17. How familiar were your athletes with plyometrics prior to your coaching? *

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
Not familiar at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very comfortable

18. On average, how much time does it takes your athletes to finish a 30 meter/ ~33 yard linear sprint test? Please choose the measurement system(s) you are most familiar with.

Gates referring to timing gates; GPS referring to global positioning devices

Check all that apply.

	2.5-3 s	3-3.5 s	3.5-4 s	4-4.5 s	4.5-5 s	5-5.5 s	5.5-6 s	6s +
Gates	☐	☐	☐	☐	☐	☐	☐	☐
Radar	☐	☐	☐	☐	☐	☐	☐	☐
Stop watch	☐	☐	☐	☐	☐	☐	☐	☐
GPS	☐	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐	☐

19. On average, what is the approximate minimal level of relative lower body strength you look for your athletes to have prior to introducing them to plyometric training

BW= body weight

Mark only one oval per row.

	No requirement	.5x BW	1x BW	1.5x BW	2x BW	>2x BW	N/a
Back Squat	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Deadlift	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Clean	⬭	⬭	⬭	⬭	⬭	⬭	⬭

20. Do you use any other criteria to determine whether to use plyometric work with your athletes? If so, please explain the test and the cut-off criteria.

Plyometric training and testing

21. What portion of sport performance do you primarily use plyometrics for? *

Mark only one oval.

- Testing
- Training
- Competition
- Mixture
- Other: ____________

22. What is your primary performance goal for using plyometrics? *

23. Do you consider any adaptations (e.g. neural adaptations, stiffness, etc.) in addition to performance outcomes (e.g. speed, strength) that support sport performance? Please describe targeted change. *

24. What surface do you typically prescribe plyometric work on? *

Check all that apply.

- [ ] Track
- [ ] Concrete
- [ ] Wooden flooring
- [ ] Artificial turf
- [ ] Grass
- [ ] Sand
- [ ] Compliant ground surface
- [ ] An even mixture of surfaces
- [ ] Do not care/ monitor

Other: [ ] ______________________

25. What type of foot wear do your athletes typically wear during prescribed plyometric work? *

Mark only one oval.

- ◯ No footwear/ bare feet
- ◯ Cross-training shoes
- ◯ Track spikes
- ◯ Sport specific shoes (i.e. rugby boots, soccer cleats, etc.)
- ◯ Unspecified/uncontrolled
- ◯ Other: ______________________

26. Is there anything you plan to change about your plyometric training program going forward?

____
____
____
____
____

27. Please explain any limitations with using plyometrics in your athletes

____
____
____
____
____

Periodisation

28. Do you primarily implement plyometric training as an individual/isolated block or in conjunction with other training modalities? *

Mark only one oval.

- Primarily only used in warm-up/testing settings
- As the primary exercise modality in a training block
- In conjunction with other training modalities
- Other: ____________________

29. If used in conjunction, what other training styles do you pair plyometrics with? *

Check all that apply.

- [ ] Sprint training
- [ ] Eccentrics
- [ ] Traditional resistance training
- [ ] Olympic weightlifting-type movements
- [ ] Gymnastics

Other: [ ] ____________________

30. On average, how many cumulative training weeks do you use plyometric training in a 52-week calendar year? *

(1 block of 4 weeks, + 1 block of 6 weeks= 10 weeks)

____

31. At what phase(s) in your yearly training cycle do you use plyometrics, and for how many weeks do you typically use them?

Mark only one oval per row.

	0 weeks	1-2 weeks	3-4 weeks	5-8 weeks	9-12 weeks	>12 weeks
Pre-season	◯	◯	◯	◯	◯	◯
Early comp.	◯	◯	◯	◯	◯	◯
Mid-comp.	◯	◯	◯	◯	◯	◯
Late comp.	◯	◯	◯	◯	◯	◯
Playoffs	◯	◯	◯	◯	◯	◯
Offseason	◯	◯	◯	◯	◯	◯
Other	◯	◯	◯	◯	◯	◯

32. How many times weekly do you implement plyometric training when it is a specific focus? *

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
0 sessions	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	10 sessions

33. How many rest days do you have between plyometric sessions? *

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No rest, plyometrics are on back-to-back days	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	10 days

34. If used during a competition period, how many minimum rest days would you want prior to competition day after plyometric training. *

Mark only one oval.

- 0-2 days
- 3-5 days
- 6-8 days
- 9-10 days
- 11+ days

35. Do you use a constant volume, or specific periodization (systematic changes in volume loads) strategy? *

Mark only one oval.

- Constant volume
- Linear (i.e. overall incremental increases) loading
- Undulating (i.e. non-linear changes in loading) loading
- Changes in exercise selection
- No periodization strategy
- Other: ____________________

36. How do you dictate sessional plyometric volume loads? *

Mark only one oval.

- Ground contacts
- Force-velocity analysis
- Subjective visual performance
- Height or distance decrement
- Wellness
- Other: ____________________

37. When progressively loading volume across multiple weeks/focused training block, what is the typical incremental increases used? *

If first week had 40 ground contacts per session, and the second week had 60, the jump would be 20 ground contacts

Mark only one oval.

- Constant volume/ no increases
- 10 ground contacts
- 20 ground contacts
- 30 ground contacts
- 40 or above ground contacts

38. Do you include a taper or supercompensation period? *

Mark only one oval.

- Yes
- No
- Other: ____________

39. Across a focused training block what is the range of sessional ground contacts?

Check all that apply.

	Offseason	Pre-season	Early Competition	Mid-season	End of season
0-20 GC	☐	☐	☐	☐	☐
20-40 GC	☐	☐	☐	☐	☐
40-60 GC	☐	☐	☐	☐	☐
60-100 GC	☐	☐	☐	☐	☐
100-200 GC	☐	☐	☐	☐	☐
200+ GC	☐	☐	☐	☐	☐

40. On average, how much rest do you give between sets? *

Mark only one oval.

- 0-30 seconds
- 30-60 seconds
- 1-2 minutes
- 2-3 minutes
- > 3 minutes
- Don't know/ unregulated
- Other: ____________

41. Do you separate sessions based on direction or use a combination of vertically- and horizontally-based plyometrics per session?

Mark only one oval.

- ◯ Directionally-specific (separate sessions for vertical and horizontal)
- ◯ Combined vertical and horizontal sessions

Programming

42. What percentage of your plyometric training is vertically compared to horizontally based? *

Mark only one oval per row.

	0%	10%	20%	30%	40%	50%	60%	70%	8(
Vertical Plyometrics	◯	◯	◯	◯	◯	◯	◯	◯	◯
Horizontal Plyometrics	◯	◯	◯	◯	◯	◯	◯	◯	◯

43. Do you regularly include plyometric exercises combining both horizontal and vertical components?

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Other: ____________

44. Across a focused training block what is the range of vertical sessional ground contacts?

Check all that apply.

	Offseason	Pre-season	Early Competition	Mid-season	End of season
0-20 GC	☐	☐	☐	☐	☐
20-40 GC	☐	☐	☐	☐	☐
40-60 GC	☐	☐	☐	☐	☐
60-100 GC	☐	☐	☐	☐	☐
100-200 GC	☐	☐	☐	☐	☐
200+ GC	☐	☐	☐	☐	☐

45. What is your rationale for using this number? *

46. Across a focused training block what is the range of horizontal sessional ground contacts?

Check all that apply.

	Offseason	Pre-season	Early Competition	Mid-season	End of season
0-20 GC	☐	☐	☐	☐	☐
20-40 GC	☐	☐	☐	☐	☐
40-60 GC	☐	☐	☐	☐	☐
60-100 GC	☐	☐	☐	☐	☐
100-200 GC	☐	☐	☐	☐	☐
200+ GC	☐	☐	☐	☐	☐

47. What is your rationale for using this number? *

48. On average, how many ground contacts per set are used?

GC= total ground contacts

Check all that apply.

	1-3 GC per set	3-6 GC per set	6-10 GC per set	10-20 GC per set	20+ GC per set
Vertical Plyometrics	☐	☐	☐	☐	☐
Horizontal Plyometrics	☐	☐	☐	☐	☐

49. What is the average intensity of your plyometric training? *

Mark only one oval per row.

	Low-intensity	Moderate-intensity	High-intensity
Vertical Plyometrics	◯	◯	◯
Horizontal Plyometrics	◯	◯	◯

50. How do you quantify vertical intensity? *

____

51. How do you quantify horizontal intensity? *

____

52. What forms of regulating intensity do you use in your plyometric training? *

Check all that apply.

	Body-weight plyometrics	Changes in vertical height	Changes in horizontal distance	Exercise choice perceived difficulty	Absolute load plyometrics	Relative load plyometrics	Vari suspe syst ba
Vertical Plyometrics	☐	☐	☐	☐	☐	☐	☐
Horizontal Plyometrics	☐	☐	☐	☐	☐	☐	☐

53. What percent (relative to body mass) added load have you previously used with your athletes during plyometrics?

Check all that apply.

	Only body weight exercises	1-5% added load	6-8% added load	9-12% added load	12-20% added load	20-30% added load	Above 30% added load
Vertical	☐	☐	☐	☐	☐	☐	☐
Horizontal	☐	☐	☐	☐	☐	☐	☐

54. What is your rationale for using these load percentages? *

____

____

____

____

____

55. What vertical bilateral (on two legs simultaneously) exercises do you primarily use in a plyometric training session? *

Primary exercises being defined as exercises used in the majority of, if not all, focused plyometric sessions.

Check all that apply.

- [ ] Countermovement jump
- [ ] Drop jump
- [ ] Depth jump
- [ ] Tuck jump
- [ ] Hurdle jump
- [ ] Box jump up
- [ ] Box jump down
- [ ] Hops

Other: [ ] ______________________

56. What horizontal bilateral (on two legs simultaneously) exercises do you primarily use in a plyometric training session? *

Primary exercises being defined as exercises used in the majority of, if not all, focused plyometric sessions.

Check all that apply.

- [ ] Broad jump
- [ ] Horizontal depth jump
- [ ] Horizontal bounding
- [ ] Hurdle bounding
- [ ] Sprint bounding

Other: [ ] ______________________

57. What primary vertical unilateral (one leg) exercises do you use frequently in a plyometric training session? *

Additional/accessory exercises being defined as exercises used on a semi-regular basis in addition to your primary exercises.

Check all that apply.

- [ ] Little to no single leg variations
- [ ] Single leg countermovement jump
- [ ] Single leg drop jump
- [ ] Single leg depth jump
- [ ] Single leg hurdle jump
- [ ] Single leg box jump up
- [ ] Single leg box jump down
- [ ] Single leg hops

Other: [ ] ______________________

58. What horizontal unilateral (one leg) exercises do you primarily use in a plyometric training session? *

Primary exercises being defined as exercises used in the majority of, if not all, focused plyometric sessions.

Check all that apply.

- [ ] Single leg broad jump
- [ ] Single leg horizontal depth jump
- [ ] Single leg horizontal bounding
- [ ] Single leg hurdle bounding
- [ ] Single leg frontal plane hops

Other: [ ] ______________

59. What percentage of your horizontal and vertical plyometric training is bilateral compared to unilateral? *

Mark only one oval per row.

	0%	10%	20%	30%	40%	50%	60%	70%	80%
Vertical	◯	◯	◯	◯	◯	◯	◯	◯	◯
Horizontal	◯	◯	◯	◯	◯	◯	◯	◯	◯

Efficacy

60. On a scale of 0-10, how effective do you think plyometric training is at eliciting these predominantly force-based outcomes?

0 being not effective, 10 being highly effective

Check all that apply.

	0	1	2	3	4	5	6	7	
Max strength	☐	☐	☐	☐	☐	☐	☐	☐	☐
Strength-speed	☐	☐	☐	☐	☐	☐	☐	☐	☐
Horizontal Force	☐	☐	☐	☐	☐	☐	☐	☐	☐
Vertical Force	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reactive Strength	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hypertrophy	☐	☐	☐	☐	☐	☐	☐	☐	☐
Endurance	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐	☐	☐

61. On a scale of 0-10, how effective do you think plyometric training is at eliciting these predominantly velocity-based outcomes?
0 being not effective, 10 being highly effective

Check all that apply.

	0	1	2	3	4	5	6	7
Top end speed								
Speed-strength								
RFD								
Acceleration								
Power								
Quickness								
Agility								
Other								

62. On a scale of 0-10, how effective do you think plyometric training is at eliciting these adaptations? *
0 being not effective, 10 being highly effective

Check all that apply.

	0	1	2	3	4	5	6
Fascicle length							
Pennation angle							
CSA							
Fibre type							
Neural drive							
Coordination/sequencing							
MTC Stiffness							
Other							

63. What is your athlete(s) attitude toward plyometric training? *

64. Do you get athlete buy-in for your plyometric training?

Mark only one oval.

- ( ) Yes
- ( ) No
- ( ) Other: ____________

65. Why or why not do you think you get athlete buy-in? *

Appendix 12. Chapter 2 Abstract

Sprinting is a fundamental aspect of rugby union but will manifest differently depending on positional demands. An important consideration for all players underpinning athletic performance is the interaction between an athlete's force, velocity, and mechanical capabilities. Plyometric exercises targeting the stretch-shortening cycle improve specific force-velocity characteristics for superior sprinting and acceleration performance in game. Specifically, plyometric training positively affects muscle-tendon unit (MTU) efficiency, neural input and elasticity. Accordingly, a comprehensive understanding of MTU loading properties, relevant physiological mechanisms and adaptations is essential to determine the most effective training dose for optimal speed performance in semi-professional and professional rugby players.

Keywords: neuromuscular adaptations; plyometric training

Appendix 13. Chapter 3 Abstract

Substantial literature provides support for plyometric training as an effective means of improving sprint performance, however the information surrounding the best manipulation thereof is scarce. Moreover, as many of the previous reviews have been in untrained and adolescent cohorts, there is a lack of information detailing most appropriate dosing strategies for trained athletes. As such, the purpose of this systematic review was to comprehensively analyse current plyometric training programme literature via volume loads and relevant programme elements. A comprehensive literary search was performed electronically through databases: Scopus, Pubmed/Medline, Science Direct, Web of Science and SPORTdiscus. Articles were included from inception to October of 2019, only from peer-reviewed journal articles published in full-text, using English-language. Studies were included if they were investigating a lower-body plyometric training programme in adult (>18 years old) athletes, with meaningful pre-and post-assessments, and no other nutritional or interventions. Titles and abstracts were streamlined from criteria, upon which 39 articles met the outlined criteria. The primary findings of this review were: i.) athlete characteristics will dictate the rate and magnitude of adaptation; ii.) optimal exercise choice may differ by target distance; iii.) programme effectiveness is largely affected by volume load, however, lower volumes than previously established can be very effective in trained athletes. The findings of this systematic review suggest that athlete characteristics, loading strategies and exercise choice influence the effectiveness of plyometric training for improving sprint performance.

Keywords: exercise choice; plyometric volume loads; sprint performance

Appendix 14. Chapter 4 Abstract

Speed and acceleration are crucial to competitive success in all levels of rugby union. However, positional demands affect an athlete's expression of force and velocity during the match. The current study investigated maximal sprint performance and horizontal force-velocity (FV) profiles in 176 rugby union players participating in amateur club, professional, and international competitions. Rugby players were divided into five positional groups: tight-5 (n = 63), loose forwards (n = 35), inside (n = 29), mid (n = 22), and outside (n = 27) backs. Sprint performance was averaged across two trials of a maximal 30-m sprint, separated by three minutes rest. Results demonstrate differences in sprint performance and FV profile characteristics across competitions and positional groups. Specifically, both international and professional players possessed significantly faster split times and superior FV profiles than club players ($p< 0.01$; ES: 0.22 – 1.42). International players were significantly faster across 0-10 m than professional players ($p = 0.03$; ES: 0.44), while professional players had faster 10-20 m times ($p = 0.01$; ES: 0.51) and a more force-dominant profile ($p < 0.01$; ES: 0.71 – 1.00). Across positions, split times decreased, and maximal velocity characteristics increased in proportion with increasing positional number with outside backs being the fastest (ES: 0.38 – 2.22). On the other hand, both forwards groups had more force-dominant profiles, and sprint momentum across all distances than all backs positions. Interestingly, loose forwards had a more forceful profile and slower 10-, 20-, and 30-m split times, but similar maximal velocity characteristics to inside backs, highlighting unique positional demands and physical attributes.

Keywords: Sprinting; FV profiling; rugby union

Appendix 15. Chapter 5 Abstract

Plyometric training is an effective method for improving speed and acceleration. However, a gap appears to exist between research recommendations and practitioner's actual programmes. Some reports suggest as many as 400 jumps per session, while anecdotally some strength and conditioning coaches are using as few as 15 – 40 jumps even with elite athletes. Thus, the purposes of this study were to obtain a clearer understanding of the practitioner's perspective on plyometric training strategies as compared to literary recommendations and to compare any trends across competition level or sport categories. An integrative mixed methods model was employed. Globally, 61 strength and conditioning practitioners completed an anonymous online survey, containing five sections 1. Sport and coaching background information, 2. Plyometric training focus, 3. Periodisation strategy, 4. Plyometric programme details, and 5. Efficacy of plyometrics for sport performance. Questions included yes/no, multiple choice, Likert scale, percentage based and open–ended questions. The majority (70.5%) of respondents reported regularly implementing plyometric training and overwhelmingly (96.7%) reported positive athlete feedback surrounding its perceived efficacy. Findings confirmed that many practitioners regularly employ significantly lower session volumes than previous literary recommendations ($p < 0.05$). Additionally, significant differences were noted in many programme details across competition level and sport category including volume periodisation, exercise choice, and plyometric intensity. Practitioners may want to reflect on these reported group differences when building training programmes best suited for their athletes. Meanwhile, future research should consider these reported perspectives when formulating interventions in attempts of bridging the gap between practice and theory.

Keywords: Plyometrics; plyometric training; programming; practitioner; knowledge transfer

Appendix 16. Chapter 6 Abstract

Previous research supports use of plyometric training for improving sprint and neuromuscular performance. However, the optimal dosing strategies and manipulation thereof is poorly understood. Therefore, the purposes of this acute study were to investigate vertical and horizontal jump kinetic performance with progressively increased within-session plyometric volume. Academy rugby players (n = 11; age = 20.0 ± 2.0 years; mass = 103.0 ± 17.6 kg; height = 184.3 ± 5.5 cm; $IMTP_{abs}$ = 2104.4 ± 345.7 N) volunteered for this study. Vertical and horizontal jump sessions were conducted one week apart and consisted of a 40-jump low-volume plyometric stimulus using five exercises, after which volume was progressively increased to 200 jumps, using countermovement jump (CMJ) for vertical sessions and broad jump (BJ) for horizontal sessions. Jump performance was assessed via force plate analysis at baseline (PRE-0), following the low-volume plyometric stimulus (P-40), and every subsequent 10 jumps until the end of the high-volume session (P-50, P-60, P-70…P-200). Statistical analyses reveal the low-volume stimulus was effective in potentiating BJ, but not CMJ, performance. These performance enhancements were maintained throughout the entire high-volume session, while CMJ realised small but significant decrements in jump height P-50 to P-80 before recovering to pre-session values. While performance was mostly maintained or improved, underlying kinetic performance and phase-specific durations were altered in both sessions. Most prominently, increases in eccentric impulse in both sessions were associated with decreases or maintained concentric impulse, indicating a breakdown in performance augmentation. These kinetic fluctuations were earlier and more consistent in BJ assessment. Thus, practitioners should consider differences when making programming decisions surrounding dosing strategies.

Keywords: training direction; dose response; plyometric training

Appendix 17. Chapter 7 Abstract

Rugby union is a physically demanding and complex team sport requiring athletes across all positions to express speed and acceleration. Plyometrics can effectively improve speed profiles by enhancing both force- and velocity- (FV) characteristics, however the optimal dose and exercise direction for trained athletes is still relatively unknown. Therefore, the aim of this investigation was to determine the efficacy of a low-dose, directionally specific plyometric training programme for improving speed profiles in semi-professional rugby players. Players were randomly allocated to one of two plyometric training groups that performed low-volume (40 – 60 ground contacts per session) plyometrics twice weekly, or a control group that did not participate in any plyometric training. The two training groups underwent reverse back-to-back three-week vertically- and horizontally-focused plyometric training programmes, with a 12-day washout. Body composition, aerobic capacity and sprint performance (10-, 20-, 30-m split time, horizontal FV profile) were measured. During the intervention, HV-1 (horizontal/vertical training group 1) improved sprint performance ($n = 12$; Δ30 m = -0.020 s; $p = 0.038$), VH-2 (vertical/horizontal training group 2) maintained sprint performance ($n = 8$; Δ30 m= +0.049 s; $p = 0.377$), and the control group progressively declined in sprint performance ($n= 12$; Δ30 m= +0.071; $p = 0.019$). Additionally, vertical plyometrics may preferentially benefit secondary acceleration (Δ10-20 m split time: -0.01s; $p=0.03$) and many force oriented FV profile characteristics. Correlational analyses ($r^2 = -0.568 — 0.515$) showed sprint improvements were hindered in athletes with lower initial aerobic fitness, suggesting accumulated fatigue may have limited the magnitude of adaptation. Therefore, including low-volume plyometric training may be beneficial for improving sprint profiles or attenuating decrements realized during periods of high-volume sport specific training.

Key words: Sprinting, plyometrics, low dose, force-velocity profile

Appendix 18. Chapter 8 Abstract

Horizontal single-leg drop jumps (SLDJ) have previously been shown to be effective at improving sprinting performance, but the optimal dose is up for debate. Therefore, the purpose of this study was to compare moderately-low volume (MLV: 30 – 70 ground contacts (GC $.session^{-1}$)) and ultra-low (ULV: 10 – 28 GC.$session^{-1}$) volume protocols for improving sprint performance. Two experimental groups (MLV = 11; ULV = 11) underwent twice-weekly horizontal SLDJ training for four weeks, with concurrent rugby and resistance training. Plyometric volumes for both groups were progressed for three weeks with a 30% reduction the fourth week. Maximal vertical jump and sprint assessments were performed pre- and post-intervention. There were no significant differences at baseline for any variable ($p > 0.05$). An analysis of variance was performed to detect changes between- and within-subjects. There was a significant training interaction between groups for 10- and 30-m sprint performance. While MLV significantly decreased 10-, 20-, and 30-m times (-0.03 to -0.05s; ES = 0.32 – 0.54), ULV did not significantly change split times at any distance ($p < 0.05$) . There was a small non-significant decrease in maximal velocity only in the ULV group (-1.79%), while both groups were able to produce substantial improvements in vertical jumping performance with no between-group differences (+14.7 – 38.4%; ES = -0.67 to 1.12). In conclusion, adding MLV protocols may preferentially improve sprint performance and maintain maximal velocity characteristics when compared to ULV protocols. However, higher volumes did not additionally improve vertical jump performance more so than low volumes.

Key words: Sprinting, horizontal plyometrics, volume

Chapter 12 – The end