

The effects of different wearable resistance loads and placements
during vertical jumping and sprint running

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

A handwritten signature in blue ink, appearing to read 'P. Macadam', is written in a cursive style.

Paul Macadam

Date 17/7/2016

ARTICLES

Published peer review articles

Macadam, P., Cronin, J., Simperingham, K. (2016). The effects of wearable resistance training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping: a systematic review. *Journal of Sports Medicine*. doi: 10.1007/s40279-016-0622-x

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Peer review articles under review

Macadam, P., Simperingham, K., Cronin, J. (2016). Acute kinematic and kinetic adaptations to wearable resistance during vertical jumping. *European Journal of Sport Science* (submitted for review 10 September 2016)

The student was the primary contributor (>80 %) of the research in this thesis. All co-authors have approved the inclusion of the joint work in this thesis.

Signatures

A handwritten signature in black ink, appearing to read 'John Cronin', written in a cursive style.

John Cronin

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Kim Simperingham

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ABBREVIATIONS

1RM	one repetition maximum
AP	acceleration phase
AWR	anterior wearable resistance
BM	body mass
CV	coefficient of variation
CMJ	counter movement jump
CT	contact time
DJ	drop jump
F_{air}	aerodynamic friction force
F_h	net horizontal force
F_0	theoretical maximum force
FT	flight time
F_v	vertical ground reaction force
F - v	force velocity profile
HR	heart rate
LWR	lower body wearable resistance
MVP	maximum velocity phase
NCAA	national collegiate athletic association
PAP	post-activation potentiation

PJ	pogo jump
P_{\max}	peak power production
PWR	posterior wearable resistance
RER	respiratory exchange ratio
RSI	reactive strength index
SF	stride frequency
SJ	squat jump
SL	stride length
SPF	step frequency
SPL	step length
SSC	stretch-shortening cycle
TM	treadmill
UL	unloaded
UWR	upper body wearable resistance
VJ	vertical jump
V_0	theoretical maximum velocity
$VO_2 \max$	maximal oxygen consumption
WR	wearable resistance
WRT	wearable resistance training

UNITS OF MEASUREMENT

cm	centimetre
ES	effect size
kg	kilogram
km/h	kilometre per hour
m	metre
min	minutes
N	newtons
r	correlation coefficient
s	seconds
SD	standard deviation
W	watts
%	percentage

ETHICAL APPROVAL

Ethical approval for this research was obtained from the AUT Ethics Committee (reference 15/07) on the 14 of April 2015 (see Appendix 1).

ABSTRACT

Several training options are available to produce specific adaptations depending on the requirement of the sport and the athlete. Specific strength exercises that closely mimic the sporting performance action enable overload and most likely optimise transference of adaptation to the sport/activity of interest. An example of this is wearable resistance (WR) (i.e. an external load attached to the body) which enables movement specific actions to be performed with additional resistance attached to various areas of the body. WR may be a potential training option that allows athletes to train full body strength, speed and power exercises without compromising technique. Acute and longitudinal performance increases have been reported in jumping and sprint running with WR; however, clarity is lacking when specifying the optimum load and load placement position. Previous WR research has involved weighted vests, hand held weights or loads attached to the thigh, ankle or foot. However, recent technological developments have enabled WR loading configurations to be attached to multiple areas of the body allowing greater functional dynamic actions to be performed. Therefore, the purpose of this thesis was to determine the acute kinematic and kinetic changes in vertical jump (VJ) and sprint running performance with differing load magnitudes and load placements.

The aim of the first study was to determine the acute changes in kinematics and kinetics when an additional load equivalent to 3 or 6% body mass (BM) was attached to the upper or lower body during vertical jumping. Twenty athletic subjects performed the counter movement jump (CMJ), drop jump (DJ) and pogo jump (PJ) in a randomised fashion wearing no external load, 3 or 6% BM affixed to the upper or lower body (three jumps per condition). The main finding in terms of the landing phase was that the effect of WR was non-significant. However, landing relative vertical ground reaction force (F_v) tended to be higher with the same magnitude of lower WR compared to upper WR. With regards to the propulsive phase the main findings were that: 1) for both the CMJ and DJ, WR resulted in a significant decrease in jump height (CMJ: -12 to -17%, DJ: -10 to -14%), relative peak power (CMJ: -8 to -17%, DJ: -7 to -10%) and peak velocity (CMJ: -4 to -7%, DJ: -3 to -8%); 2) there was no significant effect of load placement; and, 3) PJ reactive strength index was significantly reduced (-15

to -21%) with all WR conditions. Consideration should be given to the inclusion of WR in sports where VJ's are important components as it may provide a novel training stimulus.

The purpose of the second study was to determine the acute changes in kinematics and kinetics when an additional load equivalent to 3% BM was attached to the anterior or posterior surface of the lower limbs during sprint running. Nineteen male rugby athletes performed six 20 m sprints in a randomised fashion wearing no resistance or 3% BM affixed to the anterior or posterior surface of the lower limbs (two sprints per condition). No significant differences were found between the anterior and posterior WR conditions in any of the variables of interest. There was no significant change in sprint times over the initial 10 m; however the 10 to 20 m split times were significantly slower (-2 to -3%) for the WR conditions compared to the unloaded sprints. A significant change in the relative force-velocity (F - v) slope (-10 to -11%) and theoretical maximum velocity (V_0) (-5 to -6%) was found, while a non-significant increase in theoretical maximum force (F_0) (5%) occurred. WR of 3% BM may be a suitable training modality to enhance sprint running acceleration performance without negatively affecting sprint running kinematics, particularly for athletes requiring a more force dominant F - v profile.

WR provides a novel overload training method for an athlete that enables vertical jumping and sprint running to be performed without negatively impacting on kinematics. WR training may benefit athletes for whom explosive lower-body movements such as jumping and sprint running are performed as part of training and competition.

CHAPTER 1: INTRODUCTION

Rationale and significance of the Thesis

Wearable resistance (WR) in the form of weighted vests, shorts, arm and leg sleeves enables movement specific actions to be performed with resistance (i.e. an external load attached). WR has been widely examined amongst various sports teams and individual athletes. The purpose of such training is to elicit an enhancement in performance due to the overloading stimulus from the external load leading to greater neuromuscular adaptations in relation to the sporting action i.e. principle of specificity.

Both vertical jumping and sprint running are important actions in many team sport events and in individual athlete training programs. Several training methods have been used to optimise the kinematic and kinetic factors relating to enhanced vertical jump (VJ) and sprint running performance, including resistance training, plyometric training and resisted modalities such as sled pulling/pushing, and vest and limb loading (20, 40, 61, 86). Specificity of velocity and movement pattern training are fundamental components of an athlete's prescribed exercise program that can affect sporting performance (12, 88), therefore, resisted training provides a movement specific overload. Faccioni (28) reported that resisted jumping increases muscle fibre recruitment and neural activation resulting in greater power output, while resisted sprint running supplies a sports specificity for neuromuscular adaptation which may enhance velocity during the acceleration phase of sprint running.

Previous resisted jump studies include WR trunk loaded vests (44, 49, 59); elastic resistance such as Vertimax (64, 85); and barbell and/or dumbbell resistance (4, 8, 18, 79, 95). Resisted jump training facilitates an emphasis on rapid force production by enabling an increased load for the athlete to overcome (44). Compared to unloaded jumping, this additional load may increase muscle fibre recruitment along with a concomitant increase in neural activation (28) subsequently increasing power production from the lower body musculature leading to improved jump performance (78). Despite the previous acute and longitudinal research into resisted jumping, no studies have assessed the effects of loads attached to the lower body during jumping. When loads are attached to the lower body, it may

require the athlete to produce more force to overcome the external loading without negatively affecting jump technique. It is quite possible that loading the upper as opposed to the lower body with the same relative load will provide differential adaptations. Moreover, no trunk loading studies have assessed the effects of loads less than 6.6% body mass (BM) on jump performance.

Previous resisted sprint running studies have used sled pulling (14, 105); parachutes (2, 82); WR in the form of a trunk loaded vest (2, 22); loads attached to the leg (97); ankle (86) or foot (61). However, to date, no research has examined lower limb loading using an anterior or posterior load during sprint running. When a load is attached to the anterior surface of the lower limbs it may elicit greater recruitment of the hip flexor musculature resulting in improved front side force production mechanics during sprint acceleration. Research has shown that increased hip flexor strength improved sprint performance (17, 25). Whereas posterior limb loading may enhance hip extensor musculature recruitment during sprint running with strong hip extensors potentially enabling greater horizontal force production. Increased horizontal force production may enhance sprint running performance (74), with the retention of a high ratio of horizontal to total force production a central factor in improving acceleration (72).

The external loading method for WR used in this thesis was the LilaTM ExogenTM exoskeleton suit (Sporthboleh Sdh Bdh, Malaysia). The exoskeleton suit enables fusiform shaped loads (with Velcro backing) of 50-300 g to be attached in numerous configurations while still enabling the wearer to perform functional high speed movements such as sprint running and jumping. The exoskeleton suit is compartmentalised and is comprised of compression shorts, vest, arm, forearm and calf sleeves.

This thesis also provides a framework for future research into different %BM loads and different loading positions for WR during vertical jumping and sprint running. Knowledge into the effects of WR on kinematic and kinetic variables during vertical jumping and sprint running may assist strength and conditioning practitioners towards more effective performance programming. Moreover, practitioners involved in athlete rehabilitation may be interested the effects of WR in improving factors that limit the efficacy of return to sport programming.

Research Aims and Hypothesis

The overarching question that guided the thesis was what are the effects of different WR loads and placements on vertical jumping and sprint running? To answer this question, the main aims of this thesis were to:

- 1) Determine and compare the acute kinematic and kinetic effects of WR using upper body and lower body loading positions vs. unloaded during vertical jumping.
- 2) Determine and compare the acute kinematic and kinetic effects of WR using anterior and posterior loading positions vs. unloaded during sprint running.

The following hypotheses were posited for the studies undertaken in this thesis:

- 1) WR jumping would result in a decreased jump height with greater propulsive vertical ground reaction forces (F_v) compared to unloaded jumping.
- 2) WR sprint running would result in decreased velocity and split times over 20 m compared to unloaded sprint running.

Originality of the Thesis

The originality of the thesis is reflected in the following observations:

- 1) There is a great deal of conflicting evidence regarding the effects of WR during walking, running, sprint running and jumping.
- 2) The optimum load magnitude for centralised loading has yet to be clearly established in acute or longitudinal jump based studies.
- 3) No research exists on improving jump performance through lower limb loading.
- 4) No research exists on improving sprint running performance through anterior or posterior lower limb loading methods.

Framework of the Thesis

This thesis aimed to determine the effects of different WR loads and placements on vertical jumping and sprint running. The thesis is organised into five chapters. Chapter 2 consists of a literature review examining the effects of WR on walking, running, sprint running and jumping. Chapter 3 is a cross sectional study investigating the acute kinematic and kinetic effects of WR with upper body and lower body loading on VJ performance. Chapter 4 is a cross sectional study investigating the acute kinematic and kinetic effects of WRT with anterior and posterior lower limb loading on sprint running performance. Chapter 5 contains a general summary of the research findings, practical applications for strength and conditioning practitioners and future research directions for WR.

Chapters 2-4 have been published or submitted for publication in scientific journals. Each chapter is therefore written in the format of the journal they were submitted to. Consequently, there is some repetition in the articles between the chapters. References are not included at the end of each chapter; rather, an overall reference list from the entire thesis has been collated at the end of the final chapter. The reference format selected is a specific style required for submission to the *Journal of Strength and Conditioning Research*, based on a numerical system. All other relevant material from the studies is present in the appendices.

CHAPTER 2: LITERATURE REVIEW

The effects of wearable resistance training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping: a systematic review

(Published in Sports Medicine)

Abstract

Background: Wearable resistance training (WRT) provides a means of activity or movement specific overloading, supposedly resulting in better transference to dynamic sporting performance.

Objective: The purpose of this review was to quantify the acute and longitudinal metabolic, kinematic and/or kinetic changes that occur with WRT during walking, running, sprint running or jumping movements.

Data Sources: Pubmed, Sports Discuss, Web of Science and MEDLINE (EBSCO) were searched using the Boolean phrases (limb OR vest OR trunk) AND (walk* OR run* OR sprint* OR jump* OR bound*) AND (metabolic OR kinetic OR kinematic) AND (load*).

Study Selection: A systematic approach was used to evaluate 1,185 articles. Articles with injury-free subjects of any age, gender or activity level were included.

Results: Thirty-two studies met the inclusion criteria and were retained for analysis. Acute trunk loading reduced velocity during treadmill sprint running but only significantly when loads of 11% body mass (BM) or greater were used, while over the ground sprint running times were significantly reduced with all loads (8-20%BM). Longitudinal trunk loading significantly increased jump performance with all loads (7-30%BM) but did not significantly improve sprint running performance. Acute limb loading significantly increased maximum oxygen consumption and energy cost with all loads (0.3-8.5%BM) in walking and running, while significantly reducing velocity during sprint running.

Limitations: The variation in load magnitude, load orientation, subjects, testing methods and study duration no doubt impact the changes in the variables examined and hence make definitive conclusions problematic.

Conclusions: WRT provides a novel training method with potential to improve sporting performance,

however, research in this area is still clearly in its infancy with future research required into the optimum load placement, orientation and magnitude required for adaptation.

1 Introduction

Several training options are available to produce specific adaptations depending on the requirement of the sport and the athlete (40). Specificity of training is a fundamental component of an athlete's prescribed exercise program that can affect the magnitude of the adaptive response from the macro to micro myofibrillar level (12, 62). Wearable resistance training (WRT) involves an external load being attached to certain segments of the body during various sporting movements and is an example of the application of the concept of training specificity. WRT is used in athletic training with the aim of increasing power output and performance by enabling specific movements to occur with additional loading without adversely affecting the action being performed (40). Heavy resistance training (load > 80% one repetition maximum) performed with a slow or moderate velocity is prescribed for strength development (35, 37, 78, 106). However, this type of training may not be optimal for improving power production, which can require high velocity movements with relatively lighter loads (< 60% one repetition maximum) (36, 37, 78). In contrast, movements performed with WRT enable acceleration to occur throughout the full range of motion (78) in a movement specific context. WRT provides an increased resistance to the athlete's regular training and thus provides overload of the musculature system, which in turn can result in training adaptation and crossover to sporting performance (40).

An aim of WRT is to identify the optimum load that gives the greatest training stimulus without inducing undesirable changes in sporting technique. Previous research into WRT has found a great deal of conjecture and confliction in results mainly due to the differences in load magnitudes, load orientations, subject's training status, testing methods and the duration of the studies. To date, WRT has been attached to the body by either trunk or limb loading. Trunk loading (e.g. weighted vests) enables an overload to be evenly distributed near an individual's centre of mass potentially increasing

the ability to produce greater ground reaction forces and power production (4, 14, 20). While in limb loading the loads are typically placed at the end of the distal segments and therefore are likely to considerably increase the moment of inertia and subsequently increase the required muscle activity (18, 38). Limb loading usually involves a relatively light load (<10% body mass (BM)) while trunk loading enables a heavier load to be attached (ranging 5-65%BM). While acute and longitudinal changes in sporting performance have been observed with training tools such as weighted vests and ankle and hand weights (22, 61, 83, 86), recent advances in WRT technologies (e.g. the Lila™ Exogen™ exoskeleton suit and Titin Tech™ weighted compression vest) now enable much greater customisation of load magnitudes, orientations and locations around the body. Given this plethora of loading options it would be of value to the practitioner to understand the benefits and limitations of WRT for exercise prescription and targeted adaptation. The purpose of this review therefore was to quantify the acute and longitudinal metabolic, kinematic and/or kinetic changes that occur with WRT during walking, running, sprinting or jumping movements. These movements will be discussed in the terms of cyclic and acyclic actions. Cyclic actions are characterised by the motor action involving repetitive movements (e.g. walking, running, sprinting, continuous jumping), while acyclic actions consist of movements performed in one action (e.g. shot put, discus, single jump) (5). Studies were grouped by the loading strategy used (i.e. trunk or limb loading) and further sub divided by the duration of the study (acute or longitudinal). Such a treatise of the literature should enable gaps and limitations to be identified as well as providing insight into the adaptations provided by WRT training.

2 Methods

2.1 Literature Search

The review was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) statement guidelines (68). A systematic search of the research literature was undertaken for acute (cross-sectional) and longitudinal studies assessing the effects of WRT on

walking, running, sprinting and jumping from international peer-reviewed journals. Studies were found by searching PubMed, SPORTDiscus, Web of Science and MEDLINE (EBSCO) electronic databases from inception to November 2015. The following Boolean phrases were used for the searches (limb OR vest OR trunk) AND (walk* OR run* OR sprint* OR jump* OR bound*) AND (metabolic OR kinetic OR kinematic) AND (load*). Additional studies were also found by reviewing the reference lists from retrieved studies.

2.2 Inclusion and Exclusion Criteria

Studies with injury-free subjects of any age, gender or activity level were included. No restrictions were imposed on publication date or publication status. Studies were limited to the English language. Studies incorporating a direct assessment of changes to metabolic, kinematic or kinetic variables that occurred when the added load was actually being worn on the body were included. Post-activation potentiation (PAP) studies, where changes are only assessed after the load was removed, were excluded. Studies that used an assistive device for bearing load (e.g. Gregorczyk et al. (34)) were also excluded.

2.3 Study Selection

A search of electronic databases and a scan of article reference lists revealed 789 relevant studies (Figure 1). After applying the inclusion and exclusion criteria thirty-two studies were retained for further analysis.

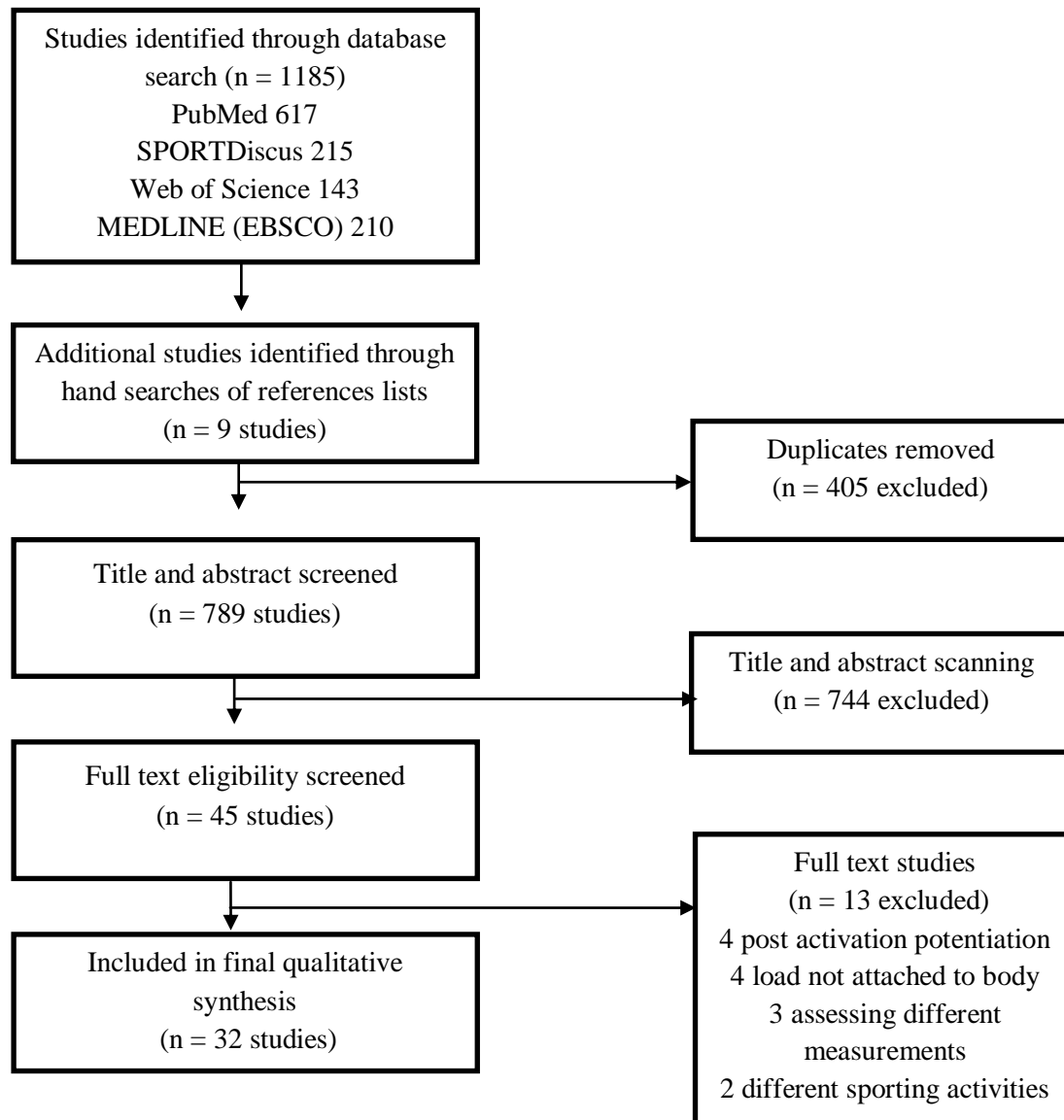


Figure 1. Flow chart of information through the different phases of the systematic review.

3 Results

3.1 Study characteristics

Thirty-two studies were analysed with a total of 452 subjects (323 male, 116 female, 13 gender unspecified) (Table 1). Subjects included were characterised as either healthy sedentary, recreationally active or competitive athletes from various sporting backgrounds. In order to compare findings, data from studies that used an absolute load is shown as a percentage of body mass (%BM).

When scaled to BM the trunk loading ranged from 5.0 to 65.3%BM, while the limb loading ranged from 0.3 to 8.5%BM. Acute and longitudinal studies of trunk loading are summarised in Tables 2 and 3, respectively. Acute limb loading studies are summarised in Table 4. To date, no longitudinal limb loading studies have been completed.

Data was extrapolated from the Figures in Sands et al. (91) and Ropert et al.(86) which potentially introduces measurement error. To differentiate between speeds during locomotion, a classification scheme was used based on the included studies' description of speeds: walking (<7.5 km/h); running (≥ 7.5 to <25 km/h); sprinting (≥ 25 km/h) (53, 93). The variables discussed in this review are defined as metabolic, kinematic and/or kinetic and are clarified as follows.

Metabolic variables:

Oxygen consumption (VO_2): the amount of oxygen taken up and utilised by the body per min (ml/kg/min).

Exercise intensity: calculated from age-predicted maximal heart rate, expressed using the formula (exercise heart rate/age predicted maximal heart rate) x 100 (83).

Energy workload: the mechanical work measures for lower body segments determined by quantifying the change in mechanical energy levels (61).

Energy cost: expressed as millimetres of oxygen consumption per min per kilogram of total weight (ml/kg/min) (100).

Respiratory exchange ratio (RER): the ratio between the amount of carbon dioxide and oxygen produced in metabolism.

Heart rate: the speed of the heartbeat measured by the number of contractions of the heart per min (bpm).

Blood lactate: the blood lactic acid level which rises when oxygen delivery to the tissues is insufficient to support normal metabolic demands (mmol/L).

Kinematic variables:

Step length: the horizontal distance between the heel of one foot at foot strike to the heel of the other foot at foot strike (m).

Step frequency: the number of steps that are completed per second (Hz).

Stride length: the distance between two successive placements of the same foot. In essence two steps constitute a stride (m).

Stride frequency: the number of strides that are completed per second (Hz).

Contact time: the period of time from when the foot contacts the ground to when the foot toes off the ground (s).

Flight time: the time from toe off from one foot to the time of first contact of the other foot (s).

Leg stiffness: calculated from the ratio of force to the change in spring length. (For calculations see Slider (96) and Janssen (44)).

Acceleration phase: ten steps following the initial two steps at push-off during treadmill sprint running. 0-15 m during over the ground sprint running.

Maximum velocity phase: ten steps following the acceleration phase during treadmill sprint running. Greater than 15 m during over the ground sprint running.

Kinetic variables:

Vertical ground reaction force (F_v): the vertical force exerted by the ground on a body in contact with it (N).

Peak power: the highest power output before take-off during jumping (W).

Loading rate: defined as the change in force over time from heel strike to impact peak force (Ns).

Impulse: the change in momentum given by the product of force and the time over which the force was applied (Ns).

Table 1. Study characteristics of trunk and limb loading for all studies (n = 32).

Study	Subjects (sex and mean \pm SD age, height and mass)	Methodology (measurements)	Load placement and amount	Acute / longitudinal
Soule and Goodman (100)	10 males, 22 years, 174 cm, 70 kg	Treadmill walking for 20 min (speeds: 4, 4.8, 5.6 km/h)	Limb: 6 kg each foot (8.5%BM)	Acute
Cureton et al. (23)	4 males, 2 females, 26 years, 176 cm, 64.8 kg Trained distance runners	Maximum incremental treadmill running test Track running for 12 min	Trunk vest: 5, 10 and 15%BM	Acute
Jones et al. (47)	14 males, 30.4 \pm 3.7 years, 174.5 \pm 5.8 cm, 75.1 \pm 5.8 kg 6 distance runners, 8 sedentary or occasional runners	Treadmill walking for 6 min (speeds: 4.0, 5.6 and 7.3 km/h) for 1) and 2) Treadmill running for 4 min (speeds: 8.9, 10.5 and 12.1 km/h) for 1) and 3)	Limb: 1) running shoes 0.6 kg, 2) military boots 1.7 kg, 3) shoes as per 1) with added lead mass to equal mass of 2) (0.8 and 2.2%BM)	Acute
Bosco (6)	5 males, 26 \pm 2.2 years, 181.2 \pm 6.4 cm, 71.4 \pm 5.5 kg	DJ 15 s continuous vertical jumps SJ	Trunk vest: 11%BM	Longitudinal 3 weeks
Martin (60)	15 males, 29 \pm 3 years, 72 \pm 9 kg Long distance runners with high levels of fitness	Treadmill running for 8 min at 12 km/h	Limb: 1) 0.25 kg each thigh. 2) 0.25 kg each foot. 3) 0.5 kg each thigh. 4) 0.5 kg each foot (0.3 and 0.7%BM)	Acute
Bosco et al. (7)	7, 22.3 \pm 2.1 years, 182.8 \pm 4.4 cm, 74.5 \pm 4.7 kg High level national sprinters, 3-6 years experience	DJ from 60 cm: male, 40 cm: female 15 s continuous vertical jumps SJ Treadmill running to exhaustion	Trunk vest: 7-8%BM	Longitudinal 3 weeks
Jones et al. (46)	7 females, 25 \pm 2.7 years, 166 \pm 8.7 cm, 59.9 \pm 8.7 kg 3 active runners, 4 sedentary	Treadmill walking for 6 min (speeds: 4, 5.6 and 7.3 km/h) Treadmill running for 4 min (speeds: 8, 9 and 10.5 km/h)	Limb: 1) running shoes 0.5 \pm 0.05 kg, 2) military boots 1.3 \pm 0.1 kg (0.8 and 2.1%BM)	Acute
Rusko and Bosco (87)	10 males, 2 females, 25 \pm 2.6 years, 175.9 \pm 8.4 cm, 66.2 \pm 10.2 kg Endurance athletes	Submaximal running Treadmill running to exhaustion	Trunk vest: 8-9%BM	Longitudinal 4 weeks
Claremont and Hall (13)	5 males, 3 females, 42 \pm 8.3 years Regular runners for several years	30 min treadmill running (1% gradient) self selected speed (8.9 to 13.7 km/h)	Limb: 0.45 kg each ankle	Acute
Martin and Cavanagh (61)	15 males, 29 years, 72 kg Distance runners	Treadmill running for 8 min at 12 km/h	Limb: 1) 0.25 kg each thigh, 2) 0.25 kg each foot, 3)	Acute

Study	Subjects (sex and mean \pm SD age, height and mass)	Methodology (measurements)	Load placement and amount	Acute / longitudinal
			0.5 kg each thigh, 4) 0.5 kg each foot (0.34 and 0.69% BM)	
Cooke et al. (16)	8 males, 21.3 \pm 2.3 years, 175.5 \pm 4.4 cm, 63.8 \pm 4 kg Cross country runners	Treadmill running for 3 min (speeds: 9.6, 11.1, 12.8 and 13.1 km/h)	Trunk vest: 5 and 10% BM	Acute
Fowler et al. (31)	8 males, 21 years, 175 \pm 12 cm, 73.8 \pm 9.3 kg Physically active, no experience of plyometric jumping	DJ from 26 cm	Trunk vest: 8.5 kg weighted vest (11.5% BM)	Acute
Sands et al. (91)	11 females, vest group (n=5), 19 \pm 1.5 years, 166.1 \pm 5.2 cm, 59.7 \pm 5.2 kg, control (n=6), 19 \pm 1.2 years, 171.9 \pm 10.3 cm, 64.3 \pm 7.3 kg Track and field athletes	Standing vertical jump and reach test	Trunk: Week 1 8% BM Week 2 10% BM Week 3 12% BM	Longitudinal 3 weeks
Ropret et al. (86)	24 males, 20.1 \pm 0.9 years, 179.6 \pm 8.4 cm, 74.5 \pm 9.8 kg Physical education students	30 m sprint	Limb: 0.6, 1.2, or 1.8 kg each ankle (0.8, 1.6 and 2.4% BM)	Acute
Driss et al. (26)	22 (6 elite weight-lifters and 16 volleyball players): 20.9 \pm 3.1 years, 177 \pm 12 cm, 75 \pm 9.8 kg 20 sedentary: 10 males, 27.4 \pm 2.6 years, 180 \pm 13 cm, 72.2 \pm 11.2 kg 10 females, 23 \pm 3.7 years, 166 \pm 5 cm, 64.9 \pm 6.7 kg	SJ	Trunk vest: 5 and 10 kg (6.6 and 13.3% BM)	Acute
Puthoff et al. (83)	3 males, 7 females, 23.4 \pm 1.7 years, 173.1 \pm 6.6 cm, 70.5 \pm 7 kg	Treadmill walking for 4 min (speeds: 3.2, 4, 4.8, 5.6, 6.4 km/h)	Trunk vest: 10, 15 and 20% BM	Acute
Alcaraz et al. (2)	11 males, 22 \pm 4 years, 180 \pm 8 cm, 75 \pm 7 kg, 7 females, 19 \pm 2 years, 167 \pm 7 cm, 59 \pm 5 kg Competitive track athletes	Flying sprints greater than 30 m	Trunk belt: 9% BM	Acute
Cronin et al. (19)	16 males, 4 females, 19.9 \pm 2.2 years, 176 \pm 8 cm, 76.5 \pm 10.7 kg Competitive athletes from mixed sports	30 m sprints	Trunk vest: 15 and 20% BM	Acute
Clark et al. (14)	6 males, 19.7 \pm 0.1 years, 182 \pm 8 cm, 79.1 \pm 5.26 kg NCAA Division 3 lacrosse players	Sprinting distance reviewed: 18.3-54.9 m 2 x 60 min sessions a week of periodised sprint training program with weighted vest	Trunk vest: 18.5% BM	Longitudinal 7 weeks

Study	Subjects (sex and mean \pm SD age, height and mass)	Methodology (measurements)	Load placement and amount	Acute / longitudinal
Khelifa et al. (49)	27 males, 23.6 \pm 0.9 years, 192 \pm 7 cm, 82.4 \pm 0.66 kg Tunisian 1 st division basketball players	Vertical and horizontal jumping 2 x 90 min (weeks 1 to 3) 3 x 90 min (weeks 4 to 10)	Trunk vest: 10-11% BM	Longitudinal 10 weeks
Simpson et al. (98)	15 females, 22.3 \pm 3.9 years, 169 \pm 10 cm, 61.2 \pm 5.3 kg Active hikers	Walking 8 km at self-selected pace	Trunk backpack: 20, 30 and 40% BM	Acute
Janssen et al. (44)	10 males, 17.1 \pm 0.1 years, 202 \pm 6 cm, 86.5 \pm 10.2 kg Elite volleyball players	Volleyball block jumping	Trunk vest: 9.89 kg (11.4% BM)	Acute
Simpson et al. (99)	15 females, 22.3 \pm 3.9 years, 169 \pm 10 cm, 61.2 \pm 5.3 kg Active hikers	Walking 8 km at self-selected pace	Trunk backpack: 20, 30, 40% BM	Acute
Markovic et al. (59)	11 males, 182 \pm 6 cm, 81 \pm 0.1 kg Physical education students	SJ CMJ 3 x week of periodised CMJ	Trunk vest: 30% BM	Longitudinal 8 weeks
Konstantinos et al. (50)	24 males, 18-23 years, 178 \pm 5 cm, 74.2 \pm 8.9 kg Sport science students	Flying sprints greater than 50 m	Trunk vest: 8, 15, 20% BM	Acute
Cross et al. (22)	13 males, 22.9 \pm 3.3 years, 179 \pm 6 cm, 82.5 \pm 8.4 kg Sport active university level athletes	6 s maximal sprints on a non motorised force treadmill	Trunk vest: 9 and 18 kg (10.9 and 21.8% BM)	Acute
Seay et al. (94)	14 males, 18.9 \pm 0.5 years, 179.5 \pm 7.8 cm, 84.1 \pm 12.0 kg U.S. Army enlisted	Treadmill marching at 4.8 km/h for 10 min	Trunk vest: 15 and 55 kg (17.8 and 65.3% BM)	Acute
Simperingham and Cronin (97)	8 males, 29.2 \pm 3.8 years, 177.1 \pm 7.5 cm, 81.8 \pm 9.7 kg Athletic sprint based backgrounds	6 s maximal sprints on a non motorised force treadmill	Trunk vest and limb: 5 % BM	Acute
Barr et al. (4)	8 males, 22.4 \pm 2.7 years 182 \pm 6 cm, 95.3 \pm 7.1 kg National rugby players	40 m sprint Weighted vest worn all day and during skills, conditioning and strength training sessions	Trunk vest: 12% BM	Longitudinal 8 days
James et al. (43)	10 males, 10 females, 27.8 \pm 6.8 years, 173 \pm 11 cm, 72.3 \pm 16.6 kg	Treadmill walking for 1.5 min at 4.8 km/h	Limb: 0.45 and 0.9 kg (0.6% and 1.2% BM)	Acute
Krupenevich et al. (51)	22. 11 males, 20 \pm 2.3 years 179 \pm 6 cm, 79.1 \pm 13.3 kg	Walking over a force plate at 5.4 km/h	Trunk backpack: 22 kg	Acute

Study	Subjects (sex and mean \pm SD age, height and mass)	Methodology (measurements)	Load placement and amount	Acute / longitudinal
	11 females, 20 \pm 1.8 years 171 \pm 8 cm, 72.9 \pm 15.1 kg Army reserve officers		(males: 28%BM, females: 30%BM)	
Silder at al. (96)	16 males, 11 females, 33 \pm 8 years 175 \pm 9 cm, 70 \pm 9 kg Recreational runners	Treadmill running for 2 min stages at self-selected pace (average pace 12 km/h)	Trunk vest: 10, 20, 30%BM	Acute

BM = body mass; SJ = squat jump; CMJ = counter movement jump; DJ = drop jump; NCAA = National collegiate athletic association; SD = standard deviation

3.2 Trunk Loading

Table 2. Acute trunk loaded studies with changes to metabolic, kinematic and kinetic variables (n = 16).

Load %BM	Metabolic	Kinematic	Kinetic
5	Running (TM): No significant change in VO_2 (16) Running (TM): Significant decrease in VO_2 max (relative to load) (6.2%), non-significant change relative to BM or fat free mass (23)	Running (TM): Significant increase in SF (1.6%) (16) Running: Significant decrease in maximal treadmill running time (-4.4%) and 12 min over the ground run for maximal distance (-4%) (23). Sprint running(TM): Significant increase in CT during AP (3.8%) and MVP (4.7%), and decrease in FT during AP (-15%) No significant effect on peak velocity, SPF, SPL or time to cover any distances (97)	Sprint running (TM): Significant decrease in relative values for peak F_v (-5.4 to -6.4%) and mean F_v (-3.8 to -4.0%) during AP and MVP, respectively (97)
6.6			SJ: Significant decrease in peak power for sedentary female and male (-3.7 and -4.1%), non- significant increase for athletes (1.6%). Significant increase in F_v for sedentary male and female (2.6 and 4.1%), and athletes (2.7%) (26)
8		Sprint running: Significant decrease in sprint times over 50 m, and each subsequent 10 m phase (-4.1 to -5.1%) (50)	
9		Sprint running: No significant changes in body lean, thigh angle, hip angle, knee angle. Non-significant decrease in	

Load %BM	Metabolic	Kinematic	Kinetic
		velocity and SPL (both - 3%) (2)	
10	Walking: Significant increase in VO_2 (6-8%), and non-significant increase in relative intensity (3.9-6.6%) (83)	Running (TM): Significant increase in SF (4.5%) (16) Running: Significant decrease in maximal running time (-7.5%) and 12 min over the ground run for maximal distance (-5.8%) (23) Running (TM): Significant increase in vertical stiffness (2.8%) and CT (4 %) (96)	Walking: Significant main effect for loaded vest condition was found for F_{v1} (11.6%) and F_{v2} (5.5%) in and loading rate (5.3%) at all speeds (83) Running (TM): Significant increase in peak F_v (3.8%) (96)
10.9		Sprint running (TM): Significant decrease in peak velocity (-3.6%), increase in CT (5.6% MVP), decrease in FT (-17.4% MVP) and SPL (-4.4% MVP). Non-significant increase in SPF (0.8%) (22)	Sprint running (TM): Non-significant increase in peak F_v (3.1% MVP), mean F_v (3.4%, AP and MVP), decrease in peak power output (3.7% MVP) (22)
11.4		Volleyball block jump: Significant decrease in jump height (-10.6%), significant increase in hip flexion (7.3%) (44)	Volleyball block jump: No significant changes in peak F_v (2.7%) and loading rate (-3.4%) (44)
11.5			Drop jump: Significant increase in average peak F_v (5.2%) and loading rate (26.2%) (31)
13.3			SJ: Significant decrease in peak instantaneous power for sedentary female and male (-4.7 and -5.2%), non-significant increase for athletes (0.4%). Significant increase in F_v for sedentary (5.9 and 6.1%), and athletes (6.7%) (26)
15	Walking: Significant increase in VO_2 (7-10.2%) and relative intensity (8.3-9.9%) (83)	Running: Significant decrease in maximal treadmill running time (-10.9%) and 12 min over the ground run for maximal distance (-8.6%) (23) Sprint running: Significant decrease in sprint time over 30 m (-7.5%), increase in stance phase duration (12.8%) and decrease in swing phase (-8.4%) (19) Sprint running: Significant decrease in sprint times over 50 m, and each subsequent 10 m phase (-6.9 to -7.5%) (50)	Walking: Significant main effect for loaded vest condition was found for F_{v1} (12.6%) and F_{v2} (10.5%) and loading rate (11.2%) at all speeds (83)
17.8		Walking: Significant increase in hip ROM (4.8%), knee extension moment (8%), and ankle ROM (6%) (94)	

Load %BM	Metabolic	Kinematic	Kinetic
20	Walking: Significant increase in VO ₂ (10.3-17.4%) and relative intensity (7.4-10.8%) (83) Significant increase in heart rate (6.9%) (98)	Sprint running: Significant decrease in sprint time (-11.7%), increase in stance phase duration (24.5%) and decrease in swing phase (-14.4%) (19) Walking: Significant increase in peak trunk flexion (7.2%) and non-significant decrease in velocity (5.1%) (98) Walking: Significant decrease in knee angle at initial contact (-1.7%), and non-significant decrease in SL (-1.3%) (99) Sprint running: Significant decrease in sprint times over 50 m, and each subsequent 10 m phase (-8.3 to -9.9%) (50) Running (TM): Significant increase in vertical stiffness (12.5%) and CT (4%) (96)	Walking: Significant main effect for loaded vest condition was found for F _{v1} (18.1%) and F _{v2} (12.4%) and loading rate (14.6%) at all speeds (83) Walking: Significant increase in vertical impulse (16.2%) and non-significant increase in mediolateral impulse (33.4%) (99) Running (TM): Significant increase in peak F _v (7.4%) (96)
21.8		Sprint running (TM): Significant decrease in peak velocity (-5.7%), increase in CT (9.2%), decrease in FT (18.9, 26.7% MVP, AP), decrease in SPL (-4.4%). Non-significant decrease in SPF (-1.5%) (22)	Sprint running (TM): Significant increase in peak F _v (8.2% MVP), mean F _v (11.1, 10.6%, MVP, AP), decrease in peak power output (14.3% MVP) (22)
28		Walking: Significant decrease in SL (-1.9%) and increase in trunk forward lean (11%) (51)	Walking: Significant increase in F _{v1} (21.9%) and F _{v2} (21.2%) (51)
30	Walking: Significant increase in heart rate (6.9 %) (98)	Walking: Significant increase in peak trunk flexion (10.2%), and non-significant decrease in velocity (-10.2%) and SL (-1.9%) (98) Walking: Significant decrease in knee angle at initial contact (-2.3%), and non-significant decrease in SL (-3.1%) (99) Running (TM): Significant increase in vertical stiffness (20.5%) and CT (7.7%) (96) Walking: Significant decrease in SL (-1.3%) and increase in trunk forward lean (13%) (51)	Walking: Significant increase in vertical impulse (24.4%) and mediolateral impulse (33.4%) (99) Running (TM): Significant increase in peak F _v (10.8%) (96) Walking: Significant increase in F _{v1} (20.5%) and F _{v2} (21.9%) (51)
40	Walking: Significant increase in heart rate (7.7 %) (98)	Walking: Significant increase in peak trunk flexion (13.1%), and non-significant decrease in velocity (-15.3%) and SL (-3.2%) (98) Walking: Significant decrease in knee angle at initial contact , and non-significant decrease in SL (-1.9%) (3.4%) (99)	Walking: Significant increase in vertical impulse (26.4%) and mediolateral impulse (33.4%) (99)
65.3		Walking: Significant increase in hip ROM (15%), knee extension moment (12%) and ankle ROM (26.3%) (94)	

BM = body mass; TM = treadmill; CT = contact time; FT = flight time; SF = stride frequency; SL = stride length; SPF = step frequency; SPL = step length; AP = acceleration phase; MVP = maximum velocity phase; F_v = vertical ground reaction force; VO₂ max = maximal oxygen consumption; ROM = range of motion; SJ = squat jump

Table 3. Longitudinal trunk loaded studies with changes to metabolic, kinematic and kinetic variables (n = 8).

Load %BM	Duration	Metabolic	Kinematic	Kinetic
7-8	3 weeks	Sprint running (TM): Non-significant decrease in lactate levels during 35 s of sprint running (-15%) and sprint running to exhaustion (-0.7%) (7)	Jumping: Significant increase in DJ height (6.5%) and SJ height (9.5-14%). Sprint running: Non-significant change in sprint running to exhaustion time (4.8%) (7)	Jumping: Significant increase in power output in 15s of jumps (5%) and DJ (% change not provided). The force-velocity curve shifted to the right and was significant in all areas of the curve (7)
8-12	3 weeks		Jumping: Significant increase in vertical jump height (10.9%) compared to control group (3.6%) (91)	
9	4 weeks	Running (TM): Significant increase in blood lactate (20.7%) and oxygen uptake (2.7%) in submaximal running, and decrease in 2 mmol lactate threshold in running to exhaustion (-9.4%) (87)		
10-11	10 weeks		Jumping: Significant increase in SJ (9.9%), CMJ (12.2%), CMJ-SJ value (27.4%) and 5JT (7.5%) (49)	
11	3 weeks		Jumping: Significant increase in DJ height (12.8%) and decrease in CT (3.3%). Significant increase in SJ height (19.4%) and 15s jumping height (9.4%) and decrease in CT (5.5%) (6)	Jumping: The force-velocity curve significantly shifted to the right (11%). Significant increase in mechanical power (10%) (6)
12	8 days		Sprint running: No change in 40 m time after 2 or 9 days for vest group. Control group times decreased 1.2% after 2 days and increased 1.2% after 9 days (4)	
18.5	7 weeks		Sprint running: No significant difference between unloaded and loaded conditions. Increase in maximum velocity (1.2%), decrease in sprint time (-1.2%), decrease in SL (-2.2%), increase in SF (3.3%), decrease in CT (-1.5%), decrease in FT (5.4%) (14)	
30	8 weeks		Jumping: Significant increase in SJ height (11.6%), CMJ height (7.8%). Significant increase in 1RM squat (7.8%) (59)	Jumping: Significant increase SJ average power (11%) and CMJ average power (3%) (59)

BM = body mass; TM = treadmill; SJ = squat jump; CMJ = counter movement jump; DJ = drop jump; 5JT = 5 consecutive strides and jump; 1RM = one repetition maximum; SF = stride frequency; SL = stride length; CT = contact time; FT = flight time

3.2.1 Acute Metabolic Effects

The acute metabolic effects of trunk loading (see Table 2) were investigated in four studies, with significant changes observed in oxygen consumption (VO_2), exercise intensity and heart rate (16, 23, 83, 98). Subjects (15 male and 24 female) were reported to have a wide variety of athletic ability e.g. active hikers to well trained cross country runners. Cooke et al. (16) were the only authors to assess the metabolic effects at speeds greater than walking speed, a limitation which the reader needs to be cognizant of when reading the following section.

3.2.1.1 VO_2 consumption

Non-significant, small increases (0.1-0.3%) in VO_2 consumption were found during trunk loaded running for three min at four speeds (9.6-13.1 km/h) utilising 5 and 10%BM loading (16) while moderate and significant increases (6-17%) were found during trunk loaded walking (10-20%BM) for 4 min stages at speeds of 3 to 6.4 km/h (83).

3.2.1.2 Exercise intensity

Trunk loading (10-20%BM) had no significant effect on relative exercise intensity at a low walking speed (3.2 km/h), but the effect of the weighted vest condition became more pronounced ($p < 0.05$) at higher speeds (4-6.4 km/h) (83).

3.2.1.3 Heart rate

Significant increases (6.9-7.7%) in heart rate responses due to trunk backpack loading were quantified across three loads (20, 30 and 40%BM) while walking for 8 km at a self-selected pace (the average speed recorded was 5.3, 5, 4.8 km/h for the three loads, respectively) (98).

3.2.2 Acute Kinematic Effects

The authors of twelve studies reported acute changes to kinematic variables with trunk loading (Table 2). Acute kinematic changes were quantified for walking ($n = 4$; loads: 17.8-65.3%BM), running ($n = 2$; loads: 5-30%BM); sprint running ($n = 5$; loads: 5-21.8%BM); and volleyball block jumping ($n = 1$; loads: 11.4%BM). The reader needs to be aware that when interpreting the findings of Alcaraz et al. (2) load placement differed from the other studies. Alcaraz et al. (2) used a load that was attached to a belt around the waist with the authors noting that the total torque on the trunk was relatively small and when using a vest instead of a belt, the applied load would be shifted upward and farther away from the hips.

3.2.2.1 Step variables

This section discusses the effects of acute trunk loading on the step variables investigated by the reviewed researchers, namely stride and step length, stride and step frequency, flight and contact times (see Table 2).

Walking: Two studies used backpack trunk loading with loads of 20-40%BM. Both studies used similar walking speeds, and found similar changes in stride length (20-40%BM = -1.3 to -3.2%; $p > 0.05$ (98); 28-30%BM = -1.3 to -1.9%; $p < 0.05$ (51)), though significant and non significant differences were reported.

Running: Significant increases in stride frequency (5%BM = 1.6% and 10%BM = 4.5%) (16) and contact time (10% and 20%BM = 4%; 30%BM = 7.7%) (96) were observed at a constant treadmill running pace ranging from 9.6 to 13.1 km/h.

Sprint running: A non-significant decrease in step length (9%BM = -3 %) was found during over the ground sprint running (2). Similarly, a lighter load (5%BM) had no significant effect on step length or step frequency (97) during non-motorised treadmill sprint running. However, greater loads (~11%BM and ~21%BM) resulted in a significant decrease in step length (-4.4%), but no significant changes were found in step frequency during non-motorised treadmill sprint running (22). The effect of trunk

loading on contact time during acceleration and maximum velocity running has been detailed in three studies (19, 22, 97). All loads (5-21.8 %BM) were found to significantly increase (3.8-24.5%) contact time/stance phase (19, 22, 97). Similarly, flight time was found to decrease ($p < 0.05$) by -8.4 to -26.7% across these loads.

3.2.2.2 Velocity and sprint performance

This section examines the effects of acute trunk loading on velocity and sprint performance (i.e. time taken to complete a specific distance) (Table 2).

Walking: One study quantified the effects of trunk loading during walking for 8 km (98). An increase in trunk loading resulted in a decrease in average velocity (20%BM = -5.1 %, 30%BM = -10.2%, 40%BM = -15.3%). Although the outcome from increased loading was a greater decrease in velocity, the findings were non-significant ($p > 0.05$).

Sprint running: The effects of trunk loading on treadmill and over the ground sprint times or velocity have been investigated across loads ranging from 5 to 21.8%BM (2, 19, 22, 50, 97). As load increased past a threshold of 8%BM the decrement in performance was fairly linear (11%BM = -3.6%, 15%BM = -6.9 to -7.5%, 20%BM = -8.3% to -11.7%; $p < 0.05$) during over the ground sprinting. Interestingly the decrement in sprint performance seems less when non-motorised treadmills are utilised (11%BM = -3.6% and 21%BM = -5.7%; $p < 0.05$) (22).

3.2.2.3 Joint angles

This section discusses the effects of acute trunk loading on the joint angle changes, namely hip, knee and ankle joints (see Table 2).

Walking: The effect of trunk loading on joint angle changes during walking has been detailed in four studies. Backpack trunk loading (28-30%BM) resulted in significant increase in trunk forward lean in male (11%) and female (13%) subjects during treadmill walking (96). Two studies quantified the effects of trunk loading (20, 30 and 40%BM) on female hikers during over ground walking for 8 km at self-selected speeds. It would seem that trunk loading across all loads leads to more of a forward

lean due to the significant increase in peak trunk flexion (7.2, 10.2, 13.1%) (99).

Jumping: Only one study investigated trunk loading on vertical jump performance (44). For athletes with a substantial jump-landing history (elite volleyballers) the addition of trunk loading of ~11% did not make any significant difference in leg stiffness and any of the range of motion measures at the ankle, knee or trunk as compared to the unloaded condition of a volleyball block jump. The only statistically significant differences were noted in decreased jump height (-10.6%) and at the hip, where the addition of the load decreased (-7.3%) hip flexion (44).

3.2.3 Acute Kinetic Effects

Acute changes to kinetic variables with trunk loading across nine studies have been investigated (Table 2). Acute kinetic changes were quantified for walking (n = 3; loads: 10-40%BM), running (n = 1; loads: 10-30%BM), sprint running (n = 2; loads: 5-21.8%BM); and jumping (n = 3 studies; loads: 6.6-13.3%BM).

3.2.3.1 Ground reaction force

This section discusses the effects of acute trunk loading on ground reaction force during walking, sprint running and jumping (see Table 2).

Walking: Trunk loading of all loads (10-30%BM) significantly increases vertical ground reaction force (F_v) and the rate of loading (5.3-14.6%). Trunk loaded walking (10-20%BM) was found to significantly increase vertical ground reaction force first peak (F_{v1}) (11.6-18.1%) and vertical ground reaction force second peak (F_{v2}) (5.5-12.4%) (83), while heavier loads (28-30%BM) resulted in F_{v1} (20.5-21.9%) and F_{v2} (21.2-21.9%) in male and female subjects (51). A significant increase in vertical impulse (15.2-28.7%) was found with all loads (20, 30 and 40%BM), while increases in mediolateral impulses (33.4%) were only significant for loads of 30 and 40%BM during walking for 8 km (99).

Running: It would appear that trunk loading results in a significant linear increase (10%BM = 3.8%; 20%BM = 7.4%; 30%BM = 10%) in F_v during treadmill running (96).

Sprint running: Trunk loading (~11 and ~21%BM) did not significantly change peak F_v during the acceleration phase but peak F_v did increase (8.2%; $p < 0.05$) with ~21%BM loading during the maximum velocity phase while sprint running on a non motorised treadmill (22).

Jumping: Squat jumping with 6.6 and 13.3%BM loads was found to significantly increase (2.9-6.7%) peak forces in sedentary male and females as well as athletes (26), whereas the addition of trunk loading (~11%BM) did not make any significant difference to peak F_v or loading rate for F_v in elite volleyballers during a countermovement volleyball block jump (44). Conversely, Fowler et al. (31) who studied landing mechanics from a drop jump, reported significant increases in peak F_v (5.2%) and loading rates (26.2%) when comparing similar magnitude trunk loading (~11.5%BM) to an unloaded condition.

3.2.3.2 Power production

This section examines the effects of acute trunk loading on power production detailed from two studies.

Sprint running: Only one study assessed the effects of trunk loading (~11 and ~21%BM) during sprint running (22). The main findings were that a significant decrease in peak power output (-14.3%) was found during the maximum velocity phase with ~21%BM loading but no significant changes were found during the acceleration phase. A lighter load (~11%BM) did not statistically change peak power output in either the acceleration or maximum velocity phase.

Jumping: Driss et al. (26) quantified the effects of trunk loading (6.6 and 13.3%BM) on power production during a concentric only squat jump on a force platform in athletes and sedentary individuals. Peak power decreased (~4-5%) with increasing load in sedentary individuals, whereas mean power was significantly greater (1.6%) with a 6.6%BM load in power-trained athletes.

3.2.4 Longitudinal Effects

3.2.4.1 Longitudinal metabolic effects

The longitudinal results of two trunk loading studies (7-9%BM) reported changes to metabolic variables (Table 3). Following a 4 week study (9%BM) with highly trained endurance athletes, Rusko and Bosco (87) found that during submaximal running there was a significant increase in blood lactate concentration level (20.7%) and oxygen uptake (2.7%), while a short running test to exhaustion resulted in an increased blood lactate concentration (9.4%). However, in a 3 week study (7-8%BM) non-significant decreases in blood lactate levels during 35 s of treadmill sprint running (-15%) and during treadmill sprint running to exhaustion (-0.7%) were found in elite sprinters (7).

3.2.4.2 Longitudinal kinematic effects

Seven studies reported longitudinal kinematic effects of trunk loading (Table 3). Longitudinal kinematic changes were quantified for sprint running (n = 3; loads: 7-18.5%BM) and jumping (n = 5 studies; loads: 7-30%BM). One study assessed sprint running and jumping. Subjects varied from physical education students to well trained track and field and team sport athletes.

Sprint running: Three longitudinal studies investigated trunk loading on sprint running performance. Following a three week study (7-8%BM loading) using high level sprinters, a 4.8% ($p > 0.05$) increase in treadmill sprint running time to exhaustion was found (7). Two studies assessed over the ground sprint running with an eight day study (12%BM loading) (4) assessing sprint performance on rugby players over 40 m while a seven week study (18.5%BM loading) (14) assessed lacrosse players over ~25 m. Although no significant differences between the loaded and unloaded conditions were found in either study, sprint time was reduced (-1.2%) following the seven week study, while no change in sprint time was found in the eight day study. A moderate decrease in contact time (-1.5%) and stride length (-2.2%) occurred while greater changes were found in stride rate (3.3%) and flight time (-5.4%) following seven weeks of trunk loaded training (14).

Jumping: Five studies reported the effects of longitudinal trunk loaded training on jump performance.

It would seem that jump performance can be improved with all loads (7-30%BM) for all study durations (3-10 weeks) and for athletes of varied training status and sporting activities (physical education students to high level national sprinters). Significant increases in jumping performance were found in the squat jump (9.5-19.4%) (6, 7, 49, 59); counter movement jump (7.8-12.2%) (49, 59); drop jump (6.5-12.8%) (6, 7); five strides and broad jump (7.5%) (49); 15 s continuous jumping (9.4%) (6); and vertical jump and reach (10.9%) (91).

3.2.4.3 Longitudinal kinetic effects

Only three studies assessed the longitudinal kinetic effects of trunk loading (7-30%BM). All three studies assessed jump performance. Two studies, both using three week duration, reported a significant rightward shift (11%) in the force-velocity curve with loads of 7-11%BM, while mechanical power output in 15 s continuous jumps (5-10%) and drop jumps was significantly greater. A greater load (30%BM) was used for an eight week study resulting in significantly increased power production (11%) in the squat jump and significantly increased power production (3%) in the counter movement jump in physical education students (59).

3.3 Limb Loading

Table 4. Acute limb loaded studies with changes to metabolic, kinematic and kinetic variables (n = 9).

Load %BM	Load placement	Metabolic	Kinematic	Kinetic
0.3	Foot and thigh	Running (TM): Significant increase in VO ₂ max (1.7 and 3.3% thigh and foot) and energy transfer (9.1% foot only). Non-significant increase in HR (0.5 and 1.4%, thigh and foot) (60) Running (TM): Energy transfer and work measure increased (9.1% foot load). No increase in thigh load (61)	Running (TM): Non-significant increase in SL (0.7% foot load), FT (3.2% foot load), and swing time (1.1% foot load) (60)	
0.6	Foot		Sprint running: Significant decrease in velocity (-1.8 and -5.9%) and SF (-1.9 and 2.4%) in AP and MVP. No change in SL (86) Walking: Significant decrease in SL (0.8%) and in hip flexion angle at initial contact (7.8%) (43)	Walking: Significant increase in F _v (6.3%) (43)
0.7	Foot and thigh	Running (TM): Significant increase in VO ₂ max (3.5 and 7.2%, thigh and foot) and energy transfer (19.7% foot only) (60) Non-significant increase in HR (1.3 and 3.4%, thigh and foot) (60) Running (TM): Energy transfer and work measure increased (19.7% foot load). No increases in thigh load (61)	Running (TM): Significant increase in SL (1.2% foot load), FT (6.1% foot load), and swing time (1.3% foot load) (60)	
1.2	Foot		Sprint running: Significant decrease in velocity (-3.7 and 6.3%) and SF (-2.9 and 7%) in AP and MVP. No change in SL (86) Walking: Significant decrease in SL (2.2%), hip flexion angle at initial contact (13.2%), and increase in knee (14.6%) and ankle angle (20%) at initial contact (43)	Walking: Significant increase in F _v (12.4%) (43)
1.8	Foot		Sprint running: Significant decrease in velocity (-1.9 and 3.7%) and SF (-2.1 and 5.2%) in AP and MVP. No change in SL (86)	
2.1	Foot	Boots compared to shoes: Walking: Significant increase in VO ₂		

Load %BM	Load placement	Metabolic	Kinematic	Kinetic
		max (6.3-11.2%, speeds 5.6-10.5 km/h) (46)		
2.2	Foot	Boots compared to shoes: Walking: Significant increase in VO_2 max (5.9-7.9%) Running (TM): Significant increase in VO_2 max (8-10%, speeds 8.9-12.1 km/h) (47)		
5	Thigh and shank		Sprint running (TM): Significant increase in CT (4.3% AP, 4.7% MVP), significant decrease in SPF (-3.6% AP, -3.5% MVP), significant decrease in split times between 15 m and 25 m and the peak velocities achieved (-2.0% AP, -5.3% and MVP). Non-significant change in FT, SPL or the time to cover 2 to 10 m (97)	Sprint running (TM): Significant increase in F_v (4% AP, 4.6% MVP), significant increase in F_v mean (4% AP) (97)
8.5	Foot	Walking: Significant increase in energy cost 41% at 4.0 km/hr, 48.7% at 4.8 km/hr, and 50.8% at 5.6 km/hr (100)		
0.45 kg	Ankle	Running (TM): Non-significant changes: 2.7% increase in HR 4.3% in VO_2 max, 2.7% increase in RER (13)	Running (TM): Non-significant changes: 5.2% decrease in SL, 2.7% decrease in CT, 2.5% decrease in trunk angle (13)	

BM = body mass; TM = treadmill; CT = contact time; FT = flight time; SF = stride frequency; SL = stride length; SPF = step frequency; SPL = step length; AP = acceleration phase; MVP = maximum velocity phase; F_v = vertical ground reaction force; VO_2 max = maximal oxygen consumption; RER = respiratory exchange ratio; HR = heart rate

3.3.1 Acute Metabolic Effects

The acute metabolic effects of limb loading were assessed in six studies (Table 4). Subject (67 males, 10 females) training status reflected mixed sporting backgrounds (sedentary to endurance runners).

3.3.1.1 VO₂ consumption

Lower body loading (0.3-8.5%BM) was found to significantly increase VO₂ values (5-11.2%) during treadmill walking (46, 47, 100) and running (1.7-10.2%) (47, 60). Moreover, greater increases in VO₂ consumption were found with a more distal placement (foot vs. thigh) at the same loads (60, 100). Claremont and Hall (13) who used lighter absolute loads (0.45 kg) reported a 4.3% increase in VO₂ ($p > 0.05$), however a limitation of this study was that the authors failed to detail the subjects' body mass therefore comparison to other studies that have normalised load by %BM is problematic.

3.3.1.2 Energy workload and cost

Significant increases in energy workload (9.1% for 0.3%BM and 19.7% for 0.7%BM) were found for loads attached to the foot during treadmill running but no significant increases were found when the same load was attached to the thigh (60). While significant increases in energy cost (41-50%) were reported during walking with a foot load of 8.5%BM at speeds of 4, 4.8 and 5.6 km/h (100).

3.3.1.3 Heart rate

Non-significant increases for ankle loading (0.45 kg = 2.6%) occurred during 30 min treadmill running (13), while linear increases were found in thigh loading (0.3%BM = 0.5%; 0.7%BM = 1.3%) and foot loading (0.3%BM = 1.4%; 0.7%BM = 3.4%) during eight min treadmill running (60).

3.3.2 Acute Kinematic Effects

Five studies assessed acute changes to kinematic variables with limb loading (Table 4). The reader needs to be aware of how the placement of load differs between studies as highlighted by boots being filled with a load (100); loads being attached to the medial and lateral aspects of the shoes (47, 60, 61); loads strapped above or around the ankle joint (13, 86); loads attached with Velcro to compression garments around the thigh and shank (97); and loads strapped around forearm (43).

3.3.2.1 Step variables

Stride length was significantly decreased with forearm loading (0.6%BM = 0.8%, 1.2%BM = 2.2%) during treadmill walking (43), while Martin (60) found significant increases in stride length (1.2%), swing time (2.1%) and flight time (6.1%) during treadmill running with limb loading of 0.7%BM attached to the foot, though the same load attached on the thigh did not produce any significant changes. Contrastingly, Claremont and Hall (13) found a 5.2% ($p > 0.05$) decrease in stride length in treadmill running (0.45 kg ankle load). Only one sprint running study (5%BM thigh and shank load) was found to significantly increase contact time (4.3 and 4.7%) and significantly decrease step frequency (-3.6 and -3.5%) during both acceleration and maximal velocity phases (97).

3.3.2.2 Velocity and performance

Limb loading appears to significantly decrease maximum velocity sprint running for all loads (0.6-5%BM), however only a significant reduction was found in the acceleration phase with lighter loads (0.6-1.8%BM) (86).

3.3.3 Acute Kinetic Effects

Only two studies reported acute kinetic findings for limb loading (see Table 4). Forearm loading during treadmill walking produced significant increases in F_v (0.6%BM = 6.3%, 1.2%BM = 12.4%) (43). Lower body limb loading with 5%BM during treadmill sprint running resulted in a significant increase in peak F_v (4% acceleration and 4.6% maximum velocity phases) and a significant increase in mean F_v (4% acceleration phase only) compared to baseline (97).

4 Discussion

4.1 Trunk Loading

Twenty-five studies assessed the effects of WRT trunk loading with three acute acyclic studies, fourteen acute cyclic studies and eight longitudinal cyclic studies.

4.1.1 Walking

Trunk loading results in significant increases in VO_2 consumption (6-17%), heart rate (6.9-7.7%), exercise intensity (3.9-10.8%), F_v (5.5-21.9%) and rate of loading (5.3-14.6%), but only when loads of >10%BM are used. Although VO_2 consumption increases occurred with a 10 to 15%BM load increase, increases of a greater magnitude were reported when the load was increased from 15 to 20%BM. The similar amount of increase in heart rate, despite the increase in loading, may be explained by the reduction in walking velocity resulting in minimising of energy expenditure (98). The minimum threshold load and pace required to elicit significant changes in heart rate have yet to be determined as the loads studied to this point in time have been $\geq 10\%$ BM and at walking pace. Trunk loading across loads (20-40%BM) overloads the knee musculature to a greater effect compared to the ankle, as significant changes were found in the knee angle at initial contact but no significant changes were found at the ankle angle (99). These findings were confirmed by Seay et al. (94) when trunk loading at ~17%BM, the postural adjustments were mainly observed in the knee (8%) compared

to hip (4.8%) and ankle (6%) range of motion changes. However, when they used a greater load (~65%BM) greater mechanical adaptations were found in the ankle joint (26.3%), compared to the knee (12%) and hip (15%) joints (94). It seems that loads of 40%BM or less require greater changes in the musculature around the knee joint, whereas when loading is increased to ~65%BM, greater changes are required at the ankle. However, loading between 40-65%BM is yet to be investigated, while the difference in walking (treadmill vs. over the ground) and speeds between studies needs to be considered when comparing findings.

4.1.2 Running

Acute trunk loading (5-30%BM) was found to significantly increase stride frequency (1.6-4.5%), contact time (4-7%), F_v (3.8-10%) and vertical stiffness (2.8-20.5%) during running speeds. Despite similar results in F_v (3.8%) and vertical stiffness (2.8%) during running with 10%BM, when the load was increased > 20%BM, vertical stiffness (12.5 to 20.5%) increased more than F_v (7.4 to 10.8%) (96). The authors proposed that vertical stiffness increased more than F_v due to the decreased stance phase leg compression. One study assessed over the ground running during a 12 min run for maximal distance with trunk loading (5, 10 and 15%BM). The magnitude of the effect of external loading was a significant decrease in the distance covered (-4 to -8.6%). The run distance completed was decreased by an average of 89 m for every 5%BM increase in external loading (23). During incremental treadmill maximum running, Cureton (23) noted that the external load decreased running time (-4.4 to -10.9%) due to the greater energy demands of running at submaximal speeds causing VO_2 max to be reached at lower speeds. Slider (96) suggested that running with an external load may cause individuals to adopt a running strategy that increases metabolic cost to reduce F_v , however further research investigating such contentions is needed.

Following a 4 week study (9%BM), a significant increase in blood lactate (20.7%) and oxygen uptake (2.7%) occurred in submaximal running, and a significant decrease in 2 mmol lactate threshold in running to exhaustion (9.4%) (87). Moreover, greater changes were found in the subjects who used

the added load during every training session compared to the subjects who used the load every other training session (87). Only one longitudinal study into running has been completed, therefore, the chronic effects of trunk loading during running remain largely unexplored.

4.1.3 Sprint Running

Acute loads of < 9%BM for the most part have small non-significant effects on peak velocity and sprint times. However, as load increased > 9%BM the decrement in speed performance was fairly linear (-3.6 to -11.7%; $p < 0.05$) during over the ground sprinting. Interestingly the decrement in sprint performance seems less when non-motorised treadmills are utilised. In short, the effect of the additional mass of vest loading is countered by a significantly reduced flight and hence the F_v and peak power are reduced or remain relatively the same until relatively heavy vest (>20%BM) loads are used. It would seem that contact and flight times are more sensitive to any loading as opposed to step frequency and step length. A great deal more research is needed to validate such a contention.

Although trunk loading did not significantly change peak F_v during the acceleration phase, ~21%BM loading did significantly increase peak F_v (8.2%) during the maximum velocity (22). A lighter load (5%BM) was used during sprint running by Simperingham and Cronin (97) who found that there was a significant reduction in relative peak F_v (-5.4 and -6.4%) and mean F_v (-3.8 and -4%) during both acceleration and maximum velocity phases. It would seem that heavier loads (> 11%BM) are needed to overload F_v during sprint running. This would seem counter intuitive, given that any additional mass will affect the standing F_v and logically running F_v . However, as with the jumps it seems that the absence of any change ($p < 0.05$) in F_v is most likely explained by the reduced rise and fall of the centre of mass or reduced flight time during the swing/airborne phase. Given that the landing F_v is influenced by acceleration due to gravity, any reduction in flight time will reduce the influence of the acceleration of the body downward, which in turn naturally affects the F_v . In short the effect of the additional mass of vest loading is countered by a reduced flight and hence the F_v is reduced or remain relatively the same until relatively heavy vest loads (> 11%BM) are used.

It appears that only a small improvement in sprint running time is found following longitudinal studies. Bosco et al. (7) proposed that the three week period was not enough time to induce significant changes in the mechanical properties of the leg musculature while further suggesting that as the athletes used were already at a high level and close to their peak performance pre-study, there was less possibility of creating an improvement in performance. Furthermore, although no significant differences between the loaded and unloaded conditions were found in two other longitudinal studies; sprint time was reduced (-1.2%) following the seven week study (14), while no change in sprint time was found in the eight day study (4). The reduction in sprint time may have resulted from a moderate decrease in contact time (-1.5%) and stride length (-2.2%) coupled with greater changes to stride rate (3.3%) and flight time (14). The authors suggested that following training with the trunk load, the subjects may have altered the vertical velocity of their center of mass at take-off leading to a reduction in stride length (14, 31). Vertical velocity at take-off has a positive correlation with stride length and flight time and a negative correlation with stride rate (41). However, Clark et al. (14) also found that after effect size comparisons the unloaded condition resulted in a greater reduction in sprint time and greater increase in average velocity compared to the loaded condition, therefore questioning the effectiveness of longitudinal trunk loading. Such findings are supported by the acute findings detailed earlier in this review with the caveats being: 1) uncertainty of vest loading effects on shorter distances (< 20 m) i.e. acceleration; 2) the effect of heavier loading, which may be needed to counteract the reduction in flight time and the reduced effects of the acceleration due to gravity; and, 3) the need for longer duration training studies. Due to limited research and the discrepancy between the studies (load and study duration), it would seem a great deal more research is needed to assess the effects of longitudinal trunk loading on sprint running.

4.1.4 Jumping

The effects of acute trunk loading appear to be influenced by the training status of subjects and the type of vertical jump measured. Driss (26) found that the effect of external loading on power output was decreased with increasing load in sedentary individuals, whereas mean power was significantly greater in power-trained athletes. Moreover, peak power did not vary significantly in the two load

conditions (6.6 and 13.3%BM) in power-trained athletes. Given that the force capability of these groups statistically increased with loading, it would seem that the concentric velocity capability of athletes remains relatively unaffected with vest loading less than 14%BM as compared to sedentary individuals.

Differences in F_v were found between studies that used different types of vertical jump. Squat jumping with 6.6 and 13.3%BM loads was found to significantly increase (2.9-6.7%) peak forces in sedentary male and females as well as athletes (26), whereas the addition of trunk loading (~11%BM) did not make any significant difference to peak F_v or loading rate for F_v in elite volleyballers during a countermovement volleyball block jump (44). Conversely, Fowler et al. (31) who studied landing mechanics from a drop jump, reported significant increases in peak F_v (5.2%) and loading rates (26.2%) when comparing similar magnitude trunk loading (~11.5%BM) to an unloaded condition. The difference between the findings of these two studies could be explained by the relatively untrained subjects using a drop jump protocol in the study of Fowler et al. (31). However, the most likely explanation is that the loading in the Janssen et al. (44) study resulted in a significant reduction in jump height (6 cm), which in turn affected the magnitude of the landing forces. That is, the decrease in jump height negated the effects of the additional loading on the F_v . The effect of the additional mass of vest loading is countered by a reduced jump height similar to the sprint changes noted previously and hence the F_v and stiffness remain relatively the same. The Fowler et al. (31) study however, standardised the drop jump height (26 cm) for all conditions so any additional load would result in greater F_v unless landing technique was altered in some manner.

Following longitudinal studies (ranging from 3-10 weeks), it would seem that jump performance can be improved with all loads (7-30%BM) and with different types of jumping, though trunk loading > 12%BM may not enhance jump height performance more than loads of 8-12%BM. The improvement in jump height performance may relate to the significant rightward shift in the force-velocity curve and the significant increase in mechanical power output. Moreover, Markovic et al. (59) explained the increased jump performance may be related to changes in the counter movement jump pattern as observed by an increased depth of jump, increased jump duration and reduced ground reaction forces.

However, the experience of subjects (basketball players vs. students) is a factor to consider when interpreting the findings. Future research into jump loading could evaluate kinematics in different planes as Janssen et al. (44) noted that frontal plane moments may be implicated with increased injury risk.

4.2 Limb Loading

Nine cyclic studies with 118 subjects assessed the effects of WRT limb loading on walking, running and sprint running. Greater metabolic effects were found when loading was attached to a more distal than proximal limb position, possibly due to the greater inertia associated with such loading (i.e. $\text{inertia} = \text{mass} \times \text{perpendicular distance from the axis of rotation}^2$).

4.2.1 Walking

All loads (0.3-8.5%BM) significantly increased VO_2 consumption (5-10.2%), energy workload (9.1-19.7%) and energy cost (41-50.8%), with greater increases occurring in more distal (foot) placement compared to proximal (thigh) loading during walking. The greater increase in energy cost (41-50.8%) found by Soule and Goodman (100) may have resulted from the greater load used (8.5%BM) compared to the much lighter loads used in the other walking studies (0.3-2%BM). Moreover, the authors noted that the attachment of the load affected the normal flexion and extension of the ankle. This restriction in ankle motion altered gait biomechanics, possibly adding to the much greater VO_2 consumption, increasing energy cost. Jones et al. (47) noted that for an increment of weight equal to 1.4%BM attached to the foot the average energy cost increased 8% or 5.7 times, while Soule and Goldman (100) proposed an equivalent load carried on the foot as opposed to the hand increased energy expenditure 4.7-6.3 times depending on the speed of ambulation.

4.2.2. Running

Significant increases in VO_2 consumption (1.7-7.2%) were found with all loads (0.3-0.7%BM) during treadmill running at a constant pace. It appears that limb loading results in contrasting findings in step

variables from the studies reviewed. Martin (60) found significant increases in stride length with foot loading but no changes with thigh loading, while Claremont and Hall (13) found a non-significant decrease in stride length with ankle loading. The changes found with foot loading which were not found with the thigh loading may have occurred due to the greater moment of inertia at the hip joint (2% increase thigh, 13% increase foot) (60). Furthermore, Claremont and Hall (13) noted that the ankle attachment placement may have affected ankle joint range of motion as subjects reported ankle tightness with the loading. It would appear that limb loading has little effect on heart rate. As only two studies have investigated the effects of limb loading on heart rate the threshold values for lower limb loading that induce significant HR changes are for the most part unknown. In summary, it would appear that distal limb loading results in significant changes in VO_2 consumption, stride length, swing time and flight time, while proximal loading results in no significant changes during running.

4.2.3 Sprint Running

Limb loading significantly decreases maximum velocity sprint running for all loads (0.6-5%BM); however only a significant reduction was found in the acceleration phase with lighter loads (0.6-1.8%BM). Similarly, mean F_v was only significantly increased during the acceleration phase while peak F_v was significantly increased during both acceleration and maximum velocity phases. Only one load was tested during sprint running, therefore it is unknown how differing loads would result in changes to kinetic findings while over the ground sprint running has yet to be investigated in limb loading. Step length was unaffected by limb loading while step and stride frequency were significantly reduced. Of note, from the two studies reviewed, the position of the load and the method of sprint running differed between studies (< 2%BM foot loading: over the ground (86); 5%BM thigh and shank loading: non- motorised treadmill (97)), possibly affecting the comparison.

4.3 Future Research

Future research is required to more fully understand the acute and longitudinal effects of WRT during different sporting activities. It is recommended that future research investigate the metabolic costs at speeds greater than 14 km/h, using over the ground running and sprint running or high intensity intermittent type activity as an alternative to treadmill based testing. Such research would provide better insight into the utility of WRT for the metabolic conditioning of sports men and women. Differences in velocity were found in sprint running between treadmill and over the ground locomotion. Therefore, future research should consider these findings with expected changes, due to inertia, regarding velocity, stride parameters and energy cost in over the ground sprint running.

The sporting backgrounds and technical proficiency of the study participants can influence both the acute kinematic and kinetic changes during WRT interventions. This was particularly evident during the acute jump studies when highly trained subjects were compared to recreationally active or sedentary subjects. Therefore, the effects of future WRT interventions may be different with athletes with less or more training and/or sporting experience. Moreover, athletes with different levels of experience and skills may require modified loading magnitudes (i.e. more or less or more %BM) to enable positive technique changes.

WRT with loads of $< 6.6\%BM$ have yet to be investigated in acyclic studies and therefore the effects of lighter loads should be considered for future research. Differences between propulsive forces and landing forces also warrant further investigation as landing force changes seem to be dependent on the jump height/flight time whereas propulsive force changes appear to be dependent on the subject's training status. Moreover, loads $> 12\%BM$ and $< 30\%BM$ have yet to be investigated in trunk loaded jump studies, while no studies have investigated the acute or longitudinal effects of limb loading on jump performance.

To date, no research has quantified the effects of limb loading during acyclic exercise, therefore, future research could investigate the acute and longitudinal effects of WRT during jumping and throwing movements. In addition, although several acute cyclic studies have been completed, the

longitudinal effects of limb loading during cyclic exercise have yet to be investigated and should be considered a potential area of research. While several previous WRT studies have been completed with weighted vests (Figure 2), future WRT research may use full body suits (Figure 3) to investigate the difference between limb load placement positions such as proximal vs. distal; medial vs. lateral; and anterior vs. posterior; as research is lacking in these areas.



Figure 2. Trunk loaded vest.



Figure 3. Trunk and limb loaded exoskeleton suit.

5 Conclusions

The heterogeneity of the included studies (load, subjects, and study duration) warrants caution when interpreting the findings of this review and their application in practice. The magnitude of load and load placement varied considerably in studies as did subject populations meaning that quantification of findings has yet to clearly establish the optimum load stimuli for training application. Pooling of data was not possible and the state of evidence precludes clear conclusions being finalised.

While several limitations and gaps in the research exist around WRT, some general comments can be made from this review. WRT with trunk loading results in a significant reduction in velocity during treadmill sprint running (but only with loads > 11%BM) and in over the ground sprint running times with all loads of 8-20%BM. It would seem that contact and flight times have greater sensitivity to any loading as opposed to step and stride frequency and step and stride length. The reduction in flight time, which reduces the influence of the acceleration of the body downward, resulted in the F_v and power production being reduced or remaining relatively the same until a relatively heavy trunk load (> 20%BM) was used. Longitudinal trunk loading has yet to result in any significant improvement in sprint running performance. However, only three studies have been completed, with contrasting loads, duration and measurements, meaning specific adaptations from WRT are yet to be confirmed or excluded. In contrast, longitudinal trunk loading appears to enhance all forms of jumping with improvements found over a range of loads (7-30%BM) and durations (3-10 weeks). It would seem that trunk loading > 12%BM may not enhance jumping height performance more than loads of 8-12%BM.

The longitudinal effects of WRT with limb loading have yet to be investigated, however acute adaptations have indicated that VO_2 consumption and energy cost are significantly increased with all loads (0.3-8.5%BM) in walking and running, while significant reductions in velocity occurred during sprint running. Moreover, greater effects were found with a more distal placement (foot vs. thigh) in all studies. Consideration should be given to the limitations relating to the differing of load placement positions between and within studies, as Martin (60) noted due to anthropometric characteristics, the position of the thigh load varied from 59 to 80% of thigh length. Moreover, the attachment of WRT

needs careful planning due to its possible unintended impact on joint excursion. This is highlighted by Soule and Goodman (100) who noted an immobilisation of the ankle joint due to the loading method for boots which prevented the normal flexion-extension of the ankle. While Claremont and Hall (13) advised that weighted bands strapped to an ankle restricted the ankle joint's range of motion, with subjects noting restricted tightness and discomfort. Consequently, a greater energy cost might have resulted due to the loading method rather than the load itself.

WRT has yet to significantly improve sprint running performance, however, it has been shown to improve jump performance through trunk loading. WRT provides a novel training method with potential to improve cyclic and acyclic sporting actions, however, research in this area is still clearly in its infancy with future research required into the optimum load placement, orientation and magnitude necessary for adaptation.

CHAPTER 3: ACUTE KINEMATIC AND KINETIC ADAPTATIONS TO WEARABLE RESISTANCE DURING VERTICAL JUMPING

(Submitted to the European Journal of Sport Science)

Abstract

The vertical jump (VJ) is a fundamental movement in many team sport events and as such the VJ and its variations are used in many athlete monitoring and training programs. One variation of VJ training is resisted or weighted jump training, where wearable resistance (WR) enables jumping to be overloaded in a movement specific manner. The purpose of this study was to determine the acute kinematic and kinetic changes in VJ performance with differing load magnitudes and load placements. Twenty athletic subjects (age: 27.8 ± 3.8 years; body mass (BM): 70.2 ± 12.2 kg; height: 174.4 ± 7.8 cm) volunteered to participate in the study. Subjects performed the counter movement jump (CMJ), drop jump (DJ) and pogo jump (PJ) in a randomised fashion wearing no resistance, 3 or 6 %BM affixed to the upper or lower body (three jumps per condition). A force plate and contact mat were used to measure the variables of interest. The main finding in terms of the landing phase was that the effect of WR was non-significant. However, landing relative vertical ground reaction force (F_v) tended to be higher with the same magnitude of lower WR compared to upper WR. With regards to the propulsive phase the main findings were that: 1) for both the CMJ and DJ, WR resulted in a significant decrease in jump height (CMJ: -12 to -17%, DJ: -10 to -14%), relative peak power (CMJ: -8 to -17%, DJ: -7 to -10%) and peak velocity (CMJ: -4 to -7%, DJ: -3 to -8%); 2) there was no significant effect of load placement; and, 3) PJ reactive strength index was significantly reduced (-15 to -21%) with all WR conditions. Consideration should be given to the inclusion of WR in sports where VJ's are important components as it may provide a novel training stimulus resulting in positive adaptations in metrics such as power and stiffness.

KEY WORDS wearable loading, limb loading, jump performance, specificity of training

Introduction

The vertical jump (VJ) is a fundamental movement in many team and individual athlete monitoring and training programs (49, 59, 103). VJ performance is affected by the intricate relationship among several factors, such as maximum force production, the rate of force development, and the neuromuscular coordination between the upper body and lower body segments (65). Several training methods have previously been used to optimise VJ performance, including resistance training, plyometric training and resisted modalities such as machine or free weight loading and weighted vest loading (4, 40, 49, 58, 59, 79). A popular training form of the VJ is resisted or weighted jumps, which are used for developing muscular power based on the contention that weighted ballistic movements can be complementary to unloaded jumps and traditional resistance exercises (103). In accordance with the overload training principle, resisted jumps emphasise rapid force production by overcoming an increased load (26, 44). Researchers have suggested that a combination of both light loads, for enhancing the rate of force production, and heavy loads, for enhancing strength, are necessary to optimise the overall power production of an athlete (1, 24, 29).

Previous resisted jump studies have included barbells positioned across the back of the shoulders (4, 8, 79); elastic resistance such as Vertimax (64, 85); hand held weights (18, 95); and wearable resistance (WR) trunk loaded vests (44, 49, 59). The focus of this paper was on the effect of WR on VJ kinematics and kinetics. Previously the acute adaptations associated with this type of loading have been investigated in three studies (trunk loading 6.6-13.3% body mass (BM)). In terms of eccentric force and landing mechanics, a significant increase in vertical ground reaction force (F_v) (5.2%) and loading rate (26.2%) was found during the drop jump (DJ) in physically active subjects with 11.5%BM loading (31). A limitation of the study was that force data was only reported from the initial drop landing and not the second landing. Researchers studying the effect of WR on the propulsive phase of the jump has mainly documented the change in jump height and concentric F_v (26, 44). Janssen (44) reported a significant decrease in volleyball block counter movement jump (CMJ) height (10.6%) but no significant change was reported in F_v with 11.4%BM loading in elite volleyball players. Conversely a significant increase was found in F_v (2.6-4.1 and 5.9-6.7%) during

the squat jump in sedentary and athletic populations with 6.6 and 13.3%BM loading (26). Differences in findings from these studies may relate to the variation in subjects' training backgrounds and/or the different jumps used.

A consideration for resisted jumping is the placement of the external loading in relation to the center of mass. For example, when an external load is placed on the shoulders it may alter the hip, knee and ankle articulation angles before and during jumping thus affecting motor pattern and power output (26). Swinton (103) found that when a load was moved from the shoulder to arms length, meaning the load is closer to the body's center of mass, athletes were able to significantly increase jump height and generate more force, power, velocity and rate of force development. Consequently, consideration of external loading placement is warranted due to its potential influence on force production capability, jumping and landing technique. Furthermore, due to the demands of the VJ, which overloads muscles and joints, the amount of external loading plays an essential role in training.

To date, no studies have assessed the effects of trunk loading with loads less than 6%BM, moreover no research has investigated the effects of WR attached to the lower body during jumping. It is quite possible that loading the lower as opposed to the upper body with the same relative load will provide differential adaptations. This was certainly the case in a research quantifying the effects of WR on sprint running, where it was noted that lower body WR (0.6-5% BM) produced significantly decreased stride frequency (-1.9 to -2.4%) (86), acceleration (-1.8 to -3.7%) (86), maximum velocity (-2.3 to -6.3%) (86) (97), and step frequency (-2.9%) (97), as compared to the same upper body load. Given these findings and the paucity of literature in this area of research, the purpose of this study was to compare the acute kinematic and kinetic effects of upper and lower body loading equivalent to 3-6%BM on jump performance.

Methods

Experimental Approach to the Problem

A cross-sectional design was used to investigate the effects on kinematic and kinetic variables when WR equivalent to 3-6%BM was attached to either the upper body or lower body during CMJ, DJ and the PJ. Subjects performed maximum effort jumps with and without WR attached to either their trunk (upper wearable resistance: UWR) or legs (lower wearable resistance: LWR). The five testing conditions were the unloaded (UL) control condition, 3%BM UWR, 3%BM LWR, 6%BM UWR and 6%BM LWR. Data for each condition were compared to one another using repeated measures analysis of variance (ANOVA) with Bonferroni post hoc comparisons used to determine statistical difference between load and placement.

Subjects

Twenty (10 males, 10 females) sport active subjects (age: 27.8 ± 3.8 years; BM: 70.2 ± 12.2 kg; height: 174.4 ± 7.8 cm) volunteered to participate in the study. Subjects were informed of the protocol and procedures prior to their involvement, and written consent to participate was obtained. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study.

Procedures

Subjects reported for two testing sessions, each session including UWR or LWR (randomised across subjects). Each session was performed at approximately the same time of the day and the sessions were 3-7 days apart. Before performing the VJ tests, subjects completed a warm-up consisting of five min of self-paced cycling followed by five min of prescribed dynamic stretching and finally five min of prescribed jump drills. Average data from the three repetitions were used for analysis. Subjects performed identical sets of three CMJ, three DJ, two sets of five PJ; UL for set one with the next two sets using either 3 or 6%BM loading (Figure 4). Subjects had a 30-second gap between reps and 4-min rest between jump types.

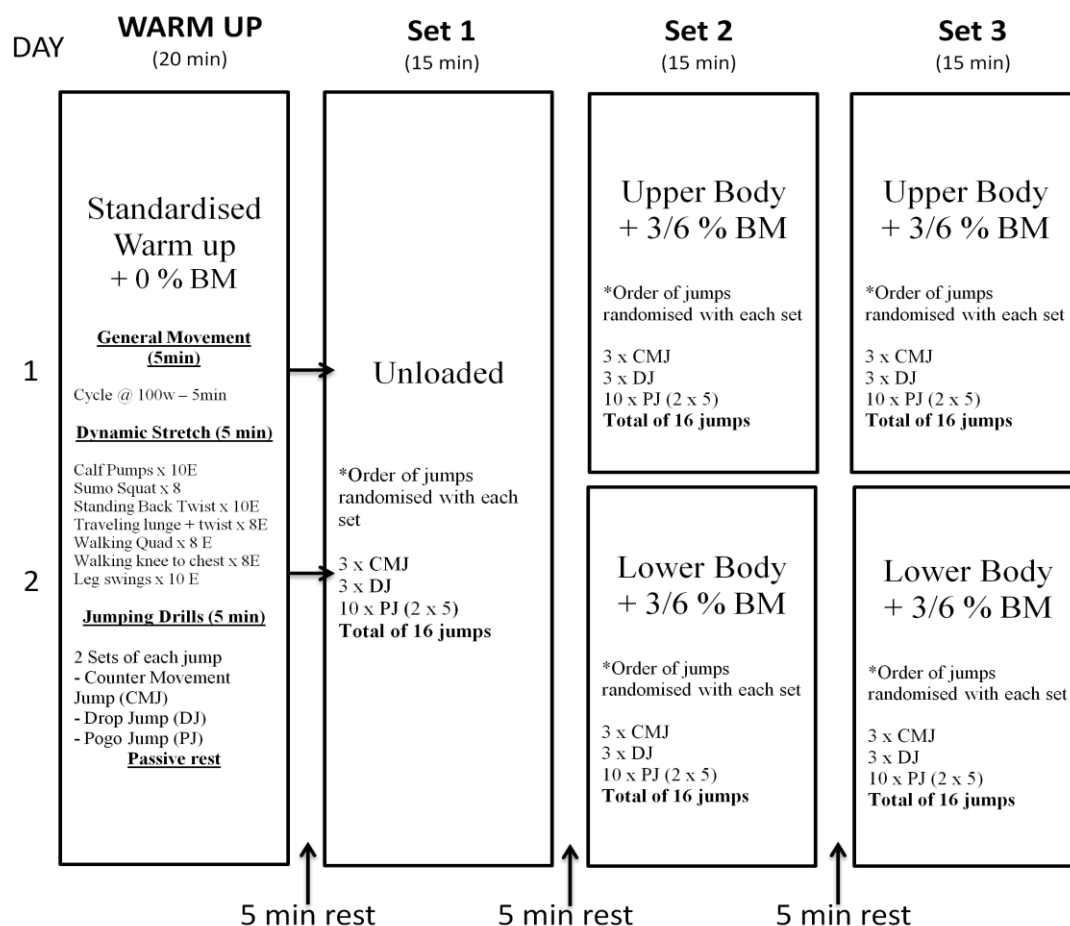


Figure 4. Flow chart detailing the vertical jump procedures.

Equipment

The CMJ and DJ were performed on a portable Fitness Technology 400 series force platform. F_v data were sampled at 600 Hz. Peak F_v was defined as the highest value attained. To specifically analyse lower body power and eliminate differences in jump technique, arm action used during VJ testing was eliminated. The elimination of arm action during jumping may allow the athlete to concentrate on leg and hip explosiveness and minimise jumping technique differences (81, 92). Once positioned on the force plate, subjects began the CMJ in the standing position, dropped into the squat position, and then immediately jumped vertically. The depth of knee flexion used during each CMJ was determined by each subject. The DJ was performed by stepping forward off a 45 cm box on to the force platform, landing in a bilateral stance followed immediately by a VJ. Subjects were instructed to minimise contact time and maximise jump height. Two F_v values were recorded.

The first from the initial landing and propulsion, following the box step-off, and the second from the landing following the VJ. The time in the air (TIA) method (69) was used to calculate jump height. TIA was identified as the duration between take-off and landing contact. From the TIA, the vertical displacement of the centre of mass was calculated using the following equation of uniform acceleration:

$$\text{TIA jump height} = \frac{1}{2} g(t/2)^2$$

where $g = 9.81 \text{ m/s}^2$, $t = \text{time in air}$.

PJ's were performed on a contact mat (Swift Performance, New South Wales, Australia) with arms akimbo. Subjects performed five consecutive jumps with each condition and were instructed to minimise contact time and maximise jump height while keeping their legs straight. Reactive Strength Index (RSI) was calculated from the following formula (30, 102) :

$$\text{RSI} = \text{jump height} / \text{contact time}$$

Wearable resistance: Subjects wore Lila™ Exogen™ exoskeleton suits (Sportboleh Sdh Bhd, Malaysia) including tops, shorts and lower leg sleeves, for the duration of the testing session (Figure 5). The Exogen™ exoskeleton suit enables fusiform shaped loads (with Velcro backing) of 100 gm and 200 gm to be attached in numerous configurations. WR of 3 or 6%BM was attached to either the upper body (anterior and posterior surfaces of the trunk) or lower body (2/3 of the load placed evenly around the thigh and the remaining 1/3 on the shank of the leg, anterior and posterior surfaces).



Figure 5. Lila™ Exogen™ exoskeleton suits with upper body and lower body loading.

Statistical Analyses

Standard descriptive statistics (means and standard deviations) were reported for all statistical comparisons. Normal distribution of the data was checked using the Shapiro-Wilk statistic. Statistical differences in kinematic and kinetic variables across the loaded and unloaded conditions were assessed using repeated measures ANOVA with Bonferroni post hoc comparisons. Statistical significance was set at an alpha level of $p \leq 0.05$. Effect size (ES) (reported using Cohens d (15)) were described as trivial (<0.20), small ($0.20-0.59$), moderate ($0.60-1.19$) and large (> 1.2).

Cohen's d was determined by calculating the mean difference between groups, and then dividing the result by the *pooled* standard deviation (15):

$$\text{Cohen's } d = (M_2 - M_1) / SD_{\text{pooled}}$$

$$\text{where: } SD_{\text{pooled}} = \sqrt{((SD_1^2 + SD_2^2) / 2)}$$

Results

Counter movement jump

CMJ height was significantly reduced in all WR conditions (UWR: -11.9 and -13.7%, ES: -0.55 and -0.63; LWR: -12.5 and -16.9%, ES: -0.58 and -0.78) as compared to the UL condition (Table 5). No between load differences ($p \leq 0.05$) in jump height were observed. With regards to the propulsive phase variables, relative peak F_v (ES: -0.25 to -0.47) was statistically unchanged across all WR conditions. However, relative peak power was significantly decreased with all WR conditions (UWR: -8 and -14.9%, ES: -0.39 and -0.66; LWR: -14.9 and -17%, ES: -0.66 and -0.74) as compared to the UL condition. A significant decrease across all WR conditions was found in peak velocity (UWR: -4.3 and -6.6%, ES: -0.40 and -0.63; LWR: -4.6 and 6.2% ES: -0.44 and -0.61) compared to the UL condition. No significant changes occurred in total impulse during propulsion (ES: -0.05 to -0.41). In terms of landing, the effect of the additional load and orientation of the load was non-significant - relative F_v (ES: -0.11 to -0.27) as compared to the UL condition.

Drop jump

With regards to propulsive mechanics, a significant decrease ($p \leq 0.05$) in jump height was found with all WR conditions compared to the UL condition during the DJ (UWR: -10.3 and -12%, ES: -0.54 and -0.64; LWR: -10 and -14%, ES: -0.43 and -0.62) (Table 6). No between load differences ($p \leq 0.05$) in DJ height were observed. Relative peak power was significantly decreased with all WR conditions (UWR: -7.4 to -9.3%, ES: -0.33 and -0.57; LWR: -6.4 to -9.6%, ES: -0.42 and -0.45). Significant reductions in peak velocity were observed in all WR conditions (UWR: -3.0 and -7.1%, ES: -0.29 and -0.66; LWR: -3.4 and 8.0%, ES: -0.34 and -0.77) compared to the UL condition. No significant

changes occurred in total impulse during propulsion (ES: -0.09 to -0.33). In terms of landing mechanics, no significant changes were observed in relative peak F_v with any WR condition during the initial landing (ES: -0.15 to 0.32) or the second landing (ES: -0.21 to -0.42).

Pogo jumping

A significant increase in contact time (UWR: 7.9 to 8.6%, ES: 0.86 and 0.87; LWR: 8.6 to 9.7%, ES: 0.91 and 0.95) was found between all WR conditions and the UL condition during the PJ (Table 7). The only significant difference in flight time was found with 6%BM loading (UWR: -8.2%; LWR: -7.7%, ES: -0.63 and -0.73); however, WR significantly decreased RSI in all WR conditions (UWR: -16.9 to -21%, ES: -0.94 and -0.99; LWR: -17.2 to -21.4% ES: -1.13 and -1.23) compared to the UL condition. No between load differences ($p \leq 0.05$) in any of the PJ variables was observed.

Table 5. Kinematic and kinetic variables during the counter movement jump for all loading conditions. Means \pm SD.

	UL	3%BM UWR	3%BM LWR	6%BM UWR	6%BM LWR
Jump height (cm)	32.0 \pm 7.6	28.2 \pm 5.9 *	28.0 \pm 6.0 *	27.6 \pm 6.4 *	26.6 \pm 6.1 *
Relative peak F _v (N/kg)	22.7 \pm 3.1	21.1 \pm 5.1	21.1 \pm 4.5	21.2 \pm 3.6	21.8 \pm 3.8
Relative peak power (W/kg)	44.2 \pm 8.6	40.7 \pm 9.2 *	37.8 \pm 10.5 *	37.6 \pm 11.2 *	36.7 \pm 11.3 *
Peak velocity (m/s)	2.61 \pm 0.27	2.50 \pm 0.28 *	2.49 \pm 0.27 *	2.44 \pm 0.27 *	2.45 \pm 0.25 *
Relative propulsion impulse (Ns/kg)	11.1 \pm 1.17	10.9 \pm 1.77	10.6 \pm 1.17	10.8 \pm 1.22	10.6 \pm 1.22
Relative landing peak F _v (N/kg)	54.5 \pm 15.7	51.7 \pm 15.7	52.7 \pm 16.2	49.6 \pm 19.5	51.9 \pm 17.1

* Significantly different from unloaded condition (UL)

BM = body mass; 3%BM UWR = 3% body mass upper body wearable resistance; 3%BM LWR = 3% body mass lower body wearable resistance; 6%BM UWR = 6% body mass upper body wearable resistance; 6%BM LWR = 6% body mass lower body wearable resistance; F_v = peak vertical ground reaction force

Table 6. Kinematic and kinetic variables during the drop jump for all loading conditions. Means \pm SD.

	UL	3%BM UWR	3%BM LWR	6%BM UWR	6%BM LWR
Jump height (cm)	30.1 \pm 6.8	27.0 \pm 4.4 *	27.1 \pm 7.0 *	26.5 \pm 4.2 *	25.9 \pm 6.7 *
Relative 1 st landing peak F _v (N/kg)	47.1 \pm 8.0	45.9 \pm 7.3	50.4 \pm 12.3	45.8 \pm 8.1	49.1 \pm 11.4
Relative peak power (W/kg)	54.2 \pm 10.9	50.7 \pm 10.3 *	50.2 \pm 7.6 *	49.2 \pm 5.8 *	49.0 \pm 11.9 *
Peak velocity (m/s)	2.87 \pm 0.31	2.78 \pm 0.31*	2.76 \pm 0.34*	2.66 \pm 0.33*	2.64 \pm 0.29*
Relative propulsion impulse (Ns/kg)	9.45 \pm 1.12	9.35 \pm 1.14	9.08 \pm 1.11	9.26 \pm 1.32	9.16 \pm 1.00
Relative 2 nd landing peak F _v (N/kg)	54.5 \pm 15.1	51.3 \pm 15.5	52.5 \pm 14.3	48.5 \pm 12.8	51.4 \pm 13.5

* Significantly different from unloaded condition (UL)

BM = body mass; 3%BM UWR = 3% body mass upper body wearable resistance; 3%BM LWR = 3% body mass lower body wearable resistance; 6%BM UWR = 6% body mass upper body wearable resistance; 6%BM LWR = 6% body mass lower body wearable resistance; F_v = peak vertical ground reaction force

Table 7. Kinematic variables during pogo jumping for all loading conditions. Means \pm SD.

	UL	3 % BM UWR	3 % BM LWR	6 % BM UWR	6 % BM LWR
Contact time (s)	0.187 \pm 0.016	0.203 \pm 0.021*	0.204 \pm 0.021*	0.204 \pm 0.023*	0.207 \pm 0.025*
Flight time (s)	0.366 \pm 0.038	0.345 \pm 0.051	0.348 \pm 0.037	0.336 \pm 0.055*	0.338 \pm 0.038*
Reactive Strength Index	90.7 \pm 19.5	75.4 \pm 16.5*	75.1 \pm 11.2*	72.5 \pm 17.3 *	71.3 \pm 10.6 *

* Significantly different from unloaded condition (UL)

BM = body mass; 3 %BM UWR = 3% body mass upper body wearable resistance; 3%BM LWR = 3% body mass lower body wearable resistance; 6%BM UWR = 6% body mass upper body wearable resistance; 6%BM LWR = 6% body mass lower body wearable resistance

Discussion

This is the first study to compare the acute kinematic and kinetic effects of upper and lower body loading during vertical jumping. The main finding in terms of landing mechanics was that the effect of the additional load and orientation of the load on CMJ and DJ relative F_v was non-significant. Landing relative F_v tended to be higher with the same magnitude of LWR compared to UWR, however, the differences in the 3 to 6%BM load placement was statistically non-significant. With regards to the propulsive phase the main findings were that: 1) for both the CMJ and DJ, light loading of only 3-6%BM resulted in a significant decrease in jump height (CMJ: -12 to -17%, DJ: -10 to -14 %), relative peak power (CMJ: -8 to -17%, DJ: -7 to -10 %) and peak velocity (CMJ: -4 to -7%, DJ: -3 to -8%); 2) there was no significant effect of load placement; and, 3) PJ RSI, which is indicative of lower body stiffness, was significantly reduced (-15 to 21%) with all WR conditions.

Landing forces are typically associated with injury as they tend to be larger than the propulsive forces (27, 63, 80). This indeed is the case in this research with the landing forces for the CMJ 2.3-2.4 times greater than the propulsive forces. It would be intuitive to assume that with additional loading that landing forces would significantly increase. However, this was not the case; in fact the additional loading reduced the landing forces in most cases. This is most likely explained by the significant decrease in jump height, found during the loaded CMJ and DJ conditions. Given that the landing F_v is influenced by acceleration due to gravity, any reduction in jump height/flight time, would reduce the influence of the acceleration of the body downward, which in turn affects the F_v . Differences, ($p > 0.05$) in CMJ landing relative F_v were found between upper and lower WR conditions with a greater decrease in UWR landing F_v (up to -9%) than LWR landing F_v (up to -4.8%). Similar findings in relative F_v occurred during the second DJ landing with a greater decrease in UWR (up to -11.1%) than LWR landing F_v (up to -5.7%). Though statistically non-significant, it would seem orientation of load impacts on the associated landing forces, with the orientation around the trunk better placed to reduce landing forces. Similarly, a distinction in relative peak and mean F_v were reported in a sprint running study with significantly less peak F_v (-2.3 to -5.8%) during the UWR condition compared to the LWR condition (97). Differences in VJ findings between the LWR and UWR positions may relate to the

loading position altering the subjects landing technique, though video analysis would be required to confirm this. For example, the additional loading attached to the legs may have reduced normal hip and knee flexion, thus increasing landing relative F_v .

As expected light loading of only 3-6%BM resulted in a significant decrease in jump height and relative peak power during the propulsive phase for both the CMJ and DJ. A further observation was that there was no significant effect of load placement on the variables of interest. It would appear however, that LWR has a greater effect on decreasing VJ performance than UWR, with a greater reduction in jump height found with LWR for both the CMJ and DJ. WR significantly reduced relative peak power in both the CMJ and DJ, independent of placement or %BM loading. A study on power production during a concentric only squat jump (trunk loads of 6.6 and 13.3 % BM) on athletes and sedentary individuals found that the effect of external loading on power output was dependent on training status/physical activity (26). Relative peak power significantly decreased (~4-5%) with increasing load in sedentary individuals but did not vary in the power-trained athletes, whereas relative mean power was significantly greater (1.6%) with a 6.6%BM load in power-trained athletes (26). Therefore, the comparative lack of power and jump training experience from the subjects in this study may have influenced the power production capabilities with WR, similar to the untrained individuals in the study by Driss et al. (26).

With regards to propulsive relative peak F_v , no statistical changes occurred across any WR conditions during the CMJ. In contrast, Driss (26) with similar trunk loading (6.6%BM) found that propulsion F_v significantly increased 2.6-4.1% in the squat jump with athletes and sedentary subjects, while F_v also significantly increased 5.9-6.7% during heavier trunk loading (13.3%BM). However, the addition of trunk loading (~11%BM) did not make any significant difference (2.7%) to relative F_v in elite volleyballers during a CMJ volleyball block style VJ (44). Given the results of this study it would seem that even though mass was added to the system and as a result force should naturally increase (force = mass x acceleration), the additional mass reduced the acceleration of the centre of mass of the jumpers, with the net effect being that relative peak force remained relatively constant. With more highly trained or stronger athletes, the effects of the WR on athlete accelerative capabilities may have

been mitigated. The significant decrease in peak velocity supports such a contention (i.e. $a = v/t$) and this reduction in velocity most likely explained the decreased power outputs discussed previously.

Decreases in the PJ RSI were found in all WR conditions compared to the UL condition, the reduction a combination of increased contact time and decreased flight time. WR significantly increased contact time across all conditions but only significantly decreased flight time with 6%BM loading. The decrease in RSI may indicate that vertical stiffness was acutely reduced with the additional loading most likely increasing flexion at the knees and/or ankles, consequently increasing contact time (i.e. greater displacement of the centre of mass) and decreasing flight time. There was no significant effect of load placement on these RSI changes. Vertical stiffness is an important factor in sprint running performance and counteracting the effects of gravity (9, 11). Therefore, the decrease in vertical stiffness found with WR conditions may be a useful training tool for athletes to overcome and adapt to during plyometric type training for sprint based and jump based sports. The reader needs to be cognizant of the lack of familiarity with the PJ technique when interpreting these findings. While the CMJ and DJ are familiar training and testing jumps, the PJ was a new jump for many subjects, thus further research is needed to verify these findings and assess any chronic effect.

This study provides descriptive information; however, it is limited in that it does not provide information on how the WR may change joint angles. Moreover, possible changes in jumping technique that may occur as a result of the WR were beyond the methodological approach undertaken in this acute study and would need to be addressed via acute three dimensional motion capture and longitudinal research. WR horizontal and lateral jump studies also warrant investigation. Subjects were sport active students, with limited jump experience, therefore investigating whether adaptation is similar in well trained athletes warrants attention. Though non-significant differences were observed, some consideration of the orientation of WR and its impact on the associated landing forces is warranted, with the orientation around the trunk better placed to reduce landing forces. Moreover, the propulsion phase for all jumps was affected more by the LWR condition than UWR condition. Finally, given the non-significant between load differences at 3 and 6%BM, consideration for future

research might be given to larger increments in loading (e.g. 5 and 10%BM) when systematically overloading using WR training.

Practical Applications

Landing forces are the forces typically associated with injury and so any increase in propulsive loading of an athlete needs to consider this outcome. From the results of this study it would seem that loads of 3-6%BM do not significantly affect the landing forces associated with VJ training. With this in mind, practitioners can safely load their athletes with UWR or LWR up to 6%BM without fear of overloading the athlete's over and above the landing forces they are typically accustomed. The CMJ is considered a slow stretch-shortening cycle (SSC), knee dominant movement with propulsive contact times typically longer than 600 ms. In this cohort of subjects loading of 3-6%BM was found to reduce jump height, power output and velocity of movement without unduly affecting the propulsive forces. As a training stimulus therefore it would seem that 3-6%BM UWR and LWR loading provided adequate overload and athletes should focus on velocity of movement to improve power output and jump height i.e. take-off velocity. The DJ and PJ have been characterised as fast SSC, ankle dominant movements, given ground contact times of ~200 ms. The loading used in this study resulted in significant reductions to jump height, relative peak power, RSI and flight times (at 6%BM only), and an increase in contact times. Once more the light loads provided significant overload without adversely affecting the landing ground reaction forces, loading of this magnitude and orientation seemingly focussing on extensor strength to reduce contact times and improve flight times and therefore fast SSC performance. UWR and LWR has provided a means to overload both fast and slow SSC motion in a movement specific manner. While alternative loading methods such as barbells and hand held weights can be used, these loading methods are more likely to alter the flight path of the athlete's center of mass and subsequent jumping technique. Specific strength exercises that closely mimic sporting performance are more likely to optimise transference, therefore WR with light loads of 3-6%BM appear a suitable tool for movement specific overload training and maximising transference to sporting performance. Consideration should be given to the inclusion of WR in sports

where VJ's are important components as it may provide a novel training stimulus resulting in positive adaptations in metrics such as power and stiffness.

CHAPTER4: ACUTE KINEMATIC AND KINETIC ADAPTATIONS TO WEARABLE RESISTANCE DURING SPRINT ACCELERATION

(Published in the Journal of Strength & Conditioning Research)

Abstract

Wearable resistance (WR) in the form of weighted vests and shorts enables movement specific sprint running to be performed under load. The purpose of this study was to determine the acute changes in kinematics and kinetics when an additional load equivalent to 3% body mass (BM) was attached to the anterior or posterior surface of the lower limbs during sprint running. Nineteen male rugby athletes (age: 19.7 ± 2.3 years; BM: 96.1 ± 16.5 kg; height: 181 ± 6.5 cm) volunteered to participate in the study. Subjects performed six 20 m sprints in a randomised fashion wearing no resistance or 3%BM affixed to the anterior (quadriceps and tibialis anterior) or posterior (hamstring and gastrocnemius) surface of the lower limbs (two sprints per condition). Optojump and radar were used to quantify sprint times, horizontal velocity, contact and flight times, and step length and frequency. A repeated measures analysis of variance with post hoc contrasts was used to determine differences ($p \leq 0.05$) between conditions. No significant differences were found between the anterior and posterior WR conditions in any of the variables of interest. There was no significant change in sprint times over the initial 10 m, however the 10 to 20 m split times were significantly slower (-2 to -3%) for the WR conditions compared to the unloaded sprints. A significant change in the relative force-velocity (F - v) slope (-10 to -11%) and theoretical maximum velocity (V_0) (-5 to -6%) was found, while a non-significant increase in theoretical maximum force (F_0) (5%) occurred. WR of 3%BM may be a suitable training modality to enhance sprint acceleration performance by overloading the athlete without negatively affecting sprint running kinematics.

KEY WORDS wearable resistance, limb loading, resisted acceleration, specificity of training,

Introduction

Team sport players who can accelerate faster tend to have an advantage due to the high frequency of short sprint accelerations (e.g., 5–20 m, 2–3 seconds) during field-based team sports (101). Players rarely cover a large enough distance to reach maximum velocity, with 68% of sprints in rugby (32) and 90% of sprints in soccer (104) being less than 20 m. Acceleration performance can be vital during decisive periods of a game such as breaking a tackle, moving in to open space or accelerating away from or towards an opponent (48, 66, 77). The ability to accelerate can be effected by an individual's sprinting technique (41, 56), force production capability (41, 48) and the ability to apply that force in the horizontal direction (52, 72, 84). The general mechanical ability to produce horizontal external force during sprint running is portrayed by the linear force-velocity (F - v) relationship (21, 89). The mechanical capabilities of the lower limbs are characterised by the variables: theoretical maximum velocity (V_0); theoretical maximum force (F_0) and peak power production (P_{\max}) (45, 70, 84). Given that mechanical power is the product of force and velocity, the slope of the linear F - v relationship (45, 76) may signify the relative importance of force and velocity qualities in determining the maximal power output and an individual's F - v profile (70).

During sprint running, the initial start (first ground contact) and subsequent acceleration phase may warrant separate investigation. Research is lacking in this area and previous studies have found conflicting results due to differing methodologies (42, 48, 67). Kawamori (48), for example, found no significant correlation between sprint times and impulses during first ground contact from a standing start in team sport athletes. While Mero (67) reported a significant correlation between velocity and horizontal propulsive forces ($r = 0.62$ – 0.71) and vertical forces ($r = 0.41$ – 0.50) from a block start in track sprinters. Acceleration phase performance was significantly correlated with net horizontal ($r = -0.52$) and propulsive impulse ($r = -0.66$) at 8 m (48), while Hunter et al. (42) reported a significant correlation with sprint velocity at 16 m and net horizontal ($r = -0.78$), propulsive ($r = -0.75$), and vertical ($r = -0.41$) impulse in both track and field athletes and team sport athletes.

Several training methods have been used to optimise the kinematic and kinetic factors relating to enhanced sprint acceleration, including resistance training, plyometric training and resisted sprinting modalities such as sled pulling/pushing, and vest and limb loading (2, 14, 20, 28, 86, 97). Specificity of velocity and movement pattern training are fundamental components of an athlete's prescribed exercise program that can affect sporting performance (12, 88), therefore, resisted sprint training provides a movement-specific overload to sprinting. Faccioni (28) suggested that resisted sprint running provided a sports specificity for neuromuscular adaptation that may enhance velocity during the acceleration phase of sprinting. A review of resisted sprinting reported that resisted sprint performance increased velocity, but results were similar to normal sprint training (40). However, the researchers of two resisted sprint studies stated that velocity increased in the acceleration phase more so than normal sprint training, whereas for distances > 20 m normal sprint training increased velocity more so than resisted sprint running (40).

Previous resisted sprint running studies have used sled pulling (14, 105); parachutes (2, 82) and wearable resistance (WR) attached to the trunk (2, 22), legs (97), foot (61) or ankle (86). A potential change in sprint technique that was induced by a sled or parachute was a greater forward lean of the trunk as the load applied to the athlete was directed backwards (2, 20, 82). WR (i.e. external loading attached directly to the trunk or limbs) is thought to provide a vertical load that increases braking forces and may overload the stretch shortening cycle to greater effect (20). The methods for attaching WR to subjects has evolved from boots being filled with a mercury load (100); lead pellets placed in bags being taped to footwear (47, 60, 61); loaded belts being strapped above or around the ankle joint (13, 86); small sandbags being placed in the pockets of a vest (4, 14, 22) to loads attached with Velcro to compression garments around the lower limbs (97).

Two previous sprint running studies used lower body WR: loads strapped around the ankle during over ground sprint running (86) and loads attached around the thigh and shank with Velcro to compression garments during non motorised treadmill sprint running (97). From these two studies, lower body WR resulted in significantly increased contact time (4.3-4.7% leg load: 5%BM) (97) and significantly decreased stride frequency (-1.9 to 2.4% ankle load: 0.6%BM) (86), acceleration (-1.8 to

-3.7% ankle load: 0.6 to 1.8%BM) (86), maximum velocity (-5.9 to -6.3% ankle load: 0.6 to 1.8%BM (86); -5.3% leg load: 5%BM (97)), and step frequency (-3.6% leg load: 5%BM) (97). However, to date, no research has examined lower limb loading using an anterior or posterior loading during sprint running. When a load is attached to the anterior surface of the lower limbs it may theoretically elicit greater recruitment of the hip flexor musculature resulting in improved front side force production mechanics during sprint acceleration. Previous research has shown that increased hip flexor strength improved sprint performance (17, 25). While posterior limb loading may enhance hip extensor musculature recruitment during sprint running with strong hip extensors potentially enabling greater horizontal force production. As previously mentioned, increased horizontal force production may enhance sprint running performance (52, 72, 84), and the retention of a high ratio of horizontal to total force production a central factor in improving acceleration (72).

Given the treatise of the literature and associated limitations the purpose of this study was to determine the acute changes in kinematics and kinetics when WR equivalent of 3%BM was attached to the anterior or posterior surface of the lower limbs during over-ground short-distance (20 m) maximal sprint running. It was hypothesised that loads of 3%BM would have no effect on the variables of interest and that the comparative effects of anterior and posterior loading would be non-significant.

Methods

Experimental Approach to the Problem

A cross-sectional design was used to investigate the effects of WR attached to the lower limbs (anterior: quadriceps and tibialis anterior or posterior: hamstring and gastrocnemius) on the kinematics and kinetics of sprint running. Subjects performed maximum effort 20 m sprints with and without WR attached to either the anterior (anterior wearable resistance: AWR) surface or posterior (posterior wearable resistance: PWR) surface of the legs. WR sprint results were compared to the unloaded (UL) control condition and AWR was compared to PWR using repeated measures analysis of variance with Bonferroni post hoc comparisons used to determine statistical difference between conditions.

Subjects

Nineteen male amateur to semi-professional rugby athletes (rugby league, $n = 6$, rugby union, $n = 13$) volunteered to participate in the study (age: 19.7 ± 2.3 years; BM: 96.1 ± 16.5 kg; height: 181 ± 6.5 cm). Based on an effect size of 0.25, an alpha level of 0.05, statistical power of 0.80 using a repeated measures within-between interaction design, a sample size of 18 was determined adequate for this study. All subjects were currently engaged in periodised strength and conditioning programs and had at least two years experience in sprint training. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study. Subjects were informed of the protocol and procedures prior to their involvement, and written consent to participate was obtained.

Procedures

Testing was performed on an indoor track. Subjects performed a 15 min standardised warm-up followed by six trials of a 20 m sprint, comprised of two repetitions under each of the three loading conditions: 1) 3%BM AWR; 2) 3%BM PWR; and 3) unloaded (i.e. 0 %BM) (UL). The order of the loading conditions was randomised and 3-6 subjects performed the testing protocol in a cycled format to maximise time efficiency and allow appropriate subject rest. Athletes started from a split-stance position with their preferred lead-foot on the starting line. Two repetitions with each condition were performed before the subject changed to the next condition. Each trial was separated by four min of passive rest. The average data from the two repetitions under each condition were used for analysis.

Equipment. Kinematic variables were recorded over the initial 15 m of each sprint with an Optojump Next system (Microgate, Bolzano, Italy). Optojump is an optical measurement system consisting of two parallel bars containing LED's. The system detects any interruptions in communication between the bars and calculates the duration to obtain kinematic variables such as step length, step frequency, contact time and flight time (33). High validity in step parameters was reported during running (intraclass correlation coefficient = 0.96-0.99; mean bias = 0.4-2.7%) (39).

The following section outlines the variables of interest in this study and the method of calculation.

Vertical stiffness (k_{vert}) was calculated based on the spring mass model paradigm (11, 71) as follows:

$$k_{\text{vert}} = F_{\text{max}} / \Delta y$$

where F_{max} = maximal ground reaction force during contact (in kN); Δy = the vertical displacement of the center of mass (in m).

The modelled maximal ground reaction force and the total vertical displacement of the center of mass were calculated from:

$$F_{\text{max}} = mg \pi/2 (FT/CT + 1) / 1000$$

$$\Delta y = F_{\text{max}} CT^2 / m \pi^2 + g CT^2 / 8$$

where m = subject's body mass (in kg); g = acceleration due to gravity (in m/s/s); FT = flight time (in s); CT = contact time (in s)

Instantaneous horizontal velocity data were collected with a radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA). The device was positioned directly behind the starting point and at a vertical height of 1 m to approximately align with the subjects' center of mass; data were collected at a sampling rate 47 Hz. All data were collected using STATS software (Model: Stalker ATS II Version 5.0.2.1, Applied Concepts, Dallas, TX, USA) supplied by the radar device manufacturer. A custom made LabVIEW program (Version 13.0, National Instruments Corp., Austin, TX, USA) was developed to calculate the variables based on the raw horizontal velocity data: V_0 ; F_0 ; P_{max} ; and sprint split times (2,5,10, 20 m). A high level of reliability (coefficient of variation: 1.11 to 2.93% and standard error of measurement: 1.40 to 3.57%), for both intra- and inter-individual comparisons, was found for the variables during over the ground-sprint running (89). The methods of obtaining these variables have been validated in previous research during maximal sprint running (45, 70, 73, 89).

During sprint running acceleration (a), velocity (v)-time (t) curve has been shown to follow a mono-exponential function:

$$v(t) = v_{\max} \cdot (1 - e^{(-t/\tau)})$$

where v_{\max} = the maximal velocity reached; τ = the acceleration time constant.

The horizontal acceleration of the center of mass can be expressed as a function of time, after derivation of velocity over time:

$$a(t) = ((v_{\max}/\tau) \cdot e^{(-t/\tau)})$$

Net horizontal force (F_h) was then modelled over time:

$$(F_h)(t) = m \cdot a(t) + F_{\text{air}}$$

where F_{air} = the aerodynamic friction force to overcome during sprint running computed from sprint velocity and an estimated body frontal area and drag coefficient (3)

Wearable resistance loading: Subjects wore Lila™ Exogen™ compression shorts and calf sleeves (Sportbolehd Sdh Bhd, Malaysia) for the duration of the testing session (Figure 6). The Exogen™ exoskeleton suit enabled fusiform shaped loads (with Velcro backing) of 50-300 g to be attached in numerous configurations. WR of 3%BM was attached to either the anterior or posterior surface of the legs, with 2/3 of the load placed evenly around the thigh and the remaining 1/3 on the shank of the leg. Previous studies using loads attached to the lower limbs (foot, ankle, leg) have used added loads between 0.34 and 5.0%BM (61, 86, 97), and the loads chosen for this study align with such loading parameters.



Figure 6. Lila™ Exogen™ compression shorts and calf sleeves with 3% body mass anterior and posterior loading.

Statistical Analyses

Standard descriptive statistics (means and standard deviations) were reported for all statistical comparisons. Normal distribution of the data was checked using the Shapiro-Wilk statistic. Kinematic analysis was split into two phases: the average of the first two steps were used to represent the start phase; and the subsequent six steps were averaged (i.e. steps 3-8) representing the acceleration phase (55). Statistical differences in kinematic and kinetic variables across loaded and unloaded conditions were determined using repeated measures ANOVA with Bonferroni post hoc comparisons. Statistical significance was set at an alpha level of $p \leq 0.05$. Effect size (ES) (reported using Cohens d (15)) were described as trivial (<0.20), small ($0.20-0.59$), moderate ($0.60-1.19$) and large (> 1.2). Cohen's d was determined by calculating the mean difference between groups, and then dividing the result by the *pooled* standard deviation (15): $\text{Cohen's } d = (M_2 - M_1) / SD_{\text{pooled}}$

where: $SD_{\text{pooled}} = \sqrt{((SD_1^2 + SD_2^2) / 2)}$

Results

No statistical differences were found between AWR and PWR in any variables of interest, therefore the ensuing discussion will focus on the WR conditions (AWR and PWR) compared to UL sprint running. There were no significant differences in sprint split times from the start to the 2, 5, 10 and 20 m marks between WR sprint running compared to the UL condition (Table 8). There was however a significant increase in the 10-20 m split time for both AWR (2.2%, ES: 0.35) and PWR (2.9%, ES: 0.50) compared to UL. Sprint running with 3%BM WR also resulted in a significant decrease in estimated V_0 with AWR (-5.4%, ES: -0.61) and PWR (-6.5%, ES: -0.84) compared to the UL condition.

In terms of the start phase, step length (ES: 0.09) and step frequency (ES: -0.19) were not significantly different between the WR and UL conditions (Table 9). Similarly, small (ES= -0.28 to -0.33) non-significant ($p \geq 0.05$) differences were observed in flight times between conditions. However, the contact time was greater (AWR: 3.4%, ES: 0.41, PWR: 4.4%, ES: 0.50, $p \leq 0.05$) and vertical stiffness was decreased (AWR: -6.2%, ES: -0.38, PWR: -12%, ES: -0.50) compared to the UL condition ($p \leq 0.05$).

No significant changes were found during the acceleration phase in step length (ES: 0.0) with either WR condition compared to the UL condition, however, step frequency was significantly decreased (AWR: -3.4%, ES: -0.43, PWR: -3.6%, ES: -0.45) (Table 10). Flight time was non-significantly different (ES= -0.10 to -0.21) between WR conditions. Contact time was greater (AWR: 3.0%, ES: 0.40, PWR: 3.0%, ES: 0.42, $p \leq 0.05$) while vertical stiffness decreased with PWR (-7.7%, ES: -0.39) during the acceleration phase compared to UL sprint running ($p \leq 0.05$).

No significant differences were found in absolute and relative F_0 (ES: 0.28) or P_{\max} (ES: 0.04 to 0.11) compared to UL sprint running (Table 11). However, WR resulted in differences (AWR: -10.9%, ES: -0.46, PWR: -10.5%, ES: -0.52, $p < 0.05$) in the absolute and relative slope of the F - v profile compared to the UL condition. The change to the slope of the F - v profile resulted in a more force dominant F - v profile.

Table 8. Average sprint split times and maximum velocity achieved for all loading conditions. Means and SD.

	UL	3%BM AWR	3%BM PWR
2m (s)	0.83 ± 0.08	0.82 ± 0.10	0.82 ± 0.10
5m (s)	1.42 ± 0.09	1.42 ± 0.11	1.42 ± 0.12
10m (s)	2.21 ± 0.11	2.21 ± 0.12	2.22 ± 0.14
20m (s)	3.56 ± 0.17	3.59 ± 0.19	3.61 ± 0.21
10-20m (s)	1.35 ± 0.08	1.38 ± 0.09 *	1.39 ± 0.08 *
V ₀ (m/s)	8.32 ± 0.76	7.87 ± 0.72 *	7.78 ± 0.50 *

* Significantly different from unloaded condition (UL)

BM = body mass; AWR = anterior wearable resistance; PWR = posterior wearable resistance;

V₀= theoretical maximum velocity

Table 9. Kinematic variables between all loading conditions during start phase. Means and SD.

	Start (Average of steps 1-2)		
	UL	3%BM AWR	3%BM PWR
Flight time (s)	0.055 ± 0.012	0.051 ± 0.016	0.051 ± 0.012
Contact time (s)	0.200 ± 0.016	0.207 ± 0.018 *	0.209 ± 0.020 *
Flight time / Contact time	0.28 ± 0.08	0.25 ± 0.09	0.25 ± 0.07
Step frequency (Hz)	3.94 ± 0.24	3.89 ± 0.28	3.89 ± 0.29
Step length (m)	1.21 ± 0.12	1.21 ± 0.10	1.22 ± 0.11
Step length /Contact time (m/s)	6.08 ± 0.68	5.88 ± 0.64	5.90 ± 0.67
Vertical stiffness (kN/m/kg)	0.156 ± 0.026	0.146 ± 0.026 *	0.143 ± 0.026 *

* Significantly different from unloaded condition (UL)

BM = body mass; AWR = anterior wearable resistance; PWR = posterior wearable resistance

Table 10. Kinematic variables between all loading conditions during acceleration phase. Means and SD.

	Acceleration (Average of steps 3-8)		
	UL	3%BM AWR	3%BM PWR
Flight time (s)	0.079 ± 0.010	0.080 ± 0.011	0.081 ± 0.009
Contact time (s)	0.159 ± 0.012	0.164 ± 0.013 *	0.164 ± 0.012 *
Flight time / Contact time	0.50 ± 0.08	0.49 ± 0.09	0.49 ± 0.07
Step frequency (Hz)	4.22 ± 0.24	4.12 ± 0.23 *	4.11 ± 0.25 *
Step length (m)	1.59 ± 0.13	1.59 ± 0.11	1.59 ± 0.13
Step length /Contact time (m/s)	10.04 ± 1.07	9.78 ± 1.08	9.70 ± 0.92
Vertical stiffness (kN/m/kg)	0.260 ± 0.043	0.245 ± 0.042	0.244 ± 0.040*

* Significantly different from unloaded condition (UL)

BM = body mass; AWR = anterior wearable resistance; PWR = posterior wearable resistance

Table 11. Kinetic variables between all loading conditions. Means and SD.

	UL	3%BM AWR	3%BM PWR
F ₀ (N)	707 ± 129	745 ± 139	740 ± 102
P _{max} (W)	1430 ± 202	1451 ± 185	1438 ± 189
F/v Profile	-85.15 ± 22.29	-95.50 ± 22.40 *	-95.11 ± 15.56 *
Relative F ₀ (N/kg)	7.29 ± 1.26	7.69 ± 1.05	7.66 ± 1.16
Relative P _{max} (W/kg)	15.1 ± 2.2	15.1 ± 2.2	14.9 ± 2.6
Relative F/v Profile (/kg)	-0.91 ± 0.15	-1.01 ± 0.17 *	-1.01 ± 0.17 *

* Significantly different from unloaded condition (UL)

BM = body mass; AWR = anterior wearable resistance; PWR = posterior wearable resistance; F₀ = theoretical maximum force; P_{max} = peak power production; F/v = Force velocity

Discussion

This is the first study to compare the kinematics and kinetics of sprint running with lower body WR of 3%BM to an UL condition. The reader needs to be cognizant that there is a paucity of research in this area, particularly differentiating the start and acceleration phases, so the integration of research findings from other studies within this discussion is problematic. The main findings were that no significant changes in sprint times over the initial 10 m occurred. However there was a significantly slower split time between 10 and 20 m (~-2 to -3%) and a significantly lower theoretical maximum velocity achieved (~-5 to -6%). There were no differences ($p \geq 0.05$) in kinematics or kinetics when the WR was positioned on the anterior compared to the posterior aspect of the legs. These findings and implications to the practitioner are discussed in more detail in the remainder of the discussion.

It would appear that the WR loading used in this study had little impact on step length (no change to 0.9%) and step frequency (-1.3% both conditions) during the start phase but did significantly affect contact time (3.4 to 4.4%). Given that step frequency is determined by flight and contact time, the increased contact times should have reduced step frequency, which was the case, however, the change was non-significant and most likely explained by the non-significant decrease in flight time. As a consequence of the longer contact times and the importance of this kinematic variable in calculating stiffness, vertical stiffness was reduced ($p \leq 0.05$). The additional loading most likely increasing flexion at the knees and/or ankles.

Horizontal force production is important to the start and acceleration phases of sprint running (52, 72, 84). During the start phase it was observed that F_0 and P_{\max} were statistically unaffected (relative F_0 : 4.9 to 5.3%; relative P_{\max} : no change to -1.4%, $p \geq 0.05$) by the additional loading. Whether the same is true of force and power in the vertical direction is unknown given the methodological procedures utilised in this study. In summary, it would seem that the additional loading had little effect on start kinematics and kinetics particularly in the horizontal plane. For those practitioners concerned that loading an athlete may negatively affect technique factors, these findings with a 3%BM load should allay most concerns and such loading can take place with very little technique breakdown. For those

practitioners who wish to significantly overload start kinematics and kinetics, it is suggested that heavier relative loading is most likely required. However, it needs to be noted that the 3%BM loading did provide a means to overload contact time and vertical stiffness. So care is needed as it would seem differential relative loading is needed to overload certain kinematic and kinetic determinants of the sprint start.

With regards to the acceleration phase, similar changes in the kinematics and kinetics were observed with the exception of a significant decrease in step frequency. It would seem with the additional steps of the acceleration phase, the influence of increased contact times were greater and hence the significant decrease in step frequency (-2.6 and -2.7%, AWR and PWR, respectively, $p \leq 0.05$). Similar findings were reported by Ropret et al. (86) with 0.6%BM (attached to the foot), which resulted in reduced stride frequency (-1.9%, $p \leq 0.05$) but no significant change to stride length. The significant increase in contact time during the acceleration phase (3% both AWR and PWR) is comparable to the findings of Simperingham and Cronin (97) who reported a 4.3% increase in acceleration phase contact time with 5%BM lower body loading attached to the legs during treadmill sprint running. Previous researchers have proposed that the greater the external load, the greater the alteration to sprint running kinematics. Therefore, some practitioners would posit that the optimal load for resisted sprint running should provide a suitable overload stimulus for adaption without negatively affecting sprint running technique (2, 54). The findings from this study for the most part support this school of thought, minimal (i.e. less than 5%) alterations in acceleration kinematics being observed during sprint running with WR.

WR resulted in a significant change in the relative $F-v$ profile (~-10 to -11%), but no significant changes were found in relative F_0 or P_{max} production. Although no significant changes were found in F_0 , WR sprint running did increase F_0 production compared to UL sprint running with increases of 5.2% (AWR) and 4.9% (PWR) found. This increase in F_0 is of interest as previous researchers have suggested that the amount of horizontal force an athlete can produce and maintain is a key component in acceleration phase performance (20, 57). In a study on soccer players, Buchheit et al. (10) found that the amount of horizontal force produced was of a beneficial impact during the acceleration phase

but became of less importance during the maximum velocity phase. While Cross et al. (21) found that sprint performance in rugby players (0-30 m) appeared to be related to a more force dominant F - v profile. The increase in F_0 found in this study may have resulted from the WR requiring the athlete to produce more horizontal force to overcome the external loading. Such findings are supported by the acute kinematic changes detailed earlier in this study. Therefore, it appears WR enhances an athlete's ability for horizontal force production in sprint running which may have partly contributed to maintaining split times over 0-10 m comparable to UL split times.

Morin and Samozino (75) have suggested that during the acceleration phase (< 20 m), a greater relationship between sprint running performance and theoretical maximal horizontal force production exists. To determine this relationship the simple modelling of the derivation of the speed-time curve that lead to horizontal acceleration data was undertaken (75). Samozino et al. (90) proposed that by assessing the F - v profile, an individual's area of relative dominance can be identified (i.e. force or velocity dominant) which subsequently may be of importance for prescribing training loads, exercises and schedules. With this in mind the addition of WR in this study resulted in a more force dominant F - v profile. This information is of utility to the practitioner e.g. a velocity-dominant athlete may benefit from additional force-dominant training to shift out the force-velocity curve and enhance horizontal power production.

The significant change in the relative slope of the F - v profile, combined with the minimal change in sprint running kinematics, may indicate that lower body WR with 3%BM could be an effective training tool for improving sprint acceleration performance. This study provides descriptive stride variable information; however, it is limited in that it does not provide information on how WR may change joint angles during sprint-running. Moreover, possible changes in sprint running technique that may occur as a result of the WR were beyond the methodological approach undertaken in this acute study and would need to be addressed via acute three dimensional motion capture and longitudinal research. Additional loading configurations (e.g. proximal compared to distal, or internal compared to external oblique loading) made possible by recent advances in WR technology could also be a focus of future research.

Practical Applications

Lower body WR with 3%BM seems to reinforce ideal early sprint acceleration with speed maintained during the initial acceleration phase (0-10 m). Sprint running kinematics appear to remain comparatively unchanged by WR of this magnitude, with most kinematic variables found to be minimally altered (less than ~5%). For practitioners who wish to significantly overload the start, it is proposed that heavier relative loading is needed. However, 3%BM loading did provide a means to overload contact time and vertical stiffness, therefore it would seem differential relative loading is needed to overload certain kinematic and kinetic determinants of the sprint start. The acceleration phase of sprint running is typified by a longer stance phase resulting in greater propulsion and horizontal force production compared to the maximum velocity phase. WR provided an overload during the stance phase resulting in the athlete having to produce a greater amount of force to overcome the additional loading. For athletes requiring a more force dominant F - v profile, and for relatively velocity dominant athletes, sprint running with WR may enable the athlete to improve their external horizontal force production. Lower body WR may be a suitable training tool for movement specific overload and maximizing transference to improved sprint running performance. Consideration should be given to the inclusion of WR in sports where sprint running is an important component as it may provide a novel training stimulus resulting in positive adaptations. It is suggested that it is used as an adjunct training tool to heavy resistance training by promoting intermuscular co-ordination via the strategic placement of light variable resistance.

CHAPTER 5: SUMMARY, PRACTICAL APPLICATIONS AND FUTURE RESEARCH

DIRECTIONS

Summary

The literature review provided rationale for investigation into the acute effects of WR on VJ and sprint running performance. Previous research into WR has found a great deal of conflict and conjecture in the outcome measures of interest. There were many methodological variations such as %BM load used, placement of the load, homogenous participants, the variables measured, and duration of study period. Despite the limitations observed from the literature review, positive findings in terms of the effects of WR on both VJ and sprint running provided sufficient reason to warrant further investigation into WR.

This thesis sought to determine the acute effects of different wearable resistance loads and placements on VJ and sprint running performance. A range of kinematic and kinetic variables were identified as performance measures. These were used to compare the effects of WR loads of 3 and 6%BM (attached upper body or lower body) during vertical jumping and 3%BM (attached to the anterior or posterior of the lower body) during sprint running. The different WR placement positions investigated in this thesis sought to fill research gaps identified in the literature review. WR training is recommended for athletes in whom explosive lower-body movements such as vertical jumping and sprint running are performed as part of competition.

Vertical jumping

WR light loading of only 3-6%BM resulted in a significant decrease in jump height for both the CMJ and DJ. The additional mass reduced the acceleration of the centre of mass of the jumpers, with the net effect being that relative peak propulsive force remaining relatively constant. The significant decrease in peak velocity most likely explained the significantly decreased peak power outputs found with all WR conditions. A further observation was that there was no significant effect of load placement on the variables of interest. It would appear; however, that LWR has a greater effect on decreasing VJ performance than UWR with a greater reduction in jump height found with LWR for

both the CMJ and DJ. The significant decreases in RSI during the PJ may indicate that vertical stiffness was acutely reduced with the additional loading most likely increasing flexion at the knees and/or ankles, consequently increasing contact time (i.e. greater displacement of the centre of mass) and decreasing flight time. The main finding in terms of landing mechanics was that the effect of the additional load and orientation of the load on CMJ and DJ relative F_v was non-significant. This may be explained by the significant decrease in jump height. Landing relative F_v tended to be higher with the same magnitude of LWR compared to UWR, however, the differences in the 3 to 6 %BM load placement was statistically non-significant.

Sprint running

Lower body WR may be a suitable training tool for movement specific overload and maximising transference to increase sprint running performance. The main findings from the acute study were that no statistical changes in sprint times over the initial 10 m occurred; however there was a significantly slower split time between 10 and 20 m (-2 to -3%) and a significantly lower theoretical maximum velocity achieved (-5 to -6%). There were no significant differences in the kinematics or kinetics when the WR was positioned on the anterior compared to the posterior aspect of the legs.

WR had little impact on step length and step frequency during the start phase but did significantly affect contact time. As a consequence of the longer contact times, vertical stiffness was significantly reduced, with the additional loading most likely increasing flexion at the knees and/or ankles. It would seem with the additional steps of the acceleration phase, the influence of increased contact times were greater and hence the statistically significant reduction in step frequency occurred during the acceleration phase. The acceleration phase of sprint running is typified by a longer stance phase resulting in greater propulsion and horizontal force production compared to the maximum velocity phase.

A significant change in the relative F - v profile (-10 to -11 % both AWR and PWR) was found, but no significant changes were found in relative F_0 or P_{\max} production. Although no significant changes were found in F_0 , WR sprint running did increase F_0 production compared to UL sprint running with

increases of 5.2% (AWR) and 4.9% (PWR) observed. The increase in F_0 may have resulted from the WR requiring the athlete to produce more horizontal force to overcome the external loading. Given the significant change towards a more force dominant $F-v$ profile using WR, lower limb WR sprint training may be most suitable for relatively velocity dominant athletes, and athletes from predominantly force dominant sports (e.g. rugby and American football).

Practical Applications

Based on the findings of the two acute studies, several practical applications are provided to assist coaches and trainers with using WR:

Vertical jumping

1) From the results in this research it would seem that loads of 3-6%BM do not significantly affect the landing forces associated with jump training. Therefore practitioners can safely load their athletes with UWR or LWR without fear of overloading the athlete's over and above the landing forces they are typically accustomed.

2) The CMJ is considered a SSC, knee dominant movement with propulsive contact times typically longer than 600 ms. In this cohort of subjects loading of 3-6%BM was found to reduce jump height and power output without unduly affecting the propulsive forces, such loading seemingly affecting the velocity of movement. As a training stimulus therefore it would seem that 3-6%BM UWR and LWR loading provided adequate overload and athletes should focus on velocity of movement to improve power output and jump height i.e. take-off velocity.

3) The DJ and PJ have been characterised as fast SSC, ankle dominant movements, given ground contact times of ~200 ms. The loading used in this research resulted in significant reductions to jump height, relative peak power, RSI and flight times (at 6%BM only), and an increase in contact times. The light loads provided significant overload without adversely affecting the landing ground reaction forces, loading of this magnitude and orientation seemingly focussing on extensor strength to reduce contact times and improve flight times and therefore fast SSC performance.

4) Specific strength exercises that closely mimic sporting performance are more likely to optimise transference, therefore WR with light loads of 3-6%BM appear a suitable tool for movement specific overload training and maximising transference to sporting performance. While alternative loading methods such as barbells and hand held weights can be used, these loading methods are more likely to alter the flight path of the athlete's centre of mass and subsequent jumping technique. Consideration should be given to the inclusion of WR in sports where VJ's are important components as it may provide a novel training stimulus resulting in positive adaptations in metrics such as power and stiffness.

Sprint running

1) Lower body WR with 3%BM seems to reinforce ideal early sprint acceleration with speed maintained during the initial acceleration phase (0-10 m). Therefore practitioners can overload their athletes without decreasing their start and initial acceleration speed.

2) Sprint running kinematics appear to remain comparatively unchanged by WR of this magnitude, with most kinematic variables found to be minimally altered (less than 5%). For practitioners who wish to significantly overload the start, it is proposed that heavier relative loading (i.e. > 3%BM) is needed. However, 3%BM loading did provide a means to overload contact time and vertical stiffness, therefore it would seem differential relative loading is needed to overload certain kinematic and kinetic determinants of the sprint start.

3) WR provides an overload during the stance phase resulting in the athlete having to produce a greater amount of force to overcome the additional loading. For athletes requiring a more force dominant $F-v$ profile, and for relatively velocity dominant athletes, sprint running with WR may enable the athlete to improve their external horizontal force production.

4) WR sprint running enables the principle of specificity training to be undertaken which may elicit an enhancement in sprint performance due to the overloading stimulus from the external load leading to greater neuromuscular adaptations. It is suggested that it is used as an adjunct training tool to heavy

resistance training by promoting intermuscular co-ordination via the strategic placement of light variable resistance.

Limitations

A number of limitations specific to each of the experimental papers are outlined below:

Vertical jump study

1) Participants were sport active students, with limited jump experience; therefore a possible difference in findings may result with athletes who have greater jump experience. Moreover, the participants in this study were both male and female.

2) The PJ was an unfamiliar jump technique for many subjects, thus warranting caution when interpreting the effects of WR on the PJ.

3) The longitudinal effects of WR %BM load and placement positions used in this acute study have yet to be investigated on VJ performance.

Sprint running study

1) Only one load used (3%BM). Greater or lesser loading may have resulted in different outcomes.

2) The sprint distance measured was 20 m; therefore, the effects of 3%BM WR over greater distances and during the maximum velocity phase remain unexplored.

3) The longitudinal effects of lower body WR on sprint running performance have yet to be investigated.

4) No video analysis was used; therefore, changes in joint angles are unknown.

Future Research

This thesis made a contribution to the effects of WR during vertical jumping and sprint running, which can be used by practitioners to inform better training practice. Nevertheless, several areas of WR require further research:

- 1) This thesis assessed the acute effects of WR on vertical jumping and sprint running; however, longitudinal studies assessing chronic changes to technique and performance are required to assess the true potential for adaptation.
- 2) The jumps performed were bilateral and vertical only. In many sports, jumps are often unilateral and horizontally oriented; therefore, future studies should consider these applications of WR.
- 3) The effects of WR may be different with athletes with less or more experience. Moreover, athletes with different levels of experience and skills may require less or more %BM to enable positive technique changes.
- 4) WR with differing %BM and placement positions warrants future investigation, with differences reported in horizontal and vertical ground reaction forces between the acceleration and the maximum velocity phase of sprint running.
- 5) The customisation of WR suits allows multiple loading configurations to be used. This thesis assessed anterior vs. posterior and upper body vs. lower body loading, however, many other configurations have yet to be investigated. Future research is warranted into the sporting performance changes with WR loading of a greater variety of magnitudes and configurations. The improved understanding of WR facilitated by such research will enhance the training prescription guidelines that can be provided to athletes and practitioners.

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8 APPENDICES

APPENDIX 1: ETHICS APPROVAL



A U T E C
S E C R E T A R I A T

14 April 2015

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **15/07 Light variable resistance training with exogen exoskeletons.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 14 April 2018.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 14 April 2018;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 14 April 2018 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

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

Cc: Kim Simperingham ksimperingham@gmail.com

APPENDIX 2: STUDY RECRUITMENT SHEET

Request for study participants

The effects of wearable resistance on sprint running and vertical jump performance in team sport athletes

Purpose of the study

Acute and longitudinal performance increases have been found in sprint running and jumping with wearable resistance (i.e. an external load attached to the body). Previous research has involved weighted vests, hand held weights or weights strapped to the feet or ankles. However, recent technological developments have enabled wearable resistance to be attached to multiple areas of the body with velcro based attachments allowing greater functional dynamic actions to be performed. Therefore, the purpose of the research is to compare anterior and posterior lower limb loading in sprint running and upper and lower body loading in vertical jumping.

Participant requirements

Team sport athletes recreationally or competitively-active

Male and female aged between 18-35

Free from any acute or chronic injury

Not using any performance enhancing or banned substance (WADA 2014)

What is involved?

Vertical jumping

This investigation will involve three sessions. Session one will involve the collection of anthropometric information and familiarisation with the Exoskeleton suits. Session two will involve performing a series of different vertical jumps (counter movement jump, drop jump and pogo jump) with lower body loading (3 and 6% Body Mass), while session three will involve the same jumps and loading but performed with upper body loading. Each condition will be performed three times (9

jumps in total) and the order of the conditions will be randomised. You will complete a standardised warm-up prior to testing and you will have a recovery period of five min before each jump.

Sprint running

This research will involve two sessions. Session one will involve collecting of anthropometric information and familiarisation with the Exoskeleton suits. Session two will involve performing a series of 20 m sprints with the following conditions: 1) Unloaded 2) 3% Body Mass Anterior Lower Limb Loading, and 3) 3% Body Mass Posterior Lower Limb Loading. Each condition will be performed twice (6 sprints in total) and the order of the conditions will be randomised. You will complete a standardised warm-up prior to testing and you will have a recovery period of five min before each 20 m sprint.

Benefits of the study

The research findings will inform and improve the effectiveness of athletic training procedures particularly in the areas of speed and power training. As a participant you can receive a report of the research outcomes and your individual results at the completion of the study. These results can be used to individualise your on-going strength and conditioning program decisions. Additionally, you will be contributing to the current body of knowledge in the speed and power field.

Further information

Researcher: Paul Macadam, paul.macadam@gmail.com, 02102286839

Project Supervisor: John Cronin, john.cronin@aut.ac.nz, 921 9999 ext 7523.

Participant Information Sheet



Date Information Sheet Produced:

18 December 2014

Project Title

Light Variable Resistance TrainingTM with ExogenTM Exoskeletons

An Invitation

My name is Kim Simperingham and I am a PhD student at SPRINZ (Sports Performance Research Institute New Zealand) at the AUT Millennium Campus of the Auckland University of Technology (AUT). We are currently conducting a study into the effect on sporting movements of added external weight using a new product called an ExogenTM exoskeleton. Your participation in this study would be greatly valued, but is entirely voluntary and you may withdraw at any time prior to the completion of the data collection.

LilaTM, the producer of ExogenTM, will provide ExogenTM suits for use during testing and may provide some grants (e.g. student scholarships) to help fund the research project. The results from the studies will be provided in de-identified form (i.e. without your associated name and personal details) to LilaTM in the form of journal or thesis publications and/or conference presentations. 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, freely give your consent to participate, and that there has been no coercion or inducement to participate.

What is the purpose of this research?

The purpose of this research is to analyse the changes in typical sporting movements (e.g. jumping, running, sprinting and cycling) that occur when small amounts of external loading are attached to the body. ExogenTM exoskeletons include shorts, sleeveless tops and upper arm, forearm and calf sleeves to which small (approximately 19 cm long) loads of 50 to 200 g can be attached with Velcro. This research will quantify the acute changes in typical sporting movements that occur when loads are attached to various sites around the body (e.g. upper vs. lower body and centrally located loading vs. loading positioned towards the extremities of the limbs). We will use relevant tests from a range of options: running and sprinting performance will be measured with radar and treadmill technology; short sprint-cycling accelerations will be measured with a custom-built stationary cycle; strength and jump performance will be assessed on a portable force platform and with video analysis; and body composition will be measured using skinfold testing with callipers. The research findings will be reported in my doctoral thesis as well as conference presentation(s) and scientific journal article(s).

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

The participants for this project are required to be healthy, injury-free recreationally- or competitively-active males and females aged 18-40 years old. You meet these criteria so we would like to invite you to participate.

What will happen in this research?

If you choose to participate in this project, you will be required to complete one testing session at AUT Millennium for approximately two hours.

. Following the standardised warm-up you will complete selected tests from the following list:

- Body composition assessment using skinfold callipers
- 30 m over-ground sprints and 15 m agility sprints
- 6 s sprints on a non-motorised treadmill

- Constant pace running on a motorised treadmill (including 3 dimensional [3D] motion analysis)
- 4 s cycle sprints on a stationary cycle ergometer
- Vertical, horizontal and lateral jumps (including 3D motion analysis)
- 3 s isometric mid-thigh pull strength test

What are the discomforts and risks?

There should be no significant discomforts or risks associated with this testing beyond those experienced during normal sprint/strength testing and training. You will likely experience some shortness of breath and perhaps some lower body muscular soreness in the 48 hours after each testing session. If you are completing 3D motion analysis testing in the laboratory then you will be asked to complete the running and jumping tasks with your shirt off to reduce the amount of clothing movement around the markers placed on your body. However if you are uncomfortable with this we will provide you with a tight fitting shirt to wear during testing.

How will these discomforts and risks be alleviated?

You will be requested to not complete any high-intensity training in the 24 hours prior to each testing session and to present to each testing session well hydrated and having not eaten in the 90 min prior to the start of testing. You will perform a comprehensive warm-up and cool-down before and after each testing session. Full recovery of at least three min will be ensured before each maximal effort test.

What are the benefits?

The research findings will inform and improve the effectiveness of athletic training procedures particularly in the areas of speed, power, change of direction and endurance running training. As a participant you can receive a report of the research outcomes and your individual results at the completion of the study. These results can be used to individualise your on-going strength and conditioning program decisions. Additionally, if you are involved in an organised sport, a summary of

your results can be made available to your team coach, manager or doctor if you agree to this on the consent form.

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?

- We will take a number of measures to protect your privacy as much as possible and to ensure your personal details remain confidential.
- The data from the project will be coded and held confidentially in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993).
- All reference to participants will be by code number only in terms of the research publications. Identification information will be stored on a separate file and computer from that containing the actual data.
- De-identified test results (i.e. without your associated name and personal details) may be stored indefinitely in the SPRINZ research database and may be used for similar research studies in the future.
- The findings of this project will be published in scientific journals, at a conference presentation(s) and in a doctoral thesis, but at no stage will you be identifiable. The results will be presented as averages and not individual responses. Your identifiable test results will only be made available to yourself and your sports coach, manager or doctor (if you agree to this option on the consent form).

What are the costs of participating in this research?

Participating in this research project will not cost you apart from your time, which we greatly thank you for. The total time commitment will be one testing session of approximately 2 hours.

What opportunity do I have to consider this invitation?

- Please take the necessary time (up to 2 weeks) you need to consider the invitation to participate in this research.
- It is reiterated that your participation in this research is completely voluntary.
- If you require further information about the research topic please feel free to contact Professor John Cronin (details are at the bottom of this information sheet).
- You may withdraw from the study at any time without there being any adverse consequences of any kind.
- You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

How do I agree to participate in this research?

If you agree to participate in this study, please complete and sign the attached consent form. This form will be collected in person prior to testing.

Will I receive feedback on the results of this research?

We will provide a summary via email of your results from the testing and the averages of all participants. If you wish to receive your results, please provide your email on the attached consent form where indicated.

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, John Cronin, john.cronin@aut.ac.nz, 921 9999 ext 7523.

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

Whom do I contact for further information about this research?

Researcher Contact Details:

Kim Simperingham

Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632.

ksimperingham@gmail.com

021 1060 330

Project Supervisor Contact Details:

Professor John Cronin

Sports Performance Research Institute New Zealand (SPRINZ) at AUT Millennium, Auckland University of Technology, 17 Antares Place, Mairangi Bay, Auckland 0632.

john.cronin@aut.ac.nz

921 9999 ext 7523

Approved by the Auckland University of Technology Ethics Committee on 14 April 2015, ATEC Reference number 15/07.

APPENDIX 4: CONSENT FORM

<h1>Consent Form</h1>	 AUT UNIVERSITY <small>TE WĀNANGA ARONUI O TAMAKI MAKAU RAU</small>
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Project title: ***Light Variable Resistance TrainingTM with ExogenTM Exoskeletons***

Project Supervisor: ***Professor John Cronin***

Researcher: ***Kim Simperingham***

- ☐ I have read and understood the information provided about this research project in the Information Sheet dated 18 December 2014.
- ☐ I have had an opportunity to ask questions and to have them answered.
- ☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ☐ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.
- ☐ I agree to take part in this research.
- ☐ I agree that my test results may be provided to my sports coach, manager or doctor.
Yes ☐ No ☐
- ☐ I agree to my test results being stored in de-identified form (without my name or personal details attached) in the SPRINZ research database and potentially used in future research studies of a similar nature:
Yes ☐ No ☐
- ☐ I wish to receive a copy of the report from the research (please tick one):
Yes ☐ No ☐

Participant's signature:

.....

Participant's name:

.....

Participant's Contact Details (if appropriate):

.....

.....
.....
.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 14 April 2015, AUTEK Reference number 15/07.