7-24-2019

Bilateral and unilateral resistance training and athletic performance

Brendyn B. Appleby
Edith Cowan University

BILATERAL AND UNILATERAL RESISTANCE TRAINING AND ATHLETIC PERFORMANCE

This thesis is presented for the degree of

Doctor of Philosophy

Brendyn Bryan Appleby

MSc, University of Western Australia

BSc, University of Western Australia

Edith Cowan University

School of Medical and Health Sciences

2019

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

Abstract

Specificity is a key programming principle for optimal transfer of physiological adaptation of training to improved athletic performance. In resistance training, it has long been identified that the closer the mechanical specificity between the training exercise and outcome performance, the greater the transfer of improved capacity. Bilateral resistance exercises are predominately prescribed for the development of maximum strength and are well demonstrated to enhance athletic performance. However, unilateral exercises appear to demonstrate greater specificity to movements such as running and change of direction as these movements are predominantly single leg actions. Nonetheless, the unstable nature and comparatively lower magnitude of external resistance could be theorised to relegate unilateral exercises to be inferior to bilateral exercises and thus of less benefit for enhancing performance.

To investigate the differences in transfer between bilateral and unilateral resistance training to athletic performance of sprint acceleration and change of direction, a series of biomechanical and training intervention studies were implemented. The first study established the reliability of the one repetition maximum (1RM) step-up test (Chapter Three). Ten moderately trained participants completed four familiarisation sessions before two repeated strength testing sessions on separate days. Reliability was estimated as the typical error ±90% confidence limits (CL), expressed as a coefficient of variation (CV%) and the intraclass correlation (ICC). The CV% for all comparisons ranged between 2.0% and 5.3% with average of left and right leg CV% less than the smallest worthwhile change. Importantly, the test was deemed reliable to monitor improvements in lower body unilateral strength.

Second, the validity and reliability of barbell displacement in heavy back squats was established (Chapter Four). Twelve well-trained rugby players (1RM 90° squat = 196.3 ± 29.2kg) completed two sets of two repetitions at 70%, 80% and 90% of 1RM squats. Barbell displacement was derived from three methods across four load categories (120-129kg, 140-149kg, 160-169kg and 180-189kg) including: 1) Linear Position Transducer attached 65cm left of barbell centre, 2) 3D motion analysis tracking of markers attached to either end of the barbell, and 3) cervical marker (C7) (criterion measurement). Validity was calculated using typical error of the estimate as CV% ±90% CL, mean bias as a percentage and Pearson product

moment correlation (r). Intraday reliability was calculated using ICC and the typical error expressed as CV% ±90% CL. Laterality of marker position increased bias between the criterion measure (C7) and predicted measures (LPT bias = 0.9-1.5%; r = 0.96-0.98; barbell ends bias = 4.9-11.2%; r = 0.71-0.97). Moderate reliability was obtained for most measures of barbell displacement (All loads: LPT: CV% = 6.6%, ICC = 0.67; barbell ends: CV% = 5.9-7.2%, ICC = 0.55-0.67; C7: CV% = 6.6%, ICC = 0.62). Due to a combination of heavy external barbell load and the pliant nature of the barbell, overestimation can occur with increasing external load and as the position tracking location moves laterally (barbell ends). The linear position transducer demonstrated high validity to the criterion and high trial-to-trial reliability.

Completing methodological rigour, within-session reliability of kinetic and kinematic variables of the squat and step-up were investigated (Chapters Five to Eight). Fifteen well-trained rugby players completed two testing sessions. Session one involved squat and step-up 1RM strength testing. Session two involved four maximal repetitions of squat and step-up at 70%, 80% and 90% 1RM assessed by three-dimensional motion analysis and in-ground triaxial force plates. Reliability was calculated for each load range using CV% ±90% CL and ICC. Across all load ranges squat and step-up peak and average ground reaction force (GRF) and total concentric impulse were found to have acceptable measures of reliability below 10% and ICC above 0.85. The majority of loads for squat and step-up displacement, concentric duration, and maximum knee flexion angle were reliable (CV% < 10%, ICC > 0.75). For the squat, measures of peak and average velocity were reliable (CV < 10%) whilst step-up velocity measures were less reliable (CV% <13%; ICC > 0.60). Reliability findings permitted confident interpretation of key variables of squat and step-up performance and application to training.

A comparison of kinetics and kinematics between squat and step-up were conducted to provide insight for potential training application. In-ground tri-axial force plates and three-dimensional motion analysis were used to capture force output and movement patterns of four maximal efforts of squats and step-ups at 70%, 80% and 90% of 1RM. The concentric phase kinetics and kinematics of each exercise were analysed using effect sizes (ES ± 90% confidence limits). Large to very large differences in peak and average GRF per leg were found for the step-up compared to the squat at all loads (Peak GRF ES: 2.56 ± 0.19 to 2.70 ± 0.37; Average GRF ES: 1.45 ± 0.27 to 1.48 ± 0.29). Additionally, per leg, the squat was inferior to the step-up for impulse at 70% (0.71 ± 0.40) and 80% (0.30 ± 0.41). The difference at 90% 1RM was unclear. Peak velocity was greater for the squat compared to the step-up across all loads squat produced large differences in peak velocity at all loads (ES = -1.74 ± 0.48 to -1.33 ± 0.48). The comparable GRF per leg between step-up and squat suggests overload sufficient for strength development in the step-up, despite a lower absolute magnitude of external resistance. Although appearing to provide sufficient overload for strength development, a training study was designed to determine the practical application of resisted step-ups on strength development and measures of speed and change of direction performance.

The final study recruited academy level rugby players (age = 23.1 ± 4.3 years, mean training age = 5.4 ± 2.9 years; 1RM 90° squat = 178 ± 27 kg) assigned to one of two groups – a bilateral (BIL) training group or a unilateral (UNI) training group. Subjects completed a comprehensive 18-week program involving a familiarisation, training and maintenance phases. Back squat and step-up strength testing was analysed for within- and between-group differences using ES ± 90% CL. Both intervention groups showed practically important within group improvements in their primary exercise during the training phase (ES ± 90% CL: BIL = 0.79 ± 0.40; UNI = 0.63 ± 0.17) with transfer to their non-trained resistance exercise (BIL step-up = 0.22 ± 0.37: UNI squat = 0.44 ± 0.39). Between groups, the improvement in squat 1RM was unclear (ES = -0.34 ± 0.55), however unilateral resistance training showed an advantage to step-up 1RM (ES = 0.41 ± 0.36). The bilateral and unilateral training groups improved 20m sprint (ES: BIL = -0.38 ± 0.49; UNI = -0.31 ± 0.31), however the difference between the groups was unclear (ES = 0.07 ± 0.58). Whilst both groups had meaningful improvements in COD (BIL COD average = -0.97 ± 0.32: UNI squat = -0.50 ± 0.54), bilateral resistance training had a greater transfer to COD performance than unilateral (between groups ES = 0.72 ± 0.55). As such, practically important increases in lower body strength can be achieved with bilateral or unilateral resistance training. Whilst increases in strength positively improved sprint acceleration, the BIL group demonstrated superior improvements in COD perhaps due to the limited eccentric training stimulus of the step-up exercise. This demonstrates the importance of targeting the underlying physiological stimulus for adaptation and not purely likeness of movement specificity of the target performance.

The research sought to address specificity and transfer of training as it pertains to bilateral and unilateral lower body resistance training. The results demonstrate that high GRF is produced per leg, comparable between the squat and step-up suggesting sufficient strength development stimulus of the step-up. Differences in total concentric impulse and velocity may provide variable training applications of either exercise. When incorporated into a resistance training program, unilateral and bilateral exercises can develop maximum strength. Importantly, strength development was demonstrated in the performance of the non-trained bilateral or unilateral exercise, demonstrating a level of transfer. Further, the training study revealed that sprint acceleration over 20m can be developed using either squat or step-up. However, whilst both groups improved COD performance, squat training had a superior transfer to COD than step-up training. This suggests that step-up training may sufficiently improve lower body strength and acceleration, however, the application to COD performance may require additional training stimulus to enhance adaptation potentially due to the lack of eccentric overload in the step-up.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(1) Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(2) Contain any material previously published or written by another person except where due reference is made in the text; or

(3) Contain any defamatory material.

I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required

Brendyn B Appleby Month, Day, Year

Acknowledgements

It has been said, "If you are the smartest person in the room, you are in the wrong room."

I was **<u>not</u>** in the wrong room. I could not afford to be. I am still stunned I was let in and have constantly been waiting for the tap on the shoulder and kind escort out the door: "Sorry Mr Appleby, there seems to have been a mistake. You should not be here."

How someone like me could have supervisors like Rob Newton and Prue Cormie still amazes me? I'm not sure what they were thinking when they said "Yes", but their belief, support, patience and experience was beyond generous. A blessed combination of amazing academic skills. Rob, your ability to see the big picture and keep me moving contributed more than you know. Prue, your meticulous attention to detail and for entertaining this idea in the first place – thank you. I am constantly inspired by your careers and the important work you do.

To have someone like Stuart Cormack "assist" is amazing and I'm humbled that I could even call him a friend. Stu, thank you for your enthusiasm in my work, your belief in me and your endless patience with my slow growth; I am deeply, deeply indebted. We've come a long way from those special whiteboard chats in the weights room.

Mervyn Travers – you have ridden this roller coaster with me and played a significant part as a friend who was always a few steps ahead, wisely pointing out the rabbit holes from the gold mines. "Spearfish, don't trawl".

To Greg Haff and Sophia Nimphius: for the greatest baptism of fire an ECU Sport Science Student may have ever had at proposal. I would not want to do again – and I am so very glad that I did. You ignited my pathway of academic rigour.

My colleagues, coaches and athletes of RugbyWA for their support and participation. To the wonderful athletes who put their trust in me, offered their precious time – thank you.

To the students who assisted with the exciting training and testing sessions – thank you; I hope you still look back on those times as fondly as I do.

To the staff at ECU, in particular Nadia, Elisabeth and Helen for their support with laboratory preparation. Nick Hart and Tania Spiteri – colleagues who raced to the finish line, but still graciously had time for a straggler like me. Bernard Liew for his assistance with data techniques.

Finally, more time than I care to admit has come and gone and my daughter cannot recall a time when I was not doing this PhD. To my wife, Jen, and daughter Holly; even though my work took more time than it should (way more!), you still allowed me early mornings and late nights in the study and library to pursue something, that I still cannot believe I actually did.

Brendyn

In Memory

Whilst some time has passed since this investigation, it is still fitting to remember Rob Shugg, Co-owner and Director of Kinetic (GymAware) who was a friend and enthusiastic supporter of this work, who tragically passed before he could see it completed.

List of Abbreviations

General

RM Repetition Maximum

1RM:BM ratio of one repetition maximum strength relative to body mass

kg Kilograms, unit of mass

m Metres, unit of displacement

cm centimetre, unit of displacement

mm millimetre, unit of displacement

m/s Meters per second, units of velocity

m/s/s Metres per second per second, units of acceleration

ms milliseconds, unit of time

Hz hertz, unit of frequency

S&C Strength and Conditioning Coach

ACL Anterior cruciate ligament

BIL Bilateral training group

UNI Unilateral training group

COM Comparison training group

COD Change of direction

SS Split squat

RESS Rear foot elevated split squat

LHS left hand side

RHS right hand side

C7 7^{th} cervical vertebra

VBT velocity-based training

VMO Vastus medialis oblique

VL Vastus lateralis

Statistical

CL Confidence limit

ES Effect size

ICC Intraclass correlation

CV% Coefficient of variation percent

SWC Smallest worthwhile change

SEM Standard error of measurement

TE Technical error

SD Standard deviation

n number of trials/participants

Laboratory

N Newtons, units of force

RFD Rate of force development

Imp Impulse

3D three dimension

GRF Ground reaction force

EMG electromyography

LPT Linear position transducer

List of Publications and Presentations

I would like to acknowledge the contribution of reviewers and editors who graciously offered their time to provide constructive feedback to enhance the quality of these papers.

At the time of submission, the following chapters had been submitted/accepted for publication.

Chapter Four (in 2018, was accepted for publication)

Appleby BB, Banyard HG, Cormack SJ, and Newton RU, Validity and reliability of methods to determine barbell displacement in heavy back squats: Implications for velocity-based training. *Journal of Strength and Conditioning Research.*

Chapter Five (in 2019, was resubmitted for second review)

Appleby BB, Newton RU, and Cormack SJ, Reliability of squat kinetics in well-trained rugby players: Implications for monitoring training. *Journal of Strength and Conditioning Research.*

Chapter Nine (in 2018, was accepted for publication)

Appleby BB, Newton RU, and Cormack SJ, Kinetics and kinematics of the squat and step-up in well-trained rugby players. *Journal of Strength and Conditioning Research.*

Chapter Ten (in 2019, appeared in print)

Appleby BB, Cormack SJ, and Newton RU, Specificity and transfer of lower body strength: Influence of bilateral or unilateral lower body resistance training. *Journal of Strength and Conditioning Research*, 33 (2), 318-326.

Chapter Eleven (in 2018, was accepted for publication)

Appleby BB, Cormack SJ, and Newton RU, Unilateral and bilateral lower body resistance training does not transfer equally to sprint and change of direction performance. *Journal of Strength and Conditioning Research.*

NB. Please note the formatting of text within the following chapters does not coincide 100% with the published manuscripts as listed above. The reference styles and abbreviations may have been modified from the preferred style of the journal to maintain consistency within this thesis. The content has been modified in appearance / formatting only, text, tables, figures and references have not been altered in any way. For example, "Table 1" in Chapter Four now reads as "Table 4.1".

Statement of Contribution

Chapters 1, 2, 6, 7, 8 and 12. Brendyn B Appleby, Prue Cormie and Robert U Newton contributed to the conception, design, analysis or writing of the chapters.

Chapters 3, 4, 9, 10 and 11. Brendyn B Appleby, Prue Cormie, Stuart J Cormack and Robert U Newton contributed to the conception, design, analysis or writing of the chapters.

Chapter 5. Brendyn B Appleby, Prue Cormie, Stuart J Cormack, Harry Banyard and Robert U Newton contributed to the conception, design, analysis or writing of the chapter.

Table of Contents

List of Figures

Figure 10.3 Mean (±SD) and individual responses for 1RM Squat (A) and 1RM Step-up (B) for each treatment group. Training phase: Base = Baseline testing; Mid = Mid testing; End T. = End training; End M. = End maintenance 163

List of Tables

Thesis Summary

To facilitate reading, this thesis is presented in five parts:

1. Part One: Establishing the position of this research, this part details essential research questions underpinning this thesis (Chapter 1 – Introduction). Chapter Two presents a comprehensive review of the literature pertaining to the application of bilateral and unilateral resistance training for enhancing athletic performance.

2. Part Two: Comprised of three chapters presenting important methodological aspects (validity and reliability) pertinent to sound experimental design.

3. Part Three: Complementing and expanding on Part Two this section presents three technical papers exploring the within-session reliability of squat and step-up biomechanical assessment. Information in this series of technical papers permits confident interpretation of data presented in Part Four.

4. Part Four: Presents the core experimental chapters. First, Chapter Nine compares kinetics and kinematics of the back squat and step-up performed by well-trained participants drawing attention to similarities and differences between the squat and step-up and providing insight regarding potential training application. These findings are explored in a training study comparing development and expression of lower body strength using back squats or step-ups and transfer of strength between the exercises. Ultimately, the success of resistance training is measured by improvement in athletic performance – speed and change of direction. The final experimental chapter presents a training study data detailing improvements and contrasts in athletic performance as a result of bilateral or unilateral resistance training.

5. Part Five: The concluding chapter summarises main findings and provides practical applications addressing the research questions presented, acknowledging thesis limitations and providing future research considerations.

Part One

Chapter 1: Introduction.

Chapter 2: Review of the Literature.

Part Two

Chapter 3: The lower body step-up exercise: Strength testing reliability and training application.

* Chapter 4: Validity and reliability of methods to determine barbell displacement in heavy back squats: Implications for velocity based training.

Chapter 5: Reliability of squat kinetics in well-trained rugby players: Implications for monitoring training.

Part Three

Chapter 6: Technical paper: Reliability of back squat kinematics.

Chapter 7: Technical paper: Reliability of step-up kinetics.

Chapter 8: Technical paper: Reliability of step-up kinematics.

Part Four

* Chapter 9: Kinetics and kinematics of the squat and step-up in well-trained rugby players.

* Chapter 10: Specificity and transfer of lower body strength – the influence of bilateral and unilateral resistance training.

* Chapter 11: Unilateral and bilateral lower body resistance training does not transfer equally to sprint and change of direction performance.

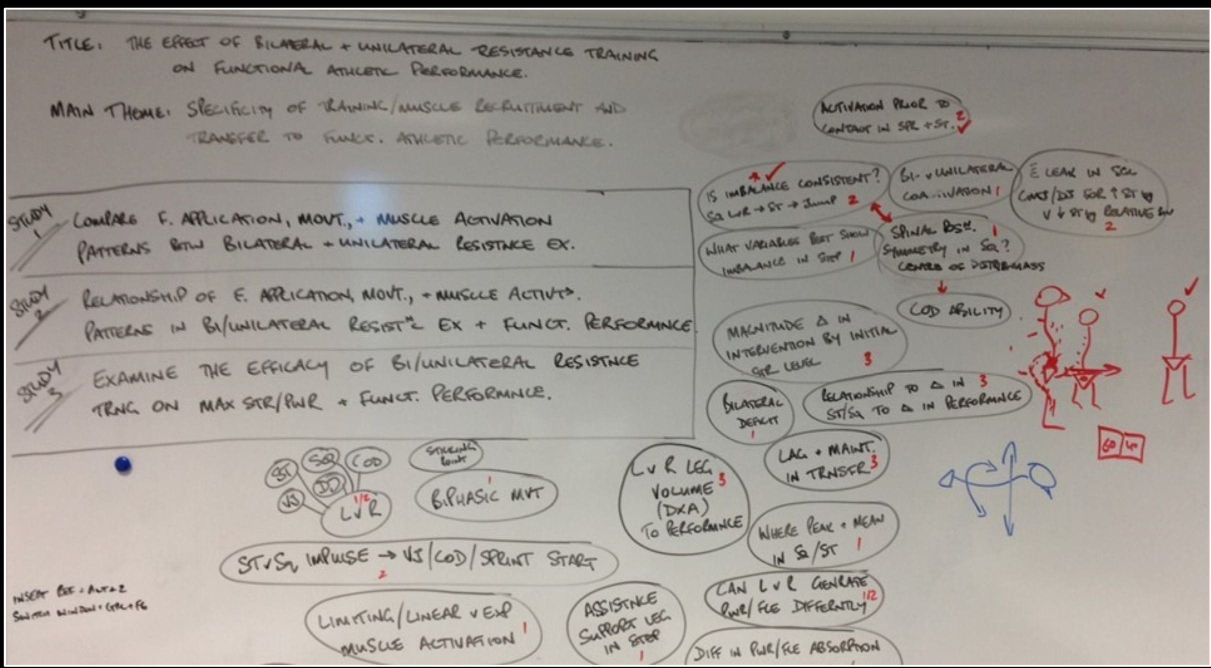
Part Five

Chapter 12: General thesis summary and conclusions.

* = *accepted for publication.*

Figure I. Schematic representation of thesis.

PART ONE



TITLE: THE EFFECT OF BILATERAL + UNILATERAL RESISTANCE TRAINING ON FUNCTIONAL ATHLETIC PERFORMANCE.
MAIN THEME: SPECIFICITY OF TRAINING/MUSCLE RECRUITMENT AND TRANSFER TO FUNCT. ATHLETIC PERFORMANCE.
STUDY 1 COMPARE F. APPLICATION, MOVT., + MUSCLE ACTIVATION PATTERNS BTW BILATERAL + UNILATERAL RESISTNCE EX.
STUDY 2 RELATIONSHIP OF F. APPLICATION, MOVT., + MUSCLE ACTIVTN. PATTERNS IN BI/UNILATERAL RESISTNC EX + FUNCT. PERFORMNCE
STUDY 3 EXAMINE THE EFFICACY OF BI/UNILATERAL RESISTNCE TRNG ON MAX STR/PWR + FUNCT. PERFORMNCE.
BIPHASIC MVT
L v R LEG VOLUME (DXA) TO PERFORMANCE
ST v SQ IMPULSE → VJ/COD/SPRINT START
LIMITING/LINEAR v EXP MUSCLE ACTIVATION
ASSISTNCE SUPPORT LEG IN STEP
COD ABILITY
BILATERAL DEFICIT
LAG + MAINT. IN TRNSFR
WHERE PEAK + MEAN IN SQ/ST
CAN L v R GENRATE PWR/FCE DIFFERENTLY
DIFF IN PWR/FCE ABSORPTION

1

Chapter One

INTRODUCTION

A myriad of morphological and neurological adaptations results from resistance training and as such, resistance training is a fundamental component of athletic preparation (182, 183, 205, 503). The nature (i.e. what type of morphological/neurological adaptations) and the magnitude of adaptation are dependent upon the many variables within the resistance training program. Two key variables in resistance training programs include exercise selection and intensity, as they are intimately linked to the principles of overload and specificity (524). These principles are the governing concepts of program design for athlete development (524, 590). In order to achieve an adaptation, the exercise stimulus must exceed normal physiological demands (i.e. principle of overload) (524). Furthermore, the nature and magnitude of adaptation varies with the exercise stimulus and transfer to the desired athletic performance is greater if the training characteristics closely simulate the targeted movement (i.e. principle of specificity) (477). To maximise the transfer of training to performance, these variables must be arranged in a sophisticated manner as part of a periodised resistance training program which elicits desired physiological adaptations (524, 590). Due to their extensive training history, elite athletes have a small window of adaptation and as a consequence, the use of overload and specificity in exercise programming for this population is even more imperative (12, 28, 208, 248, 254, 299, 431).

The mechanical specificity of an exercise refers to the similarity in muscle activation, force development and movement patterns of a training exercise to the athletic action and it is a critical factor in maximising the transfer of training to performance (523, 526). Muscles adapt in a manner specific to the training stimulus (33, 174, 187, 378, 472, 477). Common throughout the literature is evidence linking specificity of resistance training to improved athletic performance (114, 115, 360). The greater the similarity between the kinetics and kinematics of a training stimulus and the athletic demands of the sport, the greater the likelihood and magnitude of transfer of training to improved athletic performance (185, 388, 524). For example, there is strong evidence demonstrating similar kinetic features between weightlifting and the vertical jump, and as such, improvements in weightlifting performance have also resulted in improvements in vertical jump performance (86, 242, 252, 295). Further, Wilson et. al (564) analysed the changes in performance between three groups who performed either squat strength training, drop jumps or ballistic squat jump training (at the load that maximised mechanical power). Despite the similarity in movement patterns between the three groups, the authors discovered that the ballistic training group significantly increased vertical jump, 30m sprint and six second cycle capacity but did not increase isometric force, compared to the squat group who significantly increased maximum isometric force, but not sprint or cycling performance. This study among many others have clearly demonstrated that selection of mechanically similar resistance training interventions is critical for highly trained athletes to improve the transfer of force production to sporting performance (331, 590).

Bilateral exercises are commonly prescribed in resistance training programs as they allow for significant overload in mechanically specific actions, which in turn, increases strength development and has been demonstrated to transfer to performance (115). For example, bilateral resistance exercises such as weightlifting, squat and deadlifts feature prominently in resistance training for elite athletes due to the mechanical specificity to the performance of common athletic movements such as jumping, sprinting and changing direction. As such, relationships between bilateral lifting performance, and actions such as jumping and short distance sprinting have been well documented (30, 78, 95, 114, 295, 547, 581). In addition to joint angle specificity, these exercises permit substantial neuromuscular overload by the magnitude of external resistance achievable by highly trained performers. The ability to overload mechanically similar actions, improves the neuromuscular mechanisms associated with superior force and power production and is a critically important attribute of these bilateral exercises (115, 132). The highest threshold motor units are only recruited in maximal or near maximal contractions (221, 477). It is theorised that when developed in mechanically specific exercises with similar kinetics, the transfer of increased high threshold motor unit recruitment is more effectively applied to athletic performance (477). Many studies have demonstrated that superior performance in strength, measured by common bilateral resistance exercises, can differentiate sporting level and is associated with superior jumping, sprinting and change of direction performance (25, 27, 66, 209, 227). Therefore, due to the positive neuromuscular changes developed through overload in these mechanically similar exercises, their incorporation in program design for highly trained athletes has long been a strategy for increased physical performance (16, 32, 182, 183, 503).

Unilateral resistance training exercises have been more commonly prescribed in strength and conditioning practice recently due to the fact that sporting performance is dominated by the unilateral movements of jumping, sprinting and changing direction (22, 166, 385, 388). The general theory supporting the inclusion of unilateral resistance training exercises is that these may offer greater levels of specificity, and therefore a superior transfer of training to performance than the more traditional bilateral movements (22, 166, 385, 388). Unilateral resistance training exercises have traditionally been confined to inexperienced athletes or in rehabilitation settings yet have recently become prescribed in advanced strength and conditioning practice based on this general theory and the higher level of specificity required for improvement in already well-trained athletes (232, 511). The advantages of unilateral exercises compared to bilateral exercises may include utilising the bilateral deficit and the specificity of muscle recruitment patterns (421). The bilateral deficit is the phenomenon whereby the summed forces of each unilateral contraction are greater than the total forces of the bilateral contraction (265, 336). This suggests that the magnitude of force development by highly trained athletes may be less in bilateral training compared to unilateral training, and that the appropriate prescription of unilateral exercises may in fact provide greater levels of overload. Additionally, the neuromuscular factors driving movement have been demonstrated to alter based on joint angle/range of motion, contraction/movement velocity, contraction type, external resistance and/or training experience (7, 96, 239, 386). Therefore, there exists a strong theoretical rationale that the specificity of neuromuscular demands in unilateral exercises would differ to bilateral exercises.

Furthermore, bilateral muscle imbalance is well recognised as a precursor to musculoskeletal injury (122, 139, 444, 550, 578). It is possible for an athlete to unintentionally perform a bilateral exercise asymmetrically, contributing to the development and/or exacerbation of musculoskeletal imbalances (313, 432). In rehabilitation or athletic performance training situations, this asymmetry may inhibit appropriate development (478). Insufficient hip neuromuscular function has been associated with lower limb injuries and the importance of synergists to injury prevention has been well documented (302, 550). Furthermore, it has been hypothesized that coordination of synergists is of importance for agonist force production in unsupported exercises (472). The overload of these muscles through unilateral exercises may improve lower body performance compared to bilateral training (139, 148). Differences in muscle activation levels of the rectus femoris, biceps femoris and gluteus medius have been found between single and double leg resistance exercises (157). The biceps femoris and gluteus medius activation levels were significantly higher for the modified single leg squat whilst the rectus femoris was significantly higher in the back squat (386). Despite the theoretical rationale that unilateral resistance training exercises have a high degree of specificity to athletic movements, the scientific research examining the relationship between unilateral resistance training exercises and athletic movements is limited

(232, 511). Unilateral strength training has been demonstrated to improve unilateral vertical jumping ability compared to bilateral training in an eight week study, although participants in this study were untrained male and female college students (389). Additionally, the unilateral training group was performing unilateral plyometrics compared to the bilateral group which performed bilateral plyometrics only. This additional training may have influenced the improvement in single leg jumping ability due to the unfamiliar nature of the task for these untrained participants. A training study incorporating academy rugby players utilised either the modified single leg squat (unilateral) or back squat (bilateral) concluding either training exercise improved lower body strength and 40m speed (511). However, a common limitation of previous unilateral research is either the magnitude of load is low (i.e. the exercise is prescribed for rehabilitation purposes, and therefore does not provide sufficient overload for neuromuscular adaptation that leads to improved athletic performance), the limited training experience of participants, short-term study duration or the exercise selection is asymmetrical in nature but not purely unilateral (i.e. the legs are horizontally off-set and both in contact with the ground during the movement, which is not specific) (22, 63, 75, 384-386, 388, 389). These factors limit the application of current findings to program design for improving elite athletic performance.

Maximising neuromuscular adaptations in athletes requires sophisticated resistance training prescription which involves a high degree of mechanical specificity and overload (amongst other important factors). The challenge for sport scientists is to develop such training programs, as these factors are highly associated with the degree to which resistance training transfers to improved athletic performance. This is even more challenging when working with highly trained/elite athletes given their smaller window for adaptation. While bilateral exercises such as squats and weightlifting have long been recognised for their relationship to athletic performance and capacity for overload, unilateral training may offer equal or superior levels of overload and specificity. Through the use of unilateral training exercises that permit adequate loading (i.e. step-ups), athletes may benefit from greater levels of overload (i.e. not limited by the bilateral deficit) and specificity (i.e. most sporting actions are predominately performed in a unilateral manner). Despite this theoretical rationale, there is a distinct lack of research comparing the mechanical specificity of bilateral and unilateral resistance training exercises on the development of maximal strength and/or the transfer to athletic performance.

Purpose and Research Questions

The primary purpose of this research was to examine the development and transfer of maximal strength developed using the back squat or step-up to athletic performance. Specifically, this thesis was designed to address the following research questions:

One: "A comparison of the force application and movement patterns between bilateral and unilateral resistance training exercises in highly trained athletes"

- What are the force applications and movement patterns during the squat (i.e. bilateral resistance training exercise)?
- What are the force applications and movement patterns during the step-up (i.e. unilateral resistance training exercise)?
- What are the differences and similarities of force applications and movement patterns between bilateral and unilateral resistance training exercises?

Two: "An examination of the efficacy of bilateral and unilateral resistance training for maximum strength development and effect on sprint acceleration and change of direction ability."

- What is the efficacy of bilateral versus unilateral resistance training exercises for the magnitude of change in strength and athletic performance?
- Does resistance training with bilateral or unilateral movements have a superior transfer of training effect (i.e. is the adaptation of a greater magnitude)?

Significance of the Research

The essential purpose of resistance training is to increase athletic performance such as improved sprint speed, jumping ability or change of direction. Given that athletic performance is generally performed unilaterally, this research will provide valuable insight into the relationships between sprinting, change of direction and unilateral resistance training. Additionally, this research will provide insight into the fundamental principles of training: specificity, transfer and maintenance, and have direct applications for training program design.

2

Chapter Two

REVIEW OF THE LITERATURE

INTRODUCTION

Aspects of resistance training are common place in many sporting populations, with a purpose for the enhanced benefit to subsequent athletic performance (such as sprint acceleration or jumping), and not necessarily for the betterment of resistance exercise performance (394). That is, athletes do not, for example, squat to improve squatting, but squat to improve lower body strength to improve on-field performance (333, 396). Whilst evidence has been frequently presented establishing relationships between measures of lower body strength and athletic performance, resistance training to improve on-field/court performance can be complicated with a range of neuromuscular adaptations greatly influenced by exercise selection. Two guiding principles for physiological adaptation are intensity of training and specificity to maximise transfer of training to the intended performance (332, 524). Thus, exercise selection is a critical underlying consideration of athletic program design in maximising transfer – an exercise requires substantial intensity for overload resulting in adaptation and specific enough to maximise transfer to athletic performance. Superior athletic performance in the form of sprinting and agility are often contest defining attributes and a focus of preparation for many team sport athletes.

The importance of superior athletic performance and the interaction with resistance training is a broad and complex area. As such, the current literature review will broadly examine several overarching themes regarding resistance training and athletic performance, narrowing to specific bilateral and unilateral resistance training applications and their impact on athletic performance. First, the review will explore the value of sprint acceleration and change of direction capacity in team sport athletes, the assessment of such capacities and the role of resistance training in enhancing these on-field qualities. Additionally, the principles of resistance training with particular emphasis on specificity of training, will be explored, leading to a review of prominent lower body bilateral and unilateral strength applications. Finally, examples of training studies comparing bilateral and unilateral interventions on the development of maximal strength and subsequent athletic performance will be presented. The aim is to provide context for the position of this thesis in the current literature and its contribution and practical significance for enhancing athletic development.

- *1* -

ATHLETIC PERFORMANCE

A burst of speed from a striker into space for a scoring opportunity.

A slam dunk from the free throw line.

A defender's clearing kick.

The centre field throw to home.

Sprinting, jumping, kicking and throwing – decisive physical qualities of team sport performance. Research has demonstrated relationships between neuromuscular strength and athletic performance tasks such as jumping, sprinting or throwing (31, 102, 234, 295, 377, 392, 493, 530, 531). Further, superior performance of these actions have been revealed in various sports delimitating successful competitive levels and playing positions (27, 41, 66, 151, 209, 227, 329, 454, 584, 588). Underpinning power and speed is a foundation of maximal strength; the capacity to apply force (130, 529, 533). Combined with injury risk reduction and rehabilitation (342, 343), resistance training has a long integration in power-based events, such as track and field and team sports, in an effort to improve athletic performance (180, 279, 380, 397, 452). Principles of resistance training – specificity and overload – are critically linked to the development and transfer of favourable neuromuscular adaptations driving improved athletic performance. Whilst bilateral exercises are commonly prescribed due to demonstrated strength, speed and change of direction benefits, the specificity of unilateral training, including enhanced neuromuscular activation strategies, reveal a unique gap in the literature with regard to development and transfer of lower body strength to sprint acceleration and change of direction capacity.

Acceleration in Team Sports

There are three biomechanically differentiated phases of sprinting: acceleration, maximum running speed and deceleration (159, 404, 407, 557). Each phase has distinct kinematic and kinetic differences which require specific testing and training interventions (44, 159, 347). Although maximal speed is an important athletic characteristic and team field sports dimensions may exceed 90m in length, analysis of sprint profiles indicate that players seldom exceed 40m sprint distances (e.g. rugby league, rugby union, Australian Rules football and

American football) (21, 153, 164, 177, 178, 513). Time motion analysis has shown that a greater percentage of sprints by elite European soccer players are of a short distance (less than 10m) compared to longer sprints (164); that average sprint duration in international field hockey is 1.8s, suggesting short distance (514) and rugby union backs competing at international provincial level average 18m per sprint (21). As such, the sprint acceleration phase is deemed a crucial capacity for performance in such sports (21, 78, 140, 141, 178, 219, 350, 403, 424) and may separate playing and performance levels (217, 218, 450, 508, 588).

Innate differences exist between track sprinting and team sport sprinting. Whilst elite sprinters often achieve maximal velocity at ranges of 50-60m, team sport athletes are limited by time and distance constraints. However, many team sport sprint performances are initiated from a moving start, enabling attainment of velocity in excess of 90% capacity, also demonstrating the importance of acceleration capacity (164, 178, 458). Collectively, time motion analyses and practically implemented testing batteries emphasise the worth of acceleration capacity in team sports.

Physiological Characteristics of Sprint Acceleration

Laboratory Assessment

Understanding the kinetics and kinematics of sprint acceleration allows recognition of critical characteristics differentiating superior acceleration performance. The importance of training specificity dictates a comprehensive understanding of movement to facilitate training interventions improving performance (350). Laboratory based investigations have incorporated motion analysis (300, 350, 589), force plates (300, 317, 405, 413, 589) and electromyography (EMG) (405, 414) to determine step length and stride frequency (350, 405) joint angles and body posture (300), ground reaction forces (300, 317, 413, 414, 589), muscle activation, muscle and joint forces (405, 406, 414, 589). Combined, this information permits understanding of the neuromuscular characteristics of sprint acceleration performance.

Sprint acceleration is determined by the sum of ground reaction force (GRF) acting on the body (300). Of the three directions (vertical, anterior-posterior and medial-lateral) the vertical and anterior-posterior (henceforth termed "horizontal") are of most interest (300, 317). Horizontal GRF is comprised of a braking component and an acceleration component (404).

Net horizontal GRF, normalised to body mass, would appear a determining factor in acceleration performance in accordance with Newton's impulse-momentum relationship (317). Investigations of GRF during sprinting have revealed significant correlations between sprint performance and horizontal and vertical GRF (300, 404). These studies suggest that acceleration performance is a result of an optimal combination of vertical and horizontal GRF. Hunter et al investigating kinetics of sprinters at the 16-metre mark reported faster athletes produced greater magnitudes of propulsive impulse relative to body mass, supporting earlier findings in elite sprinters (300, 405). Investigating male subjects from a variety of field sports, Murphy et al reported faster stride rate and shorter ground contact time as distinguishing kinematic variables between fast and slow team sport athletes over 15m (424). These superior kinematics are the result of more favourable ground reaction force. Kawamori et al reported that faster performance over eight metres was related to horizontal impulse ($r = -0.52$). Although reporting a slightly weaker correlation compared to previous work, the initial starting technique and the heterogeneous team sport nature of the cohort may have influenced the findings. Previous sprint acceleration research has utilised track sprinters which may cluster data points influencing correlation statistics. Collectively these investigations demonstrate the relationship between high force production and superior sprint acceleration performance. Such information guides training interventions to improve the desired traits for superior performance.

Field Assessment

Whilst laboratory testing has revealed underlying kinetic and kinematic characteristics of sprint performance, the technical requirements of such testing prohibit the practical implementation in the team sport training environment. Field testing assists coaches to establish sport specific physiological profiles, and guide rehabilitation to monitor individual athlete performance or determine training effectiveness (573). Given the importance of the acceleration phase in many teams sports distances such as 5m, 9.1m (10 yards) 10m and 20m are frequently reported assessments in a multitude of field sports (Australian Rules Football, American Football, rugby league, rugby union, soccer, cricket, basketball, softball) (30, 114, 140, 203, 204, 424, 438, 569, 588).

Central to the interpretation of change is reliability which is the "reproducibility of the observed value when the measurement is repeated" (285). Reliability is maximised by standardising many aspects of testing including participant test familiarisation, consistent environmental conditions including ground surface and ambient temperature, reliable equipment, standard warm-up and fatigue free state of participants (573). Within-session reliability has been reported to be high indicating few testing repetitions are required within a session (146). Of importance is between-session reliability for new or novel tests, or new populations where existing reliability may not exist. Between-session reliability of field tests of acceleration have been performed in numerous sports and with variation in testing surface, timing gate type and configuration (Table 1). Given the array of testing variables, sprint acceleration in team sport athletes is reliable which may be explained by the degree of competence in sprinting as a familiar motor skill (412).

Table 2.1 Typical test values and between-session reliability of short sprint distance representative of team sports athletes.

Author	Subject age Ave ± SD *(n)*	Subject experience & sport	Surface	Gate model	0m Gate	Distance (m)	Time Ave ± SD (s)	CV%	TE	ICC	Trial used in analysis
Byrne (81)	21.2 ± 2.1 *(18)*	Irish collegiate hurling (M)	Indoors	6	0.5m behind	5 10 20	1.06 ± 0.07 1.81 ± 0.09 3.13 ± 0.14	2.0% 1.6% 1.1%		0.9 0.95 0.96	Fastest trial
Cormie (125)	24 ± 4.8 *(10)*	Recreational (M)	Outdoor	3	0m	5 10 20 Flying 15	1.07 ± 0.10 1.82 ± 0.11 3.12 ± 0.18 2.05 ± 0.10	6.3-9.1% 5.2-6.2% 5.4-5.6% 4.7-5.7%		0.90 0.98 0.99 0.97	Fastest trial
Carr (89)	23.8 ± 3.7 *(16)*	1st class county cricket (M)	Indoor cricket	1	0.5m behind	5 10 20	1.06 ± 0.06 1.79 ± 0.07 3.08 ± 0.12			0.95 0.96 0.96	Fastest trial
Green (238)	19 ± 1.7 *(11)*	Snr Provincial RU (M)	Indoor track	5	0.70m behind	10 30	2.04 ± 0.16 4.58 ± 0.33		SEM 0.06 SEM 0.06	0.88 0.97	Mean of 3 trials
Gabbett (220)	23.6 ± 5.3 *(42)*	Snr RL (M)	Not reported	3	0m	5 10 20	1.20 ±0.10 1.98 ± 0.13 3.39 ± 0.20		1.3%-3.2%	0.84-0.96	Fastest trial
Lockie (355)	23.8 + 7.0 *(18)*	Amateur ARF (M)	Grass outdoor	5	0.3m behind	5 10 20	1.09 (0.7*) 1.87 (0.11*) 3.26 (0.17*)	5.1% 3.5% 1.9%	0.04s 0.04s 0.06s	0.76 0.85 0.96	Average of 3 best trials
Sheppard (497)	21.8 ± 3.2 *(32)*	State level ARF (M)	Indoor wooden	2	0m	10	1.89 ± 0.05		0.01	0.865	Mean of two trials
Moir (412)	25.3 ± 6.6 *(10)*	Physical education students (M)	Indoor running track	4	0.5m behind	10 20	Graphed	2.0 1.9		0.93 0.91	Fastest trial
Mann (365)	20.5 ± 1.2 *(64)*	Div I American Football (M)	Indoor artificial turf	2	Ground hand touch pad	9.1 (10yd)	1.81 ± 0.14	1.2%	0.01	0.97	Fastest trial

Ave = average, SD = standard deviation; n = number; s = seconds; CV% = coefficient of variation, TE = technical error of measurement, ICC = intraclass correlation coefficient; M = male, Recreational: "a wide variety of sports"; Snr = senior, ARF = Australian Rules Football, RU = Rugby union; RL = Rugby league; Div I = Division one; * = denotes 90%CL reported instead of SD; 0m Gate = position of first timing gate; Distance = distance of timing gate split, m = metres, yd = yards.

Gate model: (1) Brower Timing Systems, Draper, UT, USA; (2) KMS, Fitness Technologies, Adelaide, AUS; (3) Speedlight, Swift Sports, Lismore, AUS; (4) STT = Sprint Timer Telemetry, Cranlea and Company, ENG; (5) Fusion Sport Smart Speed, Brisbane, AUS; (6) Microgate, Bolzano, ITA.

Superior acceleration capacity has been identified as a discriminator between playing levels and playing positions in many sports (214, 215, 218, 227, 308, 310, 544, 546, 588). At the elite level, starters in a professional Australian Rules Football team were significantly faster over 10m and Flying 30m (40m time minus 10m time) than their non-starting teammates (588). Further importance of acceleration capacity was demonstrated by a comparison between elite rugby union and rugby league players. Whilst rugby union players were faster at 20m (ES = 0.76), the greatest difference between backs from both codes was greatest at 2m (ES = 0.95). Estimated to 0.44m after two seconds of sprinting, the authors suggested this practical difference alluded to short-distance acceleration as important for match success (147). Linking field and laboratory analysis, the authors suggested that the more combative body orientation requirements of rugby union (greater forward lean) (159, 580) favoured horizontal force production required for superior acceleration.

Change of Direction in Team Sports

Whilst sprinting and acceleration are desired physical traits in many team sports, there are frequent events where athletic movement is characterised more by changes of direction than straight line running (153, 586). As such, agility or change of direction (COD) is an important physical requirement for team sport athletes (498). Generally defined as encompassing deceleration, a change to the direction of initial motion and then acceleration, agility is frequently assessed in a multitude of sports (204, 220, 274, 416, 438, 518). The importance and complexity of agility in sport is highlighted by the scope of research, array of available agility tests (Table 2) and the breadth of sport science sub-disciplines that investigate and enhance performance (e.g. biomechanics, physiology, motor control, psychology) (193, 237, 274, 353, 356, 495, 498, 515, 518, 579). Investigations of agility and COD performance have ranged from studies exploring biomechanical factors of injury risk and prevention (61, 161, 348, 561), various timed courses of sport specific demands (204, 238, 262, 438, 465, 500), distinction of planned versus reactive tests (193, 216, 416, 443, 497, 517, 555, 585), isolated investigations of specific neuromuscular demands of COD (170, 435, 515) and relationships between agility/COD performance to other physical capacities (such as jumping and muscular strength) (92, 95, 204, 270, 312, 354, 356, 367, 543).

Table 2.2 Typical test values and between-session reliability of COD assessments representative of team sports athletes.

Author	Subject Age Ave ±S D *(n)*	Subject experience & sport	Surface	Test	Time Ave ± SD (s)	CV%	TE	ICC	Trial used in analysis
Nimphius (439)	18.1 ± 1.6 *(10)*	Provincial softball (F)	Grass outdoor	505D	2.70 + 0.14	≥ 1.9%		≥ 0.93	Fastest trial
Barber (40)	23.9 ± 5.4 *(52)*	Netball (F)	Netball court	F505 S505	2.84 + 0.22 2.52 + 0.17		SEM = 0.04	0.97 0.95	Not reported
Cronin (145)	23.1 ± 4.8 *(40)*	Recreational (M & F)	Not reported	Modified T-Test	3.77 + 0.37	2.1%		0.88	Fastest trial
Lockie (355)	23.8 ± 7.0 *(18)*	Amateur ARF (M)	Grass outdoor	Illinois Agility Run CODAT	14.08 (13.8-14.4*) 6.10 (5.95-6.26*)	2.5% 3.0%	0.29s 0.19s	0.91 0.84	Average of 3 best trials
Gabbett (220)	23.6 ± 5.3 *(42)*	Senior RL (M)	Not reported	505 test Modified 505 L Run (m)	2.39 + 0.17 2.73 + 0.17 5.77 + 0.69		1.9 2.5 2.8	0.90 0.92 0.95	Fastest trial
Mann (365)	20.5 ± 1.2 *(64)*	Div I American Football (M)	Indoor artificial turf	L Run (yd) Pro Agility	7.41 + 0.43 4.47 + 0.29	1.2% 1.9%	0.12 0.13	0.96 0.91	Fastest trial

Ave = average, SD = standard deviation; n = number; s = seconds; CV% = coefficient of variation, TE = technical error of measurement, ICC = intraclass correlation coefficient; M = male, F = female; Recreational: “a wide variety of sports”, no specifics presented; ARF = Australian Rules Football, Senior RL = Senior rugby league; Div I = Division one; D = dominant as determined by batting stance; F505 = Flying 505 with 10m lead in to 5m out and back 180° turn; S505 = 5m out and back 180° turn; CODAT = Change-of-Direction and Acceleration Test; L-run (m) = L-run performed at 5 metres; L-run (yd) = L-run performed at 5 yards * = denotes 90%CL reported instead of SD.

The model of agility presented by Young et al (Figure 2.1) recognises two major sub-categories of perception and change of direction speed (586). While the decision-making aspect of team sport remains a critical capacity (585), the central focus of this review and subsequent thesis shall be concerned with the physical characteristics of COD.

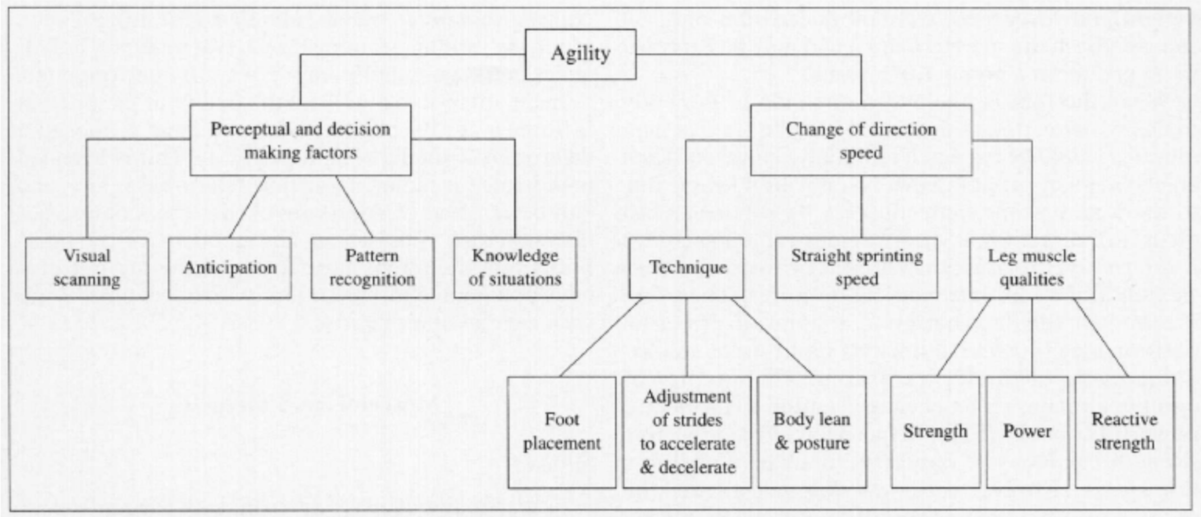


Figure 2.1 Model of main factors of agility, Young (2002) (586)

Physiological Characteristics of Change of Direction Laboratory Assessment

As with faster sprint ability, superior COD is vital in the sport setting, however, also associated with injury. Early laboratory studies of COD incorporated EMG, force plates and motion analysis, predominantly in an endeavour to understand injury risk during cutting (60, 61, 111, 162, 339, 398, 425, 429, 554, 561). Focussed predominantly on anterior cruciate ligament injury, many reported aspects such as the differences in eccentric muscle actions of quadriceps and hamstrings during foot strike (111, 429), coactivation differences between planned and reactive COD (61), the role of hip abductors and adductors in pelvic stabilisation (429) and specific joint angles at foot-strike (60, 398, 554). This research direction cultivated specific injury reduction training strategies (110, 161, 272, 348, 364, 425, 427). Common to these programs was the attention to single leg function in terms of maximal strength, proprioception, muscle imbalance and performance in physical tasks with attention to hip control (186). Neuromuscular control of the hip has been recommended as a factor to reduce the risk of knee injury during COD (398). As well as focussed interest at the knee, full body kinematics have revealed important upper body contribution to lower body moments, impulse and cutting performance (98, 162, 167, 481). Collectively, these studies portray the complexity of injury risk and demands of COD performance. The broad array of program considerations for performance enhancement and injury prevention begin to demonstrate the multifaceted nature of COD.

Whilst reducing injury risk remains important for athlete welfare, laboratory studies have also examined characteristics of superior COD performance (169, 368, 515). Although identified as a risk factor to injury, pelvic control during the single limb support phase was also determined as a key factor in superior COD performance (368). Incorporating motion analysis and force plates during a 75° cut performed by elite Gaelic hurlers, Marshall et al concluded that control during deceleration by the plant leg contributed to faster COD times. The researchers suggested prescription of frontal plane exercises in single limb stance such as single leg squats and single leg landings to enhance pelvic control. The combination of strength (the ability to produce force) and optimal mechanics is recommended for safe and effective COD (162, 171).

In a series of studies utilising force plates and EMG, Spiteri et al investigated the relationships of lower body strength to performance (515). Creating two groups based on relative isometric back squat force, it was observed that during the 45° COD test, the stronger group produced significantly higher ground reaction forces and significantly faster COD times compared to the weaker group (515). It was concluded that greater levels of relative lower body strength produced superior COD performance. This study was expanded to include eccentric, isometric and concentric strength measures and two COD tests (505 and T-Test) (518) (Figure 2.2). Many correlations between strength and superior COD performance were reported, supporting maximal dynamic strength as a crucial base for COD performance (295). Importantly, many subtle observations were made regarding the specificity and relationships of capacity testing. First, isometric strength was slightly more related to the T-Test than 505 task. The authors considered the body position and direction changes of the T-Test required greater isometric strength compared to the 505. This implies the nature of the COD task may demand different strength capacities demonstrating the specificity of the COD task to strength assessment (516, 518, 543). This is particularly important for subsequent training interventions when considering the array of testing options available. Finally, a relationship between concentric strength and COD performance was identified, in contrast to previous studies (42, 586). The authors considered the conflict between the concentric strength tests in the current study (a multi-joint box squat) to previous isokinetic testing (single joint knee extension) (42, 586) and the specificity to COD tasks.

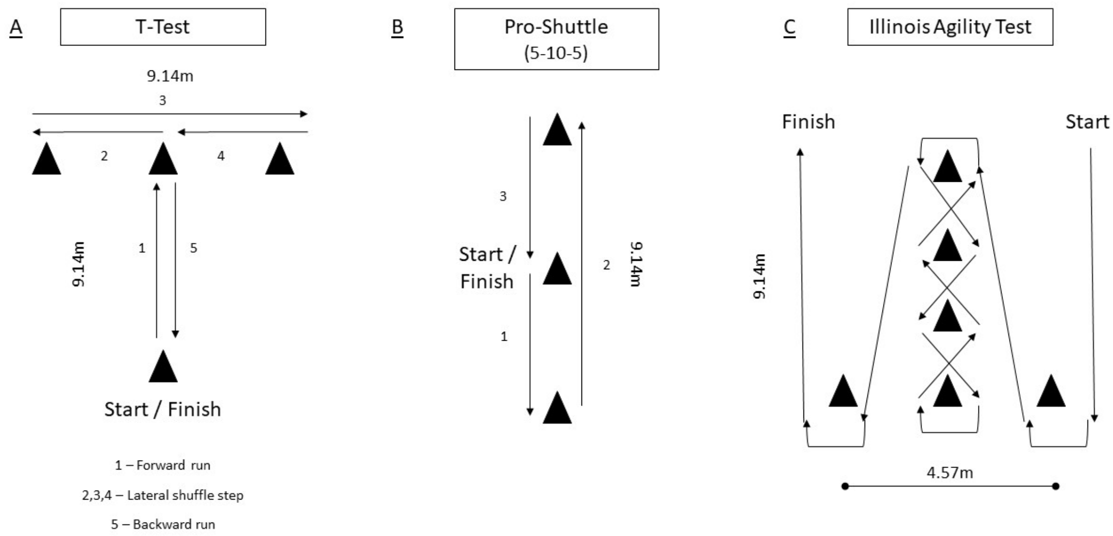


Figure 2.2 The T-Test (left), Pro Shuttle (centre) and Illinois Agility test (right).

The importance of comprehensive lower limb strength to superior COD performance was supported by Dos Santos et al testing 40 sub-elite and collegiate team sport athletes utilising the modified 505 (169). The researchers dissected COD performance analysing ground contact time and ground reaction forces of the final and penultimate step in a 180° COD task. Ground contact time, horizontal braking force and horizontal propulsive force were discriminating factors between fast and slow performers, reinforcing the importance of comprehensive lower limb strength (516). Given the complexity of mechanical demands involved in rapid direction change, the research suggested development of lower body strength is a comprehensive strategy.

Field Assessment

Although COD performance can be divided into discrete biomechanical capacities, similar to the phases of sprinting, it remains a complicated technical synchronisation of many body parts which is difficult to capture in a single test (448). As a result, there is a great diversity of tests which are problematic for distinguishing capacity (typical performance and reliability are presented in Table 2). The nature of the COD task alters the contribution of running speed and technique and the subsequent ability for investigators to isolate and interpret mechanisms for change (495). Task issues include total test time, number of direction changes, type of change (entry and exit angles), composition of linear sprinting, entry and exit speeds, and total distance of test selection (436). For example, the 5-0-5 test requires a single 180° redirection whereas the Illinois has curvilinear components and 11 direction changes. The AFL agility test requires footballers to perform two right-side turns and three left-side turns, disadvantaging left leg dominant (right-turn) athletes (262). Additionally, tests can range from 1.5s for a simple 5-0-5 test to up to 16s in duration for the Illinois Agility Test (Figure 2), the long duration potentially assessing anaerobic ability and not COD factors (436, 483).

Whilst linear speed and COD speed are considered somewhat related (120, 306, 312, 355, 371, 497), they are deemed separate qualities with unique neuromuscular requirements (83, 120, 347, 371, 435, 436, 475, 586, 587). Confusion regarding the relationships between linear speed and COD can be attributed to test design featuring few direction changes, obtuse angle and large proportions of linear speed involvement. A large proportion of straight-line sprinting can mask inferior COD capacity, a concept incorporated in new analysis protocols (435, 437). Exit speed from a direction change has discriminated faster and slower performers (515) however, it is difficult to measure in the field. The COD deficit has been applied to extract COD capacity from linear sprint speed (435, 437). Young et al demonstrated the specificity of straight-line sprint training only or COD training only (587). The researchers utilised seven variations of a 30m course increasing the number and degree of angle of direction change from straight line to five 100° changes. The straight-line sprint group improved the most in straight sprinting speed with little transfer to the 7th course with most COD, whilst the COD group improved the most in the 7th course and the least in the straight sprint test. This highlighted the specificity of training with speed and COD, distinguishing straight line speed and COD as distinct qualities (83, 371).

Test selection is critical to assess COD. Appropriate tests should be short in duration and distance minimising the influence of energy system and linear speed capacity, possess a single COD to isolate unilateral performance and have context to the athlete's sport and coaching perspective (436). Thus, whilst variation in testing protocols and sports have proved problematic for widespread conclusions, particular methodologies have identified areas of physical development for COD. When the total course distance is short and the number of direction changes few, relationships between performance and strength capacities are observed, highlighting the importance of lower body strength in COD performance (312, 518).

RELATIONSHIPS OF STRENGTH AND ATHLETIC PERFORMANCE IN TEAM SPORTS

Laboratory and field studies have shown that to accelerate from a stationary or moving start, an athlete needs to produce high levels of force to overcome the body's inertia (317, 351). Compared to maximum velocity sprinting, ground contact time is relatively high and stride rate is typically slower to maximise the development of ground reaction force (44, 347, 404, 407). Muscle contraction is characteristically concentric in nature with superior sprint acceleration related to concentric force development (507), whereas maximum velocity running has a higher elastic energy contribution (159). The postural alignment depicts a forward trunk lean positioning the centre of mass in front of the grounded foot and aligns horizontal acceleration in the direction of intended travel (159, 580). Knee extension through quadriceps activation is the primary generation of force in this posture (304, 407). Collectively, these kinetic and kinematic characteristics of acceleration are targeted variables in the prescription of maximal strength training to improve sprint capacity.

Relationships have been reported between measures of short-sprint performance and measures of lower body strength, particularly when expressed relative to bodyweight (30, 78, 100, 114, 118, 140, 159, 258, 260, 295, 375, 430, 462, 569, 581). Due to these relationships, lower body resistance training has been recommended to improve sprint acceleration. Similarly, whilst identified as a distinct capacity comprehensive lower body strength has been demonstrated important for COD performance (158, 171, 273, 542). Though studies have demonstrated variance between the performance of sprint phases and change of direction capacity (120, 347, 581), both share elements of lower body strength reinforcing the relevance of comprehensive lower body strength to sprint and COD performance in athletes (169, 515, 516, 537).

INFLUENCE OF STRENGTH IMPROVEMENT ON ACCELERATION AND CHANGE OF DIRECTION

As lower body strength underpins performance of sprint acceleration and COD performance, improvements in strength facilitate improvements in athletic performance. The role of resistance training for improving speed has long been recognised (160) with improvements in lower body strength shown to increase sprint speed in a variety of subjects (115, 278, 351, 468, 479, 532, 547, 577). However, consideration should be afforded to contextual elements of research design, that influence adaptation and transfer, and interpretation and application of training merit, such as subject training age, length of intervention and the appropriateness of the intervention. For example, less trained subjects respond more favourably to training than experienced subjects (43, 522, 566), whilst short-term training interventions may not reflect long-term adaptation (29). However, well-trained athletes (e.g. elite or professional team sport) are often difficult to access for long-training interventions and whilst untrained participants (e.g. students) may be available for longer periods, their untrained status may exaggerate the training adaptation and program merit. The appropriateness of the training intervention can also render misleading conclusions. For example, a twice per week, eight-week resistance training program returned unclear sprint (0-10m) and COD results in under-19 soccer players, however, the squat training program intensity peaked at 60% one repetition maximum (1RM), a low intensity for strength development (154, 332).

Several studies in team sport athletes have illustrated improvements in strength can transfer to sprint performance. A 15-week training program in college football players demonstrated improvements in lower body strength with reductions in sprint time (278). Two separate studies with professional soccer players demonstrated improvements in 1RM squat was associated with improvements in sprint performance over 5m, 10m, 20m and 40m (468, 532). Of similar duration, professional rugby league players have been reported to improve back squat 1RM (17.7%) and 5m (7.6%), 10m (7.3%), and 20m (5.9%) sprint times after an 8-week resistance training phase (115). A systematic review of 15 studies demonstrated the transfer of improved strength to sprinting is of practical importance to coaches (490).

Training interventions have also demonstrated concurrent improvements in strength and COD performance. Positive changes in 3RM squat and 505 COD performance have been noted in softball players during a 20-week preparation phase (439). Additionally, strength training has been demonstrated to improve COD in young soccer players, however, the adaptations were expected given the long duration of the study and young age of the cohort (320). Finally, improvements in lower body strength (measured by 1RM squat) were associated with significant improvements in pro-agility performance during a 5-week training program with Academy rugby players (511).

SUMMARY

Sprint acceleration and COD are critical capacities in many team sports. Laboratory and field analyses have revealed fundamental biomechanical characteristics of successful performance and established relationships to physical capacity for training interventions, particularly maximal strength. Whilst commonality exists in strength qualities between capacities for sprint and COD, they remain independent qualities, requiring a degree of specific training application. Due to the limited transfer, training prescription is a critical consideration for the transfer of lower body strength to sprint performance. The principle of specificity dictates that the training exercise should be highly specific to the performance outcome (524, 565). Transfer of resistance training adaptations to enhanced sprint performance is limited due to complexities in aligning movement patterns and contraction type (565, 583). Whilst lower body maximal strength was related to COD performance, the nature of direction change required altered the determinant strength capacity (isometric, eccentric or concentric) demonstrating the importance of all components of maximal strength as an important base for performance (516). It has been suggested that unilateral lower body strength may identify, particularly COD exit performance (471, 586) and COD performance may potentially be enhanced by correcting lower limb imbalance (495). Research from training studies has demonstrated the beneficial application of resistance training to enhance the physiological qualities contributing to enhanced sprint and COD performance (490). To maximise athletic performance, the method for development and transfer of enhanced neuromuscular force generating capacity is of utmost importance. An understanding of resistance training principles is required.

- 2 -

Resistance Training: Biological Adaptation and Training Principles – A Brief Review

Measures of lower body strength have been related to sprint acceleration and COD performance, and improvements in strength enhance sprint and COD (490). Ground reaction force profiles during movements such as jumps (127), maximal isometric tasks (e.g. mid-thigh pull or squat (47, 245)) and track sprint starts (35, 47, 246, 318) distinguish components such as explosive strength (rate of force development) (245), reactive strength (the contraction of a muscle preceded immediately by a stretch load, typical of a drop jump (202)) low- and high-load speed strength (431) and maximum strength (590). Maximum strength is considered a foundation capacity that supports the development of the abovementioned strength capacities and other sport specific conditioning (244, 529, 539). It is commonly measured in isometric tasks or isoinertial field-based strength tests (i.e. one repetition maximum strength tests – e.g. 1RM squat) (4, 175, 331, 402). The purpose of resistance training in many athletic settings is to increase maximum strength.

Strength enhancements can be attributed to neural and morphological adaptations resulting from resistance training interventions (205, 251, 477). Neural improvements refer to a variety of intra- and inter-muscular responses such as, firing frequency, onset of activation, motor unit synchronisation and antagonist coactivation, improving coordination of involved muscles during a specific task (52, 205, 231, 472). Morphological adaptations include increase in cross sectional area, muscle fibre pennation angle and structural improvement of tendon and connective tissue (11, 194, 205). The neuromuscular adaptations are dependent upon the manipulation of many acute variables including exercise selection, magnitude of external load (intensity), sets and repetitions (volume), lifting cadence (or time under tension), and intra- and inter-set recovery (23, 332, 333, 539). Given the recognition of strength as a motor skill, exercise selection would seem an essential consideration for the development of appropriate coordination (472, 476, 477). Exercise selection dictates the muscles recruited, contraction profile (eccentric and concentric), range of motion and magnitude of external resistance utilised which stimulate the specific neuromuscular activation and physiological adaptation. The principle of specificity is a driving factor in resistance training design (523, 565); the more similar a training exercise is to the target performance, the greater the likelihood of transfer. Specificity includes the joint angles used, the contraction type (concentric, eccentric, isometric) and the movement velocity.

NEUROMUSCULAR ADAPTATIONS TO RESISTANCE TRAINING

Neural Adaptations

Hypertrophy and cross-sectional area are critical for strength, however early adaptations to resistance training are predominantly neural unaccompanied by detectable increases in muscle size (251, 275, 415, 428, 476, 477, 520). Neural adaptations can be categorised as intra-muscular or inter-muscular. Neural response can be the number and size of muscle fibres recruited (52, 91). Neural adaptations can also be improvements in coordination resulting in enhanced muscular activation specific to the nature of the trained task (96, 205). For example, specifics of neural adaptation have been long known with research utilising isometric training demonstrating the greatest improvements in force capacity were at the angle trained during the intervention (225, 560). Isoinertial training has also demonstrated similar adaptation whereby the more similar the mechanics of training and testing, the greater the transfer of adaptation (565). The neuromuscular system adapts according to the muscular contraction task performed during training, indicating the importance of exercise prescription for performance improvement (36, 82, 174, 228, 231).

Higher force production resulting from resistance training is made possible by several intra-muscular neural adaptations which can include an increase in the number of motor units recruited, consistent activation of higher threshold motor units or an increase in the firing frequency (1, 205, 477, 552). Motor unit synchronisation has been demonstrated to improve with resistance training and synchronisation capability is different between trained and untrained individuals (410). Importantly, there are specific motor unit patterns during resistance training that can only be recruited at maximal or near-maximal loads, indicating the importance of exercise intensity for adaptation. Resistance training can positively impact neural adaptations that increase the rate of force development and peak force production (1, 476).

The significance of strength as a motor skill is emphasised by the enhancements in inter-muscular coordination for improved strength performance. Neural specificity dictates that the more disparate the training exercises and target movement (joint angle, contraction type and velocity etc.) the less the transfer of training adaptation due to dissimilar neural activation and coordination (52, 175). Effective movement requires increased agonist activity complemented by synergistic activity with coordinated antagonistic co-contraction (477, 553). Antagonist co-contraction is a vital strategy to control motion and joint stability (2, 39, 150). For example, closed kinetic chain rehabilitation exercises are preferred to open chain as the coactivation of antagonists involved limits harmful shear force and ligament strain in anterior cruciate ligament (ACL) rehabilitation (338). Whilst a degree of antagonist contraction facilitates joint stability, excessive contraction opposes the prime mover and diminishes net joint torque for movement (91). Improvements in movement with training can be attributed to refined co-contraction and decreased activation of antagonists (88, 150). When considering the complex synchronicity of the coordination of lower limb muscles involved in a vertical jump, inter-muscular coordination is paramount to force transferred efficiently into ground reaction impulse (131). As a skill, resistance training may enhance performance by decreasing activation of pathways contrary to the intended movement, increasing task efficiency (88, 91). This demonstrates resistance training as motor training, the ability to improve force generating coordination.

A unique central nervous system adaptation to resistance training is observed with cross-education or contra-lateral strength training (64, 196, 415, 559). This phenomenon explains strength increases without hypertrophy in the untrained limb following periods of unilateral resistance training. There is great variance reported in the magnitude of strength gains in the untrained limb likely due to differences in application of intensity of resistance training (196, 422). Despite variation, the positive effect promotes the prescription of unilateral exercise during rehabilitation of temporarily incapacitated limbs (149, 268).

Morphological Adaptation

Though early and continual adaptations for strength have neural components, physiological cross-sectional area (PCSA) is directly related to the force production capacity of muscle (7, 247, 296, 399, 419). Whilst structural adaptation includes enhancements in tendon and connective tissue (205), the morphological adaptation from resistance training is greater PCSA (207). Muscle hypertrophy due to resistance training predominantly involves increases in muscle fibre size (361) whilst muscle fibre angle, pennation angle or fascicle length and fibre type shifts (Type IIB to Type IIA) also change in response to resistance training (68, 69, 85, 253). The relationship between PCSA and maximal strength supports the inclusion of hypertrophy resistance training in a multitude of sports dependent upon strength (34, 155, 182, 223, 280, 503). Typical guidelines for resistance training inducing muscle hypertrophy include large resistance training volume (4-6 days per week, multiple sets of 6-12 repetitions), intermediate intensity (70-85% 1RM) with a focus on large, multi-joint exercises (85, 332). However, athlete development programs orientated towards maximal strength (high intensity (70-100% 1RM), low volume multiple sets of 1-6 repetitions) also produce a comparatively smaller degree of hypertrophy. Further, training experience does affect the adaptation response with more experienced athletes requiring greater exposure than less trained (32, 254). Both single- and multi-joint exercises have been demonstrated effective at increasing PCSA, however, multi-joint exercises (squats, deadlifts, etc) are considered superior for athletic populations due to the larger muscle mass and coordination requirements (332).

RESISTANCE TRAINING VARIABLES

The success of a strength training program depends on the prescription of stimulus via arrangement of resistance training variables (332). The importance of neural and morphological adaptations of resistance training to heightened athletic performance influences the arrangement of training variables. There are many acute training variables for consideration of resistance training design for strength enhancement: muscles to be trained, training intensity, training volume (reps and sets and load), exercise choice and arrangement, intra- and inter-set recovery, repetition speed and session frequency (144, 332, 539). The higher neural activation experienced during high intensity training serves as a stimulus for the adaptation of improved neural recruitment. Therefore, intra-muscular neural adaptations for strength are dependent on the magnitude of intensity. Additionally, if neuromuscular adaptation can be considered as motor learning, then exercise selection is a critical consideration as it can dictate the muscles to be trained, the magnitude of intensity (external resistance for overload), movement speed and transfer to subsequent performance (221, 231).

Overload and Intensity

As a fundamental training principle, overload is concerned with the delivery of a stimulus above normal level and is most commonly targeted in training programs by intensity and volume (332, 524). Intensity is often achieved by the magnitude of external load, but can also include the speed of movement and is essential for the development of strength (332, 524). Athletic performance is a result of force produced by motor unit activation and high levels of force require high levels of motor unit recruitment. The size principle of motor unit recruitment dictates that to recruit high threshold fibres heavy resistance is required, thus high intensity in training (269). The intensity of exercise prescription influences the intra-muscular neural responses to training. Training loads must constantly be of a high magnitude in order to target high threshold motor units (451), a minimum of 80% 1RM are recommended to produce neural adaptations critical for maximum strength (175, 249, 332). It has been demonstrated that joint moment or muscle activation are load dependant in lower body resistance exercises (135, 325, 447, 575). Therefore, high training intensity is a critical variable of resistance training prescription for the magnitude of strength adaptation (3, 211, 332, 487). Exercises such as squats, deadlifts and weightlifting variations are frequently incorporated into programs for athletic development due to the ability to utilise large external loads targeting high threshold motor units (5, 32, 101, 115, 257, 468)

Specificity and Transfer

The transfer of training is the degree of response in the non-trained performance from adaptation in the trained task and is a result of the interaction of neuromuscular adaptions of training (52, 91, 303, 524). Expression of strength adaptation has long been demonstrated to be closely linked to the manner in which the strength was developed and includes contraction speed and joint angles (59, 109, 206, 247, 250, 276, 418, 440, 459, 565). Whilst isometric and isokinetic investigations have clearly demonstrated joint angle or muscle length and contraction velocity specific adaptations (8, 174, 316, 346, 411, 541), isoinertial training applicable to athletic training has demonstrated improvement in force production is higher when the training exercise and test are similar (33, 565). The multifaceted nature of team sport preparation depends extensively on positive transfer of sport-specific drills from training (physiological, technical and tactical) to superior competitive performance (303). With regards to resistance training, the purpose of increasing maximum strength is the transfer to performance dependant on force expression such as sprint acceleration and COD. Given neuromuscular adaptation can be defined as a skill (the coordination of agonists, antagonists, synergists and stabilisers) exercise selection would appear critical for transfer (476).

An important consideration of transfer to performance is the "dynamic correspondence" of the exercise to final task. Specificity, as defined by Zatsiorsky and Kraemer (2006), refers to the "similarity between adaptation induced by a training drill and adaptation required by a main sport movement" (590). Stone, Stone and Sands (2007) further specificity by the degree of association of exercise variables (528). That is, the basic mechanics of the trained and target tasks and not simply external resemblance (501). The body posture of training has been demonstrated instrumental in facilitating transfer to subsequent performance. For example, squat training has been demonstrated superior to leg press training in improving vertical jump performance (568). Similarly, squat strength has been demonstrated to transfer more to vertical jumping than sprint acceleration (565). In addition to posture, the manipulation of resistance training variables alters the adaptation and subsequent expression of force and velocity in dynamic performance. Comparing weightlifters, powerlifters and sprinters, McBride et al reported specific expression of force or velocity reflective of training nuances between the three disciplines (377). However, despite limited resemblance, a positive transfer to sprinting exists and as such the squat is still regularly incorporated in a multitude of sports for enhancing sprint performance. Short-term training studies in soccer and rugby league have reported corresponding improvements in squat strength and sprint performance from resistance training incorporating the squat exercise (101, 115). In male youth soccer players, two years of resistance training improved squat strength and 30m sprint times (479). Given the relationship between ground reaction force and propulsion in sprinting, it is logical that improved force production capacity would improve sprint capacity. However, whilst there is general agreement that improvements in strength assessed by squat testing or the integration of squat training transfer favourably to enhanced sprint performance (490), the transfer is not guaranteed. Despite adhering to appropriate programming principles, studies have demonstrated measurable squat enhancement with limited sprint improvement (257, 378).

Summary

The development of maximum strength involves neural and morphological adaptations. The expression of strength can be defined as improved intra- and inter-muscular coordination of agonists, antagonists and synergists, whilst increased cross sectional area of a muscle also contributes to force development capacity. Improvements in strength are dependent on a sophisticated arrangement of resistance training variables in program design. Resistance training variables such as intensity facilitate intra-muscular adaptations of motor unit synchronisation and firing frequency. The significance of inter-muscular coordination, the summation and transference of force to the ground (or an implement), highlights the importance of exercise selection that can optimise intensity to achieve intra-muscular adaptation into a coordinated system. Exercise selection is a critical factor influencing the arrangement of crucial resistance training variables of intensity and overload, defining muscles involved and the transfer of strength improvement to the final athletic performance. This underscores the importance of exercise selection and optimal application of resistance training principles as more than a means to target neuromuscular adaptation, but as an opportunity to focus specific training benefiting future athletic performance.

- 3 -

Lower Body Resistance Training: Bilateral and Unilateral Exercise

The needs analysis of critical athletic performance, sprint acceleration and COD capacity, demonstrate the association to maximal lower body strength and that improvements in lower body strength can be realised in improvements in acceleration and COD ability. However, the transfer of strength is an essential consideration influencing exercise selection which in turn, targets appropriate muscle recruitment patterns for future performance. Therefore, movement patterns are considered when selecting appropriate lower body exercises to maximise the development and efficient transfer of strength gains underpinning athletic performance. An exercise selection challenge appears to be balancing the ability to maximize strength development and transfer to performance. Whilst bilateral exercises have been extensively researched and linked to maximal strength development and performance, these exercises appear limited in movement specificity to sprinting and COD, predominantly unilateral performances. Thus, unilateral resistance training appears an appropriate exercise selection. However, unilateral exercises typically prohibit large external resistance, and perhaps insufficient capacity to provide satisfactory neuromuscular stimulus which drives strength development. Therefore, coaches are faced with the dichotomy of specificity (strength) and transfer (performance).

If the goal of resistance training in sport was solely increased strength, the choice of exercise would be governed by selection of those most capable of improving maximal strength. However, sport specificity is a critical consideration for the transfer of strength to performance (583). Additionally, resistance training is perceived important for decreasing injury risk, a multifactorial process involving muscular strength, muscle symmetry and stabilisation (369). Thus, comprehensive athletic exercise prescription endeavours to achieve many performance enhancing objectives. Comprehensive training demands of athletes requires efficient prescription of resistance training encompassing multiple physiological adaptions, influencing exercise choice. A biomechanical understanding of lower body resistance training exercises provides important external and internal loading conditions guiding selection (9, 18, 22, 80, 93, 106, 108, 116, 157, 181, 189, 191, 198, 229, 323, 352, 386, 400, 504, 591). The following will attempt to present features that are contemplated for bilateral and unilateral resistance training selection and provide context for the current investigation. (References to bilateral or unilateral resistance training henceforth will refer purely to lower body).

FEATURES OF BILATERAL RESISTANCE TRAINING

Bilateral exercises are generally described are those with bodyweight evenly distributed in parallel stance and include the squat, deadlift and weightlifting variants such as cleans (Figure 2.3). Whilst movements such as lunges, split squats or rear foot elevated split squats also require a two-point base of support, these movements are often classified as unilateral due to their asymmetrical muscle activation (223, 434). Parallel bilateral exercises are well prescribed due to closed kinetic chain force development and demonstrated relationships and positive influence on lower body strength and athletic performance (101, 115, 192, 292, 375, 532, 569). The squat (which shall be the focus of this review) is commonly incorporated in resistance training and rehabilitation in an array of sports (16, 32, 107, 180, 277, 496, 532). A benefit of the squat is the ability to utilise large magnitudes of external mass to facilitate neuromuscular overload and adaptation. Superior squat performance has demonstrated relationships to vertical jump performance (493, 569), sprint time (acceleration and maximal velocity; (30, 78, 95, 350, 569)), COD (449)), athlete playing level (227) and superior rate of recovery from team sport competition (309, 446).

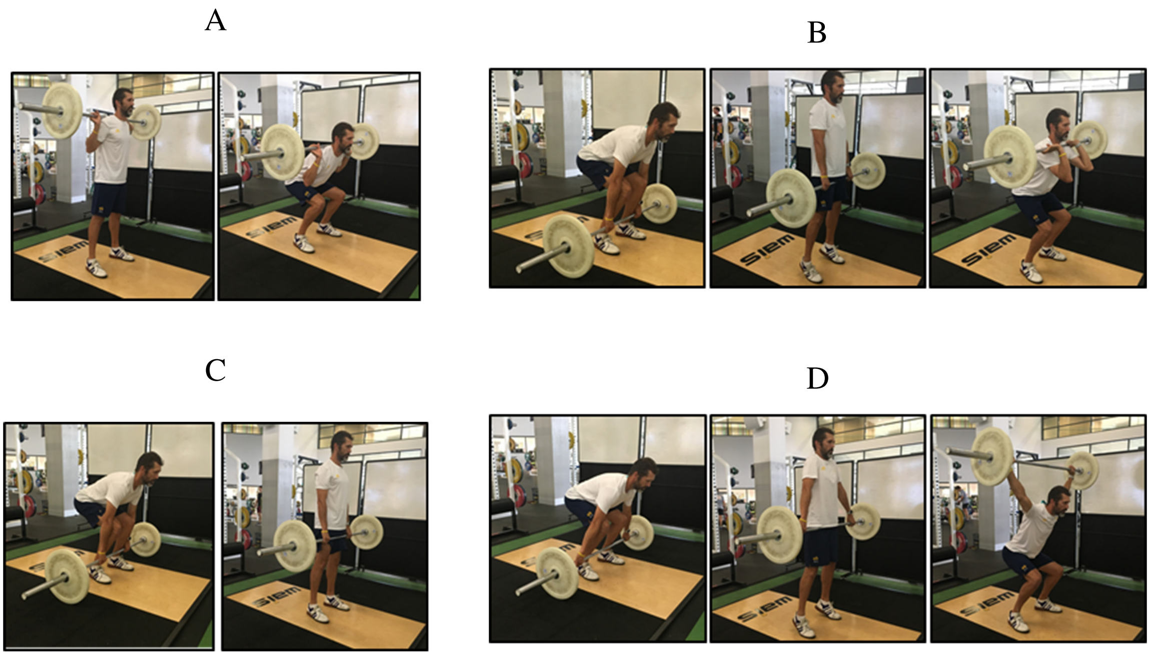


Figure 2.3 Common bilateral exercises. A – Back squat; B – Clean pull / clean / front squat; C – Deadlift; D – Snatch / overhead squat.

Characteristics of the Squat

Considered an important exercise of widespread application, the squat requires recruitment of multiple muscle groups using several joints in a single action (94, 188, 212, 488). Performed as a back squat, overhead squat or front squat there exist several technical variations modifying bar placement, squat depth, stance width and stability requirements (18, 108, 189, 229, 240, 379). As the depth of back squat and thus range of motion increases, the capacity for external load decreases (121, 173). Biomechanical analysis and review of the squat has provided critical understanding of muscle activation, joint loading and force profiles in a variety of subjects, performance intensities and training applications (e.g. rehabilitation to athletic performance) (18, 80, 94, 121, 190, 191, 198, 374, 379, 488, 506, 536, 576). The prime movers during the squat are the quadricep, hamstring and gluteal groups, requiring stabilisation through the trunk, hips and ankles (108, 121, 442, 488). Studies have demonstrated a tendency for greater knee extensor moments than hip during squat performance, although technical execution can vary the emphasis (80, 106, 201). For example, in a small sub-study utilising the 90° squat, net joint moment analysis indicated the hip as the limiting joint in 3RM back squat performance in three of the five subjects (200). This may have been due to the shallower

90° squat and reinforces the influence of depth on muscular contributions to the squat. As barbell load or squat depth increases, so does knee flexor moment (135). Furthermore, compared to shallow squats, deep squat training produced superior increases in quadricep cross-sectional area (70).

The performance of maximal effort isometric squats registers higher EMG activity for vastus lateralis (VL) (90 ± 40% MVIC) and vastus medialis oblique (VMO) (90 ± 70% MVIC) compared to the hamstrings (10 ± 10% MVIC), gluteus maximus (GMax) (20 ± 10% MVIC) and gastrocnemius (30 ± 20% MVIC) (484). Using parallel squats at 80% 1RM, Signorille reported no significant effect of foot position (toes in, neutral or outward rotation) between the VL, VMO or rectus femoris (502), however, variations in stance width and externally rotated foot alignment does increase the involvement of adductors (379, 447). A wider squat stance has also shown greater hip moments compared to narrow stance in elite male powerlifters and GMax EMG activity (188, 447). Although deeper squats have been reported to involve greater GMax activation than shallow squats (93), the involvement of hamstrings has been reported as unchanged with depth during the concentric phase of back squats (307). Whilst squat technique may influence the pattern of activation, the magnitude of external load is the major determinant (379, 447). Performance of moderate intensity back squats (75% 1RM) involves considerable VMO and VL muscle activation, compared to biceps femoris (99).

Furthermore, the use of external load also requires heightened trunk stabilisation (442). Highly mobile, vertebral bodies are supported by facet articulations, ligaments and muscles to resist vertebral shear (222). Technical instruction of the squat highlights the importance that a slight lordotic spinal curve should be maintained and the trunk as upright as possible to minimise vertebral shear and injury risk (210, 488). Externally loaded squats have been demonstrated to recruit trunk muscles to a greater extent than isolated trunk exercises and increase activation levels with increasing load (79, 372, 376, 442). However, given the ability to lift considerably large loads during half and quarter squats, research has indicated an increased risk of shear and compression spinal injury (263).

Although simple in execution, squat performance requires coordinated muscular control for extension at the hip, knee and ankle. The knee joint is composed of the tibiofemoral joint and patellofemoral joint and supported by dynamic structures (hamstrings, quadriceps, adductor group (491)) many static ligaments: medial and lateral collateral ligaments, and ACL and posterior cruciate ligament (PCL). The ACL is considered the most important knee stabiliser and an ACL injury is debilitating and frequent in many sports requiring extensive rehabilitation (6, 236, 314, 545). The co-contraction of the hamstrings, quadriceps and gastrocnemius during closed kinetic chain exercises enhance knee stability and is a rationale for the inclusion of such exercises for prevention and rehabilitation of knee injuries (267, 338, 463).

Investigations regarding stability demands have been furthered by analysing squat performance in unstable environments to enhance neural adaptations, particularly stabiliser and trunk muscles. Efforts during unstable squats have shown maintained or decreased agonist activation accompanied by decreases in isometric force or strength, due to the reduced magnitude of load capacity (9, 49, 474). These results indicate the interaction between stability, force production and muscle activation during unaltered free weight squat performance with external load and the lower force production may be disadvantageous to strength development (53).

Field Assessment of the Squat and Relationship to Athletic Performance

The back squat has been identified as a reliable test and frequently used to assess lower body strength in a variety of athletes and levels (20, 37, 117, 493, 558) (Table 2.3). Strong relationships exist between squat strength (absolute or relative to body mass) and sprint, jump and COD (87, 95, 114, 375, 441, 468, 537, 569). More importantly, the transfer of developed strength is paramount for enhanced athletic performance and evidence is compelling for resistance training programs incorporating the squat positively impacting sprint, jump and COD performance (5, 101, 115, 271, 280, 490, 511, 565, 571). Given the ability for untrained participants to respond favourably to resistance training, particular importance is given to research demonstrating improvements in trained participants. In professional handball players, a seven-week program incorporating half squats, twice a week at 4-6RM significantly improved strength, jump and acceleration performance (468). Similarly, 1RM squat increases of well-trained rugby league players was associated with improvements in 20m acceleration following an eight-week strength and power program (115). Elite, well-trained national handball players performed an eight-week resistance training program involving half-squats at 80-95% 1RM also demonstrating improvements in acceleration performance and jump height (271). Collectively, these investigations support strength improvements, utilising heavy squat variations positively impacting athletic performance.

Table 2.3 Typical test values and between-session reliability of back squat assessments representative of team sports athletes

	Subject ave age ±SD (n)	**Subject experience & sport**	**Test**	**Average ± SD (kgs)**	**CV% / %TE**	**SEM**	**ICC**
Sheppard (493)	20.8 ± 3.9 *(21)*	National indoor volleyball (M)	1 RM Parallel back squat	Absolute unreported	TE = 3.5%		0.97
Weakley (558)	17.3 ± 0.4 *(14)*	Adolescent rugby union (M)	3 RM Front Squat	103.0 ± 17.4	CV = 2.90 TE = 2.50		
Augustsson (20)	24 ± 1.3 *(20)*	University students (F)	1 RM Parallel back squat	60.5 ± 18		6.9kg	0.85
Banyard (37)	25.4 ± 3.3 *(17)*	Resistance trained (M)	1RM Full back squat	140.3 ± 27.2	CV = 2.1		0.99
Comfort (117)	21.5 ± 2.0 *(32)*	Inexperienced college athletes (M)	1RM 90° back squat	140.0 ± 21.2		2.7kg	0.99
	21.0 ± 1.9 *(12)*	Inexperienced college athletes (F)		94.6 ± 14.1		2.0kg	0.97

Note: M = male, F = female; CV% = coefficient of variation, %TE = percentage technical error of measurement; SEM = Standard error of measurement; ICC = intraclass correlation coefficient.

FEATURES OF UNILATERAL RESISTANCE TRAINING

Lower body unilateral exercise has been defined as "a weight bearing movement supported on one leg (388)". Commonly prescribed unilateral exercises include single leg squats, rear foot elevated split squats (RESS), lunges, step-ups and split squats (Figure 2.4) (75, 181, 301, 322, 330). Many exercises termed unilateral derive varying levels of support from the non-drive leg with few closed kinetic chain resistance exercises truly unilateral. Unilateral exercises have been labelled supplementary or auxiliary to the prescription of bilateral exercises, their placement in programs typically less emphasised (often following major bilateral exercises), intended to vary stimulus, assist prime movers and increase fatigue (223, 298, 388). The narrower base of support contributes to the additional coordination requirements, subsequently decreasing the magnitude of external load comparable to bilateral exercises. Given a purpose of resistance training is the increase in maximal strength, the lower magnitude of load incorporated in unilateral exercises is somewhat discouraging (266). However, the uneven emphasis of load distribution in asymmetrical performance (ie. system mass is not evenly distributed between legs) does result in the dominant/lead leg being activated at intensity sufficient for strength development (267, 311, 382). Despite the assertion that single leg exercises may not sufficiently develop strength, they are simultaneously classified "sport specific", mimicking the single leg biased movements of many sporting actions (266, 388, 480). The asymmetrical loading provide further rationale for the inclusion of these exercises as a primary exercise at all stages of athletic development: increased muscle activation of stabilisers, injury risk reduction benefits, potential benefits of trunk control and perceived sports transfer resemblance (232, 266, 340, 382, 511, 534). Although not typically prescribed for hypertrophy, unilateral resistance training has been demonstrated to have comparable improvements in CSA as bilateral training (276, 562).

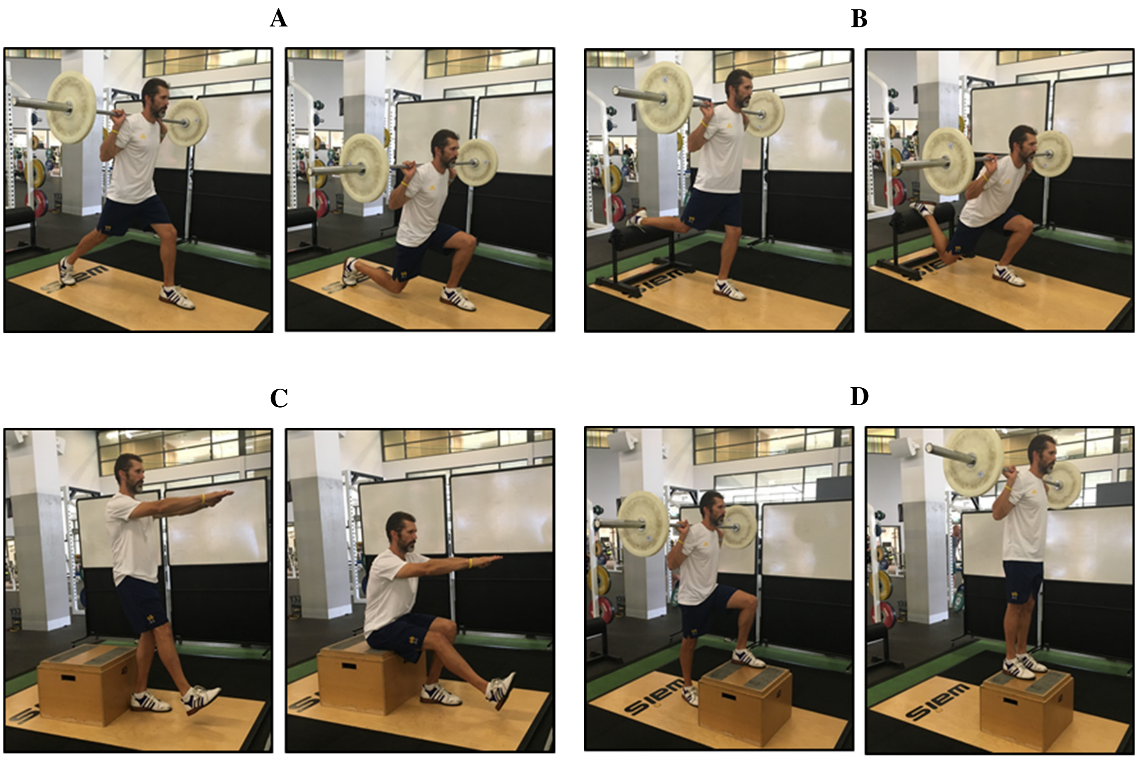


Figure 2.4 Common unilateral exercises. A – Rear foot elevated split squat; B – Lunge / split squat; C – Single leg squat; D – Step-up.

Characteristics of Unilateral Resistance Exercises

Given the asymmetrical muscle activation patterns, resemblance to activities of daily living, practical implementation and typically no or little external resistance requirement, unilateral resistance exercises feature abundantly in research regarding actions of daily activity or lower body rehabilitation literature (22, 58, 63, 73, 75, 112, 116, 179, 185, 264, 282, 334, 338, 491). As a result, methodological constraints detailing prime mover muscle activation is often characterised by low intensity performance, atypical of elite athlete training requirements. Peak quadriceps (VMO, VL, rectus femoris) activation during bodyweight only step-ups was approximately twice the maximum voluntary contraction of isometric leg extension whereas biceps femoris was only 59% of isometric flexion (63). Lower hamstring surface EMG was reported in forward, lateral and retro step-ups (backward step-up), compared to single leg wall squats during unweighted performance (22). Critically, the step height in this investigation was quite low, only 15cm high; typical of daily activity yet substantially lower than athletic training application. Increasing step height has been shown to increase quadricep and hamstring activity, similar to increased squat depth (77). Additionally, comparisons between muscle activity of bilateral and unilateral exercises often fail to equate loading parameters. For example, Schellenburg et al assessed split squats at 125% bodyweight barbell load and deadlifts at 150% bodyweight barbell load reporting gluteal activation was highest for the lead leg in the split squat compared with gluteal activation in deadlifts (485). The load in the deadlift is spread across two legs whilst the split squat load distribution asymmetrically overloads the lead leg, thus two different loading conditions were assessed. Bellon et al reported no difference in mean EMG in erector spinae, GMax, biceps femoris or VL and VMO between back squat at 75%1RM and RESS at 37.5% of back squat 1RM (58). Although half the squat load was used to compare to the RESS, more than 50% of the load can be directed through the lead leg (267). Another study assigned loads as a percentage of 1RM back squat: back squat were performed at 85% 1RM and split squat and RESS at 50% 1RM (157). Biceps femoris EMG was greater in RESS than back squats despite the lower magnitude load. However, methodological differences in relative intensity of the exercises may influence EMG activity and confound interpretation as differences in load contribute to muscle activation discrepancies and conclusions (370). Where relative intensity has been equated, quadriceps activity was high for squat performance at 75% 1RM and biceps femoris activation was significantly higher for split squats at 75% 1RM compared to squats at 75%1RM (99). Mausehund et al compared RESS, single leg squats and splits squats at relative 6RM (370). This investigation reported no significant differences in GMax and VL peak EMG. However, gluteus medius (GMed) activation was significantly different in the single leg squat compared to the RESS and split squat. This may be due to the single leg squats one-foot base of support compared to the asymmetrical two-feet base of support. As with alterations in squat technique, technical variations in step length and front shin angle have been found to significantly alter EMG and joint moments (485, 489). Trunk position has also been demonstrated to influence lower limb mechanics in single leg squats whereby hamstring forces are significantly higher with moderate trunk lean compared to a more upright posture, which in turn, reduced ACL forces (335). The favourable quadriceps:hamstring coactivation in single leg exercises compared to bilateral squats supports the integration of unilateral exercises in ACL rehabilitation and prevention programs (156, 370). These studies demonstrate limitations in previous research comparing bilateral and unilateral application whilst highlighting the diversity of unilateral exercise and influence of external load on muscle activation levels.

Stability

The narrow base of support is a critical distinction between bilateral and unilateral resistance exercise and creates a "disruptive torque" to the body (56). The greater medial-lateral forces demand altered neural strategies at the hip, knee and ankle to maintain balance (9, 386, 460). During performance there may be an additional challenge due to the shifting centre of mass which heightens frontal plane neuromuscular instability (9, 49, 344, 382, 386, 388). The higher EMG values of hip stabiliser muscles recorded during single leg performance compared to bilateral has been suggested to develop neuromuscular adaptations that may reduce the risk of injury (22, 166, 334, 461). The GMed, a hip stabiliser in the frontal and transverse planes abducting and externally rotating the femur, is frequently targeted by the prescription of unilateral exercise (334). Internal rotation of the femur results in excessive knee valgus forces, a contributing factor in lower limb injuries such as patellofemoral pain / anterior knee pain, iliotibial band syndrome and ACL tears. Early phase rehabilitation exercise prescription often entails exercise atypical of athletic resistance programming, conducted in lying or isolated fashion (184). Integration in unilateral exercises provide a practical benefit to athletes, loading in similar movement patterns to athletic performance. Unilateral training is often prescribed for rehabilitation and injury prevention due to heightened hip stability requirements (357, 453, 473). Lower hip abduction strength was statistically significant ($p=0.02$) to injury in a two-year study of collegiate athletes (345). Krause and colleagues suggested that "exercise be performed unilaterally if the intent is to provide a challenge to the GMed muscle" (334). The beneficial neuromuscular adaptations of unilateral exercise in rehabilitation settings seem a logical integration in enhancing athletic performance. Likened to the stance phase during running and COD tasks, the incorporation of unilateral resistance training has been suggested for optimum athletic performance and injury prevention (388). Furthermore, unique to unilateral movements is medial-lateral co-contraction. As with bilateral exercises, co-contraction of antagonists is crucial for joint stability and is influenced by the magnitude of force involved, the velocity of movement, movement precision, type of contraction and duration of acceleration or deceleration (49, 52, 54). Due to the narrow base of support, medial-lateral co-contraction forces may be a further benefit of unilateral exercise prescription for injury risk reduction (63). It has been proposed that the hip moment of the support leg during COD contributes to the body's stabilisation, indicating the importance of strength training of hip adductors and abductors (535). With specific regard to knee alignment and injury risk during COD performance, unilateral lower limb resistance training appears to provide benefit beyond enhanced strength development to include critical hip stabilisation.

The one-legged execution of sporting movements suggests the specificity of resistance training occur on one leg to maximise transfer (53, 266). Free weight resistance training is utilised for the inherent joint stabilisation requirements, and to provide a resemblance of force transfer during athletic movement skill execution occurring amidst postural stability challenges (243, 525). The position of load has a significant influence on the magnitude of GMed and VL activation (521). Additionally, studies have extended the application of instability by having participants perform exercises on unstable supports to increase balance demands (9, 49, 50, 137, 372). Multiple investigations have demonstrated decreased ability to utilise external mass and/or decreased motor activation of prime movers when requiring subjects to perform resistance exercise in an unstable environment (9, 49, 372). For example, addition of a foam cushion pad under the feet decreased 6RM Bulgarian squat (or RESS) by 10% and significantly decreased biceps femoris and erector spinae EMG amplitude (9). When performed in a stable environment, the EMG amplitude in the 6RM Bulgarian squat versus 6RM back squat was comparable for the VL and VMO, indicating similar motor unit activation between the unilateral and bilateral exercises at relative intensity (9). Attempting to decrease stability to replicate sport specificity beyond unilateral performance to an unstable base decreases the strength development capacity of the training exercise. Whilst sporting actions may occur on one leg, the surface is stable permitting high force production/application (137). Therefore, unilateral resistance training exercises, performed on a stable surface, may provide an optimum combination of force production and stability demands in a sport specific context, a position supported by a systematic review on unstable surface training (57).

Rehabilitation and Corrective Application

Unilateral resistance training has been incorporated in rehabilitation practice to benefit from the phenomenon of cross-education, the process where enhanced force output of the contra-lateral untrained limb is observed with unilateral training (149, 196, 268, 499). Contralateral strength improvements have been reported in many studies suggesting enhanced central neural drive (64, 149, 196, 422, 560). The practical implementation of unilateral exercises have involved training the uninjured limb to reduce substantial strength loss in the injured limb (149, 268). Additionally, lower limb contralateral strength balance may affect performance and predispose an athlete to an increased risk of injury (313, 432). As such, unilateral assessment is used as a screening tool for injury.

A further rationale for the inclusion of unilateral exercises is the unintentional imbalance of bilateral performance – the assumption that both legs contribute evenly to bilateral performance. Research has indicated that performance of the squat can be performed asymmetrically and athletes experienced with bilateral resistance training can exhibit bilateral asymmetry (48, 198, 328, 432, 482). It has been suggested that supplementary unilateral training may be required in such instances to correct imbalance that may increase injury risk or limit performance (432). Comparison of unilateral performance is an essential feature of lower body rehabilitation, particularly from ACL injury (314). Whilst the origins of bilateral asymmetry are multifaceted, discrepancy exceeding 15% has been suggested as an injury risk factor (326, 391). The prescription of unilateral exercises is suggested to assist within-subject detection and correction of imbalance (289, 432).

The bilateral deficit phenomenon has been suggested as a rationale for the incorporation of unilateral exercises in resistance training (298, 421, 511). Bilateral deficit is defined as the force produced by both limbs working simultaneously being less than the sum of both limbs working independently (305, 420). It has been demonstrated more difficult to "achieve full motor unit activation in bilateral than unilateral contractions" (476). Neural activation patterns have been speculated as the mechanisms for bilateral deficit (297, 305, 337). As such, unilateral training may be a strategy to optimize strength development. In untrained subjects, whilst bilateral and unilateral exercises improved lower body strength expression, unilateral training optimized individual lower limb force production (74). However, this finding is based on untrained subjects and whether this occurs in well-trained athletic populations requires investigation. Yet, given the expression of strength as a skill, the coordination of synergists, agonists and antagonists and the advantages of the bilateral deficit, unilateral exercises appear to maximise strength specificity for athletic performance (476).

Whilst unilateral exercises utilise lower external loading compared to bilateral exercises a potential benefit that reduction may provide is to supportive structures (such as the spine) which may promote athlete health. As the external loading in unilateral lower body exercise is markedly lower than bilateral exercises it has been suggested that the lower load decreases the compressive load on the spine and may reduce injury risk during training (157, 263).

Technical instruction for squat performance recommends vertebral alignment to minimise lumbar injury risk (168, 210, 235, 488). The spinal orientation during unilateral performance of RESS, step-ups or split squats may facilitate a more favourable vertical alignment. Trunk muscle activation has been demonstrated to increase greatly when the strengthening exercises were performed in a more unstable environment (56) and whilst trunk activation has been demonstrated during back squats, the asymmetry of unilateral exercises increases contralateral trunk stabiliser activation (10, 84). The trunk section is responsible for transferring force generated in the lower limbs to the upper limbs and inefficiency in transfer can result in force loss or injury risk due to overcompensation. Training that integrates trunk strength in the kinetic chain is favourable for athletic preparation (55, 56). Additionally, the trunk section is seen as providing a solid foundation for force transfer between upper and lower limbs (56). Furthermore, trunk control also identified in COD performance may be assisted by unilateral resistance training which has differentiated trunk demands to bilateral training (481).

Table 2.4 Typical test values and between-session reliability of back squat assessments representative of team sports athletes

Author	Subject ave age ±SD *(n)*	Subject experience & sport	Test	Average ± SD (kgs)	CV% / %TE	SEM	ICC
Speirs (511)	*18.1 ± 0.5* *(18)*	Academy RU (M)	3RM RESS	U: 76 ± 6.1 B: 75 ± 4.5			0.98
Urquhart (551)	23 ± 1.2 (14)	Untrained (M)	1RM Split squat	68.8 + 9.2	1.57		0.99
McCurdy (385)	21.0 ± 0.8 *(8)*	Untrained (M)	1RM RESS	88.6 ± 18.5		1.11	0.99
			3RM RESS	80.4 + 16.0		1.29	0.97
	23.9 ± 6.5 *(22)*	Untrained (F)	1RM RESS	45.8 + 10.7		0.56	0.97
			3RM RESS	39.8 + 10.4		1.13	0.87
	21.6 ± 1.9 *(10)*	Trained (M)	1RM RESS	121.6 + 17.7		1.20	
			3RM RESS	103.0 + 21.5		1.68	
	21.0 ± 0.8 *(12)*	Trained (F)	1RM RESS	55.3 + 11.6		0.44	
			3RM RESS	47.5 + 8.6		0.95	

Note: M = male, F = female; CV% = coefficient of variation, %TE = percentage technical error of measurement; SEM = Standard error of measurement; ICC = intraclass correlation coefficient.

Field Assessment of Unilateral Exercises and Relationship to Athletic Performance

The infrequency of unilateral resistance training as a prime strength development tool in athletic populations has limited the availability of strength testing reliability of unilateral resistance exercises typical of athletic training (Table 2.4) (385, 511, 551). Relationships between unilateral assessment and athletic performance have ranged from stability/balance tests, hops or jumps to unilateral resistance exercise (103, 313, 352, 390, 423). For example, superior dynamic stability as assessed by the Star Excursion Balance Test has been related to faster COD performance (354), leading authors to suggest that unilateral training may benefit lower body strength development and stability for sprint and COD performance. Leg stiffness measured by hopping has been correlated to sprint acceleration over 40m (103) whilst unilateral jump performance has a strong correlation to sprint performance in collegiate athletes (390). Compared to bilateral resistance training, the relationship of unilateral resistance measures to athletic performance is limited. Relationships to performance have been constrained to comparisons with seated unilateral leg press and RESS to differentiate dominant and non-dominant deficit (313, 352). Detectable strength asymmetry was unrelated to deficits in sprint performance with the inability to identify relationships to field performance attributed to the complex movements and muscle qualities (contraction speed, range of motion) of field testing than strength testing. Furthermore, in each investigation imbalances were within clinically defined parameters of imbalance (under 15%), highlighting the complexity of determining relationships between "asymptomatic" imbalance and performance limitations.

A resistance program consisting of only unilateral exercises (single leg squats, lunges, step-ups and single leg power cleans) was implemented in seven NCAA Division II female volleyball players (341). This small investigation utilised a RESS 3RM strength test and volleyball specific jump tests, pre and post a 3 session per week, 10-week intervention. Despite resistance training being performed primarily unilaterally, the small cohort demonstrated some improvement in double leg vertical jump suggesting a positive effect of unilateral resistance training on bilateral performance. This investigation demonstrates the potential of unilateral resistance training on performance, yet comparisons between bilateral and unilateral effectiveness require further investigation.

SUMMARY

Given the importance of exercise selection in determining the manipulation of training variables driving neuromuscular adaptation and expression of strength, bilateral and unilateral exercises offer unique benefits blending overload and specificity for enhanced performance. The benefits of bilateral exercise for strength development and athletic application are well established. Given the importance of task-specific resistance training (472), and the positive neuromuscular benefits of unilateral resistance training in rehabilitation settings, unilateral resistance exercises are recommended to be incorporated in programs designed to improve an athlete's strength and power (388). Despite the resemblance to one-legged athletic performance and comprehensive neuromuscular benefit, unilateral exercises lack the extent of applied research relative to bilateral exercises to athletic performance and unilateral exercises are predominantly investigated in rehabilitation application. Furthermore, a review of resistance training interventions in sprinters concluded that no clear modality of resistance training was optimal for speed development with different regimes improving performance (72). The authors concluded that resistance training at 60-100% RM be utilised and programs include unilateral movement.

- 4 -

STUDIES COMPARING BILATERAL AND UNILATERAL RESISTANCE TRAINING

TRAINING STUDIES

Given the positive benefits of unilateral resistance training and the resemblance of specificity to athletic movements, it is surprising few studies have compared unilateral and bilateral resistance interventions. McCurdy and colleagues considered the prescription of unilateral resistance exercises to be secondary to bilateral exercises and attributed to a lack of evidence demonstrating strength and power benefits from unilateral training (389). They compared changes in strength and power in untrained male and female participants aged between 18 and 24 randomly assigned to a bilateral or unilateral group training twice per week for 8-weeks. Participants had not resistance trained within the previous 12 months. The 90° back squat was the bilateral resistance test and the RESS with a 90° front knee flexion angle was the unilateral test. A 5RM protocol was used for assessment and to estimate a 1RM to determine training loads. Force plates were utilised for bilateral and unilateral countermovement tests and contact time was used for the Margaria-Kalamen stair climb test. Only the dominant leg was tested in unilateral conditions. The study design incorporated a two-week familiarisation period and two-week testing period. Whilst a complete program was not documented detailed indicated prescribed back and front squats for bilateral training and RESS, lunges and split squats for unilateral training progressing from 3 sets of 15 repetitions at 50% predicted 1RM to 6 sets of 5 repetitions at 87%. The training load was balanced between groups by sets and repetitions and individualised by predicted 1RM. Further, between weeks three and eight of the training program each condition was supplemented with bilateral or unilateral plyometrics, progressing from 3 sets of 5 repetitions to 3 sets of 15. No program was published.

This study reported similar improvements in unilateral and bilateral strength using bilateral or unilateral resistance training. The unilateral group improved single leg countermovement jump performance more than the bilateral group. The authors included the Margaria-Kalamen stair climb test as a coordinated unilateral power test involving alternating foot contact. Both bilateral and unilateral groups improved suggesting a similar neuromuscular adaptation. However, demonstrating the complexity of research design in applied training studies comparing unilateral and bilateral resistance training, there are methodological considerations. Importantly, the authors adjusted pre-test differences and the interaction of gender and group was an acknowledged limitation of the study. Additionally, the incorporation of bilateral or unilateral plyometrics further confounds interpretation with studies demonstrating different adaptations from bilateral or unilateral plyometric training (71, 362). A further compounding variable is the addition of other resistance exercises that were not included in the strength testing battery (front squats, split squats and lunges). Additional bilateral (front squats) and unilateral (split squat, lunges) exercises may have affected the study through fluctuations in training intensity as these exercises were not tested and able to be accurately prescribed. Furthermore, exercises such as the lunge require contribution from the rear leg. The authors acknowledged the interaction of gender and group however, incorporation of unilateral plyometrics on unilateral jumping performance may also have confounded strength development. The authors noted the untrained nature of the training groups as a potential limitation in application of the findings to more experienced participants.

Despite methodological constraints, this study provided initial indications of benefit of unilateral or bilateral resistance training for lower body strength.

Differences in hip muscle activation between bilateral and unilateral lower body resistance exercises was the basis of a six-week training intervention assessing speed and COD performance (197). Collegiate rugby players experienced with resistance training were randomly assigned to a bilateral or unilateral training group. The primary bilateral exercise was the barbell back squat (parallel depth) and the primary unilateral exercise was the RESS squat with dumbbells (parallel depth). It is questionable if training loads with dumbbells could be accurately equated from barbell strength testing, and if dumbbell training volume and intensity could be adequately matched to barbell back squat training. A substantial plyometric program of 10 to 15 sets of group matched bilateral or unilateral exercises was incorporated, confounding interpretation of the strength training intervention. During the training period volume and intensity of the primary exercise remained at 3x6 at 80% of baseline 1RM. Unfortunately, Fisher and Wallin did not report any post-training strength results rendering interpretation of the influence of the resistance training problematic. Further, the intervention was heavily weighted towards plyometric training compared to resistance training. For example, in the final two weeks of training subjects completed three sets of resistance training compared to 15 sets of plyometrics. When assessing 10m sprint time, Fisher and Wallin reported a statistically significant difference in favour of the bilateral group. However, there existed a large unadjusted difference at baseline between the two groups (bilateral group average of 2.12s and the unilateral group 2.04s). Fisher and Wallin reported significant changes in performance for the unilateral group compared to the bilateral group (both the bilateral and unilateral groups were evenly matched at baseline for both tests). Both the T-test and Illinois Agility test involve multiple accelerations and decelerations (Figure 1-1a,c) and the superior performance of the unilateral group may have been attributed more to the unilateral reactive strength qualities developed from the supplementary single leg plyometric training (409, 586). This study demonstrates the complexity in ascertaining the impact of training between bilateral and unilateral resistance exercise interventions with considerations of balancing training load and supplementary training as part of a comprehensive training program.

Removing confounding plyometric training, Speirs et al trained young male rugby players (18.1 ± 0.5 years) suggesting that both bilateral and unilateral resistance interventions would develop lower body strength, and unilateral training would exhibit superior transfer to sprint and COD performance (511). Similar to previous research, this study utilised the back squat and RESS although to a higher 100° knee flexion angle. Despite familiarity with the back squat, RESS exercise and sprint and COD tests, the research design included a 3-week, 6-session familiarisation phase. The researchers utilised a 3RM strength test, and tested both legs in the RESS, although only used the dominant leg in the statistical analysis. The research designed included RESS reliability testing (ICC = 0.98) reporting similar to previous work (385). The 3RM testing result was converted to a predicted 1RM to determine training loads.

Due to the competition schedule of the subjects, a shorter training period of only five weeks was conducted. Whilst a longer training duration was preferred by researchers, this reflects the applied nature of the current protocol. Unlike Fisher and Wallin who maintained a constant loading intensity for their study duration, training progressed from high volume and low intensity (4 sets of 6 repetitions at 75% 1RM) to low volume and high intensity (4 sets of 3 repetitions at 92% 1RM). Both the barbell back squat or barbell RESS exercises were the only lower body resistance training prescribed. As members of a rugby academy, all participants completed an additional four rugby specific sessions and one match per week. The bilateral training group improved back squat 1RM by 5.0 ± 3.7% and RESS 1RM by 10.5 ± 3.2% whilst the unilateral group improved back squat 1RM by 5.7± 3.8% and RESS 1RM by 9.2 ± 2.1%. The authors concluded that both unilateral and bilateral resistance training were equally effective in improving lower body strength, supporting the earlier work of McCurdy and colleagues, importantly in trained subjects. The authors acknowledged that the strength improvements may have been typical of immediate response to training in short-term interventions and suggested longer training interventions to assess chronic adaptation.

Although the training intervention improved lower body strength, only a small effect size improvement was observed in 10m time. This is despite positive relationships between improvements in lower body strength and sprint acceleration (490). The authors suggested that the five-week training period may have been too short for effective transfer of strength to improved sprinting performance. Additionally, it was also suggested that an absence of specific sprint training may have contributed to the lack of transfer. Sprint training was purposely withheld in the current study due to the periodisation model and to isolate the influence of resistance training on performance. The authors suggest that lag time – the period of time between the development of an adaptation (strength) and its performance realisation (improved speed) may have been a factor in the short five-week study. However, despite the lack of improvement in the 10m time, a moderate improvement in 40m time was observed with no difference between the bilateral or unilateral groups. Based on this result the authors concluded "that improvements in lower limb strength transfers to enhanced sprinting performance". Another important component of the research design was the inclusion of COD assessment via the Pro-Agility test (Figure 2.2). Although small in magnitude, both groups demonstrated positive improvements of 1.7 ± 1.0% and 1.9 ± 0.8% for the unilateral and bilateral groups providing some insight regarding the potential for strength transfer from unilateral or bilateral resistance training to COD capacity. Whilst the study was unable to determine performance changes in 10m sprint time, the Pro-Agility task, which involves two 180° direction changes and contains a single 10m sprint within 20m of sprinting, did show positive improvement.

Sharing similar considerations regarding unilateral specificity in sprinting and COD, plus injury risk and muscular asymmetry, Gonzalo-Skok and colleagues sought to determine the effect of unilateral or bilateral training (232). Although familiarised with the exercise procedures and a resistance training age of two years, the 22 basketball participants in this study design were young with an average age of 16.9 ± 2.1 years. The extensive testing battery included a V-cut COD test (a 25-m sprint with four, 5m 45° cuts), a 180° COD test (7.5m out and back sprint), incremental bilateral and unilateral tests to determine maximal power output, 25m sprint speed and countermovement jump performance. The maximal power output test involved bilateral and unilateral Smith Machine jump squat testing with incremental load until the attainment of maximum power. During the training intervention, the number of repetitions were post-determined; that is the set stopped when power output decreased below 10% of the target power output. The mean number of repetitions between groups was not substantially different during the course of the intervention. For the first five weeks, the squat load was increased from 80% to 100% of maximum power load, dropping to 80% in the final week. Subjects in this study performed two intervention resistance sessions in addition to their normal strength training. Four sets of unilateral or bilateral matched drop and countermovement jumps. After the six-week period, the authors reported greater improvements in unilateral maximum power output by the unilateral training group compared to the bilateral training group in the incremental unilateral squat test. Both groups improved sprint and jumping performance. The unilateral training group improved in three COD tests (V-cut, 180° right leg and 180° left leg COD tasks) compared to the bilateral group improving in just one (180° right leg). The authors suggest the combined resistance training + plyometrics as opposed to isolated resistance training contributed to the enhanced sprint performance. Limitations in the study acknowledged by the authors include the uncertainty whether improved capacity was the effect of the inclusion or combination of maximal power training, strength training, and plyometrics. The inclusion of a control group in this design may have provided further insight regarding improvements due to training as opposed to maturation in such a young population.

BILATERAL VERSUS UNILATERAL RESEARCH DESIGN CONSIDERATIONS

There are methodological considerations for all research designs, and some specific to bilateral and unilateral resistance training investigations that require consideration. Common to all research, the chronological and training age of the subjects influences the response to training and subsequent practical application to experienced and elite settings. Subjects who are chronologically young, or have a low training age, are demonstrated to respond differently to well-trained athletes (32, 254). Thus, interpretation of training effects cannot be generalised between populations of differing training ages. Studies investigating unilateral and bilateral resistance training have been limited by subject cohort training experience ((232, 389). The effects of maturation on adolescent subjects may contribute to enhanced physical progress. The inclusion of a control group may assist interpretation of the magnitude of change due to the interventions (46). Furthermore, familiarisation to the testing and training protocols is an important requirement, particularly with unilateral exercises (67). Research on unfamiliar unilateral resistance testing has highlighted the importance of establishing specific familiarisation to ensure high test reliability.

An important consideration in evaluating the effectiveness of resistance training interventions is the equitable delivery of load (volume and intensity). Common to all featured research (197, 232, 389, 511) is the equal prescription of sets and reps between the unilateral and bilateral intervention exercise. Additionally, further unilateral or bilateral resistance exercise was prescribed as well as unilateral or bilateral plyometric exercise. Whilst all studies utilised baseline strength testing and prescribed training loads from testing, the inclusion of additional resistance training makes equating training load between unilateral and bilateral exercises difficult and interpretation of the efficacy of unilateral or bilateral resistance training somewhat problematic. Fisher and Wallin pre-tested both the squat and Bulgarian with a barbell, but dumbbells were used in training for the Bulgarian squat (197).

Compounding interpretation in much of the previous work of unilateral or bilateral resistance training on sprinting and COD was the addition of unilateral or bilateral matched plyometric training (Table 2.5). Differing responses have been shown in untrained populations with either unilateral or bilateral resistance training (363). The influence of bodyweight in plyometrics using either one leg at a time or two results in vastly different magnitudes of stimulus. Matching volume-intensity between bilateral and unilateral training was a consideration of the previous studies, many equally prescribing training repetitions. However, Gonzalo-Skok et al managed the repetitions of the intervention exercise based on the decline in power output during each set. At the conclusion of the intervention, no substantial differences in the number of repetitions performed were found between groups (232). This can be further confounded by additional training. Speirs et al used one training exercise (back squat or RESS) and no supplemental plyometrics. Conversely, McCurdy et al and Fisher and Wallin supplemented training with additional unilateral or bilateral resistance exercises which provide different, unmatched stimulus between groups. Interestingly, the complexity of athletic performance is reflected in the variation of speed and COD assessments previously utilised. Sprint testing has been performed over 10m (197, 511), 25m (232)and 40m (511). Change of direction has been assessed using the Pro-agility (511), Illinois and T-Test (197), and customised V-cut and 180° (232). The complexity of these tests – the number and acuteness of direction changes, the proportion of direction changes to straight line sprinting components and the duration of the test, confound dissection of the impact of unilateral or bilateral resistance training interventions on COD performance.

Table 2.5 Summary of research investigating bilateral (squat) and unilateral (RESS) lower body resistance training.

Authors	Subjects	Study length	Resistance intervention Bilateral	Resistance intervention Unilateral	Additional training	Strength test	Sprint test	COD tests
McCurdy (389)	38 untrained men and women (ave 21yrs)	2/wk for 8 weeks	Squat	RESS	Bil / Uni matched plyometrics	5RM Squat and RESS	(Margaria-Kalamen stair-climb)	N/A
Fisher and Wallin (197)	15 collegiate male rugby (ave 20yrs)	2/wk for 6 weeks	Squat	RESS	Bil / Uni matched plyometrics	1RM Squat and RESS	10m sprint	Illinois and T-test
Speirs et al (511)	18 academy male rugby (ave 18yrs)	2/wk for 5 weeks	Squat	RESS	Nil	3RM Squat and RESS	10m and 40m sprint	Pro-agility
Gonzalo-Skok et al (232)	22 youth male basketball (ave 17yrs)	2/wk for 6 weeks	Smith machine squat	Smith machine RESS	Plyometrics	Incremental Bil and Uni squat power test	25m	V-cut and 180° test

Ave = average; /wk = per week; RESS = rear foot elevated split squat; Bil = Bilateral; Uni = Unilateral; RM = repetition maximum; wk = week

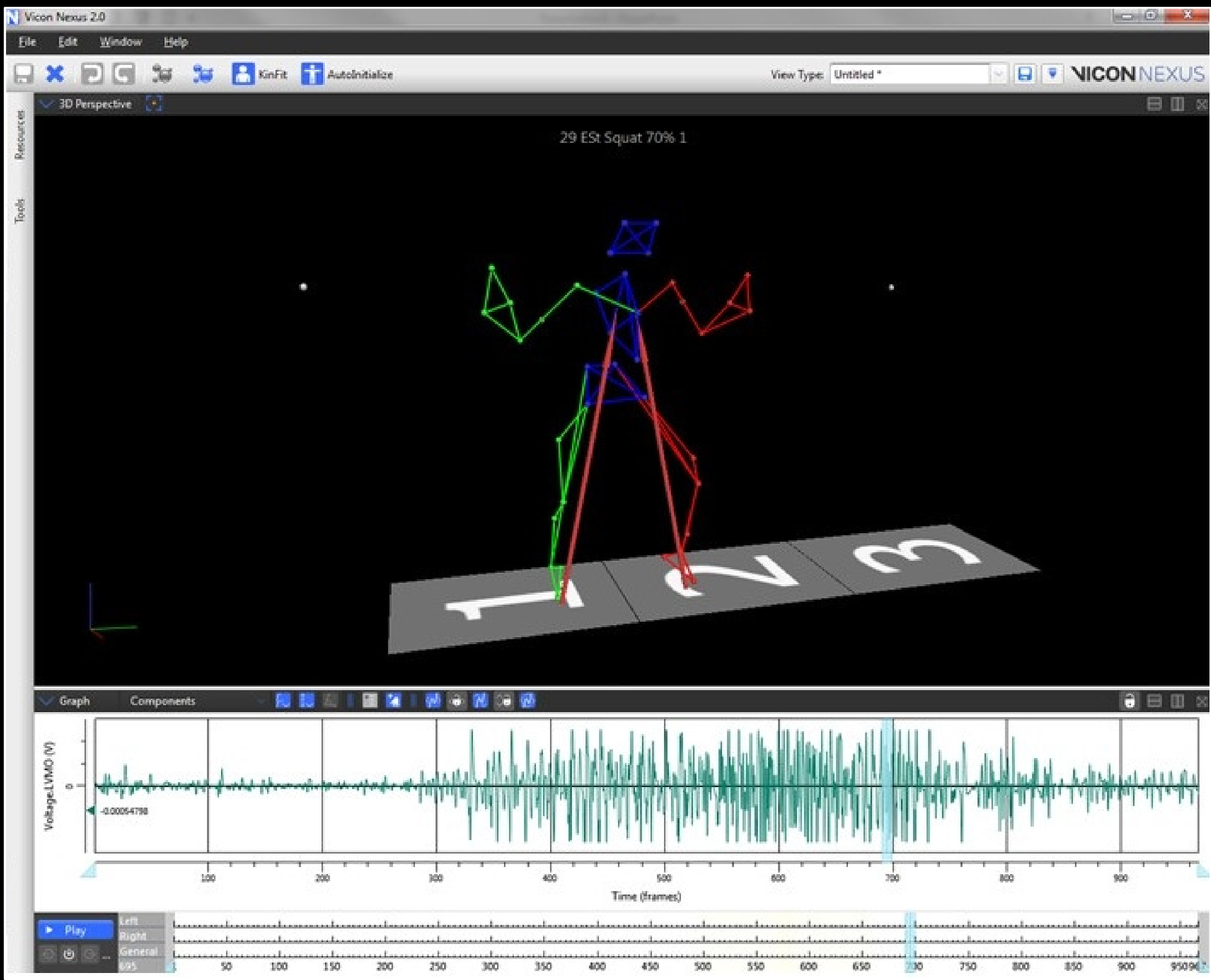
- 5 -

Summary and Thesis Implications

This review has demonstrated the importance of sprint acceleration and COD capacity in team sport performance and the relationship to lower body strength. The influence of increased strength on improvements in speed and COD are well supported, with training interventions and analysis of bilateral exercises well documented. Specificity and transfer are fundamental principles of resistance training design guiding exercise selection. Despite the apparent synergy between unilateral resistance training and athletic performance, the literature regarding unilateral integration is sparse. Research limitations include biomechanical comparison of bilateral and unilateral performance in well-trained participants. Additionally, practical implementation could be attributed to research design complexity which has rendered applied investigation problematic. Collectively, practitioners have limited empirical information from which to design programs for trained and well-trained athletes. It is acknowledged that adaptations to training in untrained, or relatively untrained individuals are easier to obtain and may not necessarily reflect the likely adaptation of trained individuals.

Furthermore, practical resistance training design comparing bilateral and unilateral intervention of previous studies have confounded the assessment with supplemental resistance exercises and/or plyometric activity. Reactive strength is a component of COD performance, therefore inclusion of bilateral or unilateral plyometric activities in previous research may have influenced COD performance changes obscuring interpretation regarding the resistance training intervention. The assessment of COD performance is also an important consideration. The number and magnitude of direction changes or the distance of the test alters the contribution of running speed and technique and the subsequent ability for investigators to isolate and interpret mechanisms for change (495). Previous comparison studies (197, 232, 389, 511) have focussed on the back squat and RESS, potentially overlooking other beneficial unilateral exercises with capacity for higher external loads capable of sufficient overload. The inclusion of a control group would provide further methodological rigour to extract the effects of training from natural development. Finally, practical training environments are characterised by periods of strength development and strength maintenance. The effect of unilateral resistance training prescribed according to typical maintenance volume-load characteristics may provide information currently unavailable concerning the influence of unilateral resistance training on strength maintenance.

PART TWO



Vicon Nexus 2.0
File
Edit
Window
Help
KinFit
AutoInitialize
View Type:
Untitled *
VICON NEXUS
3D Perspective
Resources
Tools
29 ESt Squat 70% 1
Graph
Components
Time (frames)
Play
Left
Right
General

PREFACE

A primary research question was to determine the force application and movement patterns of the squat and step-up. The experimental design developed to answer this specific research question required determination of validity and reliability of particular methodology. Thus, Part Two presents three papers establishing the rigour of methodology utilised in this thesis. Comparing the step-up to squat required establishing reliability of the 1RM Step-up maximal strength assessment (Chapter Three). A reliable unilateral test was essential to success of the thesis. Additional constraints in laboratory set-up were overcome comparing methods of determining barbell displacement in heavily loaded back squats performed by well-trained athletes presented in Chapter Four. Accurate determination of barbell displacement underpins barbell velocity calculation, an important performance variable for comparing movements in subsequent analysis. Finally, despite extensive investigation, reliability of kinetic variables in heavy back squat performance of well-trained participants has been seldom reported. Chapter Five presents information critical to interpretation of kinetic performance of the squat.

Chapter Three

The lower body step-up exercise: Strength testing reliability and training application.

Chapter Four

Validity and reliability of methods to determine barbell displacement in heavy back squats: Implications for velocity-based training (as accepted for publication: Appleby BB, Banyard HG, Cormack SJ, and Newton RU, PAP 2018 *JSCR)*.

Chapter Five

Reliability of squat kinetics in well-trained rugby players: Implications for monitoring training (as reviewed for publication to the Journal of Strength and Conditioning Research).

Chapter Three

THE LOWER BODY STEP-UP EXERCISE: STRENGTH TESTING RELIABILITY AND TRAINING APPLICATION

ABSTRACT

Unilateral exercises are perceived as sport specific, yet coaches have comparatively fewer reliable testing options for single leg strength compared to bilateral exercises. Accurate single leg assessment may provide practical benefit to coaches in the daily training environment for single leg strength and asymmetry and injury risk identification. The purpose of this study was to determine the reliability of the maximal barbell step-up test in moderately trained athletes and determining the smallest worthwhile change in performance likely to be important for this population. Ten participants completed four familiarisation resistance training sessions prior to two repeated one repetition maximum (1RM) barbell step-up tests on separate days. Reliability was estimated as the typical error ± 90% confidence limits (CL), expressed as a coefficient of variation (CV%) and the intraclass correlation (ICC). The smallest worthwhile change (SWC), calculated as 0.2 x between-participant standard deviation was used to determine the smallest important change in performance. Despite the relatively low CV% of many variables (maximum of left or right leg CV% = 3.3%; only the right leg CV% = 5.3%) only the left leg (CV = 2.0%, SWC = 3.3%, ICC = 0.98) and average of the left and right leg (CV = 2.7%, SWC = 3.1%, ICC = 0.95) are able to detect the SWC. The CV% ranged from 0.6 – 1.8 times the smallest worthwhile change. The 1RM step-up test is a reliable test for coaches to monitor improvements in unilateral strength. Coaches using the 1RM step-up can confidently detect important changes in performance of approximately 5%. Regular programming of the step-up in the daily training environment may assist coaches monitor unilateral lower body strength.

INTRODUCTION

Unilateral lower body strength exercises are prescribed as a sport specific training strategy. Such exercises are utilised due to the heightened recruitment of secondary stabilizer muscles, the higher potential for force development per limb due to the bilateral strength deficit and the identification and potential correction of asymmetry (298, 480). Compared to unilateral resistance exercises, the reliability of bilateral exercises is widely available and movements such as the squat can be seamlessly integrated into training plans and sessions for both training and testing (37, 117). Given the importance of single leg training for sport specificity and injury rehabilitation (386), a reliable unilateral test would provide coaches with a tool that can be incorporated in the routine training environment.

It is well accepted that interpretation of testing results requires confidence in their accuracy (285) and new methodologies should quantify "error" or "noise" from both biological and technical sources, such as depths or angles of displacement and population training age and familiarity (259). With regards to familiarisation, it is suggested that three to four sessions are required for inexperienced lifters, or unfamiliar testing protocols to ensure a true maximal assessment (20, 67, 510). For example, Augustsson and Svantesson (20) found a significant 11% difference between two testing sessions of one repetition maximum (1RM) squat performance in female university students (intraclass correlation [ICC] = 0.85), and suggested a familiarisation test session for inexperienced participants. However, familiarity with technical execution may not be sufficient, and experience with the testing intensity may be of greater importance (385). Several studies have demonstrated high ICC's and low coefficients of variation (CV%) can be achieved with trained participants within three trials (37, 385, 464).

Regarding unilateral lower body strength testing, the step-up exercise is an example of a lower body training and testing exercise yet to be examined for reliability. Additionally, it is also critical that the level of detectable improvement be established to inform program practice and decision making (288). Therefore, the aim of this study was to establish the reliability and smallest worthwhile change of the 1RM barbell step-up in moderately trained participants.

Methods

Experimental Approach to the Problem. To establish the reliability and smallest worthwhile change of a free-weight barbell box step-up (step-up) 1RM test, a group of 10 well trained, yet unfamiliar participants were selected. In a two-week period (four training sessions), participants completed four sets of 2 to 4 repetitions of increasing moderate, to moderate-high intensity (Figure 3.1). In the third week participants attended two sessions separated by four days to determine 1RM reliability.

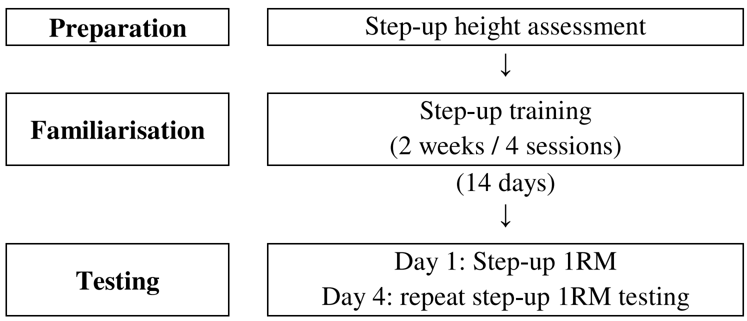


Figure 3.1 Experimental design schematic.

*Subjects***.** Ten academy level rugby union players were recruited (age = 21.4 ± 2.9 yrs; mass = 99.7 ± 13.4 kg; height: 184.7 ± 6.0; training age = 5.2 ± 2.3 yrs). All participants were notified of the potential risks involved and gave informed consent. This study was approved by the University's Human Research Ethics Committee. All participants were free of injury or previous injury history which may have affected performance. All participants identified themselves as right foot dominant in reference to their preferred leg to kick a ball (261, 385).

Procedures. *Step-up Height Assessment.* The exercise required the participant to achieve a knee angle of 90° at the commencement of the concentric phase of the movement. A 90° knee angle has been frequently used in studies that assessed barbell back squats and other lower body resistance exercises such as split squats or rear foot elevated split squats (385, 551). A line joining the greater trochanter to lateral tibial condyle, and lateral tibial condyle to the lateral malleolus of the right leg was used to determine a 90° knee angle during the step-up. Participants were filmed from a right, lateral view performing a 40kg barbell step-up on a series of boxes of incremental step height of 20mm from 300mm to 420mm high. A video camera (Sony Handycam HDR-HC3 HDV 1080i) was placed on a tripod 0.95 metres high and approximately four metres perpendicular from the centre position of the first box for lateral filming. Participants were filmed performing a minimum of two step-ups with their right leg on each step. Computer software (Kinovea, version 0.8.15) was used to measure knee angle. The 90° knee angle was defined as the minimum angle of the knee at contact of the lead foot on the step. All repetitions were analysed and the closest step-up box to that which resulted in a 90° knee angle was allocated to the participant.

Familiarisation training. Over four training sessions, participants completed four sets of two to four repetitions (Table 3.1). Loads were refined each session as participants improved with confidence in the exercise.

Table 3.1 The familiarisation protocol.

Week	Session	Repetitions	Intensity
1	1	4,4,4,4	6-8 RM
	2	4,4,3,3	5-7 RM
2	3	3,3,3,3	4-5 RM
	4	3,3,2,2	3-4 RM

One Repetition Maximum Testing. Participants were tested after a rest day on both occasions. Upon arrival at the testing facility, participants followed the 20-minute standard testing warm-up protocol which consisted of stationary bike riding (seven minutes of steady state intensity plus three minutes of short interval efforts of increasing intensity), followed by lower body mobility exercises (bodyweight squats and lunges) and concluded with five sub-maximal countermovement jumps and five depth jumps. Participants completed a series of warm-up sets (four repetitions at 50% of estimated 1RM, three repetitions at 70%, two repetitions at 80% and one repetition at 90%) each separated by three minutes recovery. Following the warm-up, a series of maximal attempts were performed until a 1RM was obtained. Verbal encouragement was provided throughout the testing. This protocol was modified for single leg testing, based on a previous protocol for assessment of maximal strength (377). To execute the step-up, the participant was located within a power cage with the safety racks raised to approximately chest height (Figure 3.2). From this position, the participant un-racked the barbell across their upper back and performed the step-up inside the rack. The step-up was deemed a fail if the participant could not extend the leg fully on the box without support from the uninvolved limb. The order of step-up leg was randomised amongst participants and a 1RM was obtained for each leg.

Figure 3.2 Performance of the step-up.

Statistical Analysis. The inter-day reliability of 1RM step-up strength testing was calculated using the intraclass correlation coefficient and the typical error expressed as a percentage (coefficient of variation (CV%)), ±90% confidence limits using a customised Excel spreadsheet (283). A measure was deemed reliable if the CV% was less than 10%, a threshold reported in many human performance reliability studies (19, 124, 143). The smallest worthwhile change, representing the smallest practically important change, was calculated as 0.2 x the between-participant pure SD (283). A test was considered capable of detecting the smallest worthwhile change if the CV% was less than the SWC (455).

RESULTS

Across all participants and trials, the average ± standard deviation 1RM step-up of the left leg and right leg was 129.1kg ± 19.2kg. The CV for all comparisons ranged between 2.0% and 5.3% with the left leg and average (left and right leg) CV% less than the smallest worthwhile change.

Table 3.2 Reliability of 1RM step-up testing between trial 1 and trial 2.

	Trial 1 1RM mean (kg)	Trial 2 1RM mean (kg)	CV% (CL)	ICC (CL)	SWC%
Left leg	125.0 (20.4)	132.5 (20.7)	2.0 (1.5-3.3)	0.98 (0.97-1.00)	3.3
Right leg	127.5 (16.2)	131.5 (21.2)	5.3 (3.8-8.8)	0.82 (0.75-0.97)	2.9
Maximum	128.5 (17.6)	134.5 (20.3)	3.3 (2.4-5.5)	0.92 (0.89-0.99)	2.9
Average of left and right	126.3 (18.2)	132.0 (20.7)	2.7 (2.0-4.5)	0.95 (0.93-0.99)	3.1

Data presented as mean (SD), CV (90% CL), ICC (90% CL) and SWC%. **1RM:** one repetition maximum; **Left leg:** value of left leg step-up; **Right leg:** value of right leg step-up; **Maximum:** the maximum value at session 1 to session 2; **Average of left and right:** average of left leg and right leg; **CV%:** coefficient of variation; **ICC:** intraclass correlation; **CL:** 90% confidence limits; **SWC%:** Smallest worthwhile change from pure SD.

DISCUSSION

In this paper we present a single leg lower body exercise with practical application as both a sport specific training exercise and unilateral assessment for athletes. The primary result of this study is the high reliability within four sessions in moderately trained athletes. Furthermore, some variables were sufficiently sensitive to measure the smallest important change. This is a vital finding, as the ability of a test to detect a small but important change in performance at an individual level is critical for strength and conditioning coaches who wish to assess unilateral lower body performance using the step-up exercise.

Whilst the incorporation of unilateral lower body resistance training attempts to address sport specificity, (232, 511) objective assessment of unilateral training is limited compared to the range of proven reliable bilateral testing options (e.g. squat, power clean, clean pull) (117, 119, 256, 291). The reliability of 1RM step-up on both legs is considered acceptable (CV% < 5.3) with ICC values > 0.82 (Table 3.2) and compares favourably to those previously reported for back squats and power cleans across a range of athlete training experience and sport (117, 493). The results of the current study are particularly interesting compared to bilateral testing, as the reduced base of support introduces more technical variation (67), yet despite more degrees of freedom, the unilateral test can be highly reliable in trained athletes when they have been sufficiently familiarised with the task.

Previous reliability investigations of lower body unilateral strength have involved the barbell split squat (SS) (551) and rear-foot elevated split squat (RESS) (385) reporting excellent inter-trial reliability (SS: %CV_{TE} = 1.57%, ICC = 0.99; RESS: ICC = 0.98). Although these studies recognised the importance of unilateral training and testing to assess lower leg function, unfortunately both only tested the dominant leg, potentially limiting practical application. In the current study, participants were required to perform the test on both sides, as per normal training practices, providing a more complete practical analysis. Although the majority of load is directed through the front leg in both SS and RESS (70-85% (267, 386)), in comparison the step-up movement contains a purely unilateral component.

An important methodological reliability component of this study is the homogenous participant group. Achieving high levels of reliability can be difficult in homogenous groups where the bounds of performance are clustered (285). Despite the homogenous and trained nature of this population, and their prior unfamiliarity with the exercise, they were able to demonstrate reliable performance within four sessions. Importantly, the combination of reliability (CV% and ICC) and SWC presented in the current study, enables coaches to accurately assess the impact of training interventions utilising the step-up.

An essential rationale for unilateral training and testing is identifying and addressing lower limb asymmetry. During lower body rehabilitation, it is common practice to utilise unilateral performance to assess progress by making comparisons to the non-injured side (385). In team sports such as soccer, rugby, Australian Rules Football and netball, it is common for athletes to suffer a lower body injury (62, 445, 563, 572). By incorporating the step-up in a periodised annual plan, with routine 1RM assessment, coaches can have historical unilateral data which may provide critical "return to training/play" data points in the event of lower body injury that requires rehabilitation. Knowledge of the CV% and smallest worthwhile change permit objective assessment regarding progress between current and previous performance. Such information may provide training targets to inform rehabilitation programming to return asymmetry to pre-injury levels (63, 393, 426).

PRACTICAL APPLICATIONS

We present a highly sport specific application for coaches wishing to assess single leg lower body performance. The results are that 1RM step-up is a reliable test in trained participants after four familiarisation sessions. Importantly, coaches can confidently detect changes in step-up 1RM when there is a change in performance of approximately 5%. This test may be utilised to provide coaches with an insight into unilateral training adaptations, symmetry performance and requirements of athletes. Routine incorporation of the exercise in the daily training environment may assist coaches to monitor unilateral lower body performance.

REFERENCES

19. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217-238, 1998.

20. Augustsson RS and Svantesson U. Reliability of the 1 Rm Bench Press and Squat in Young Women. *European Journal of Physiotherapy* 15: 118-126, 2013.

37. Banyard HG, Nosaka K, and Haff GG. Reliability and Validity of the Load-Velocity Relationship to Predict the 1rm Back Squat. *Journal of Strength and Conditioning Research* 31: 1897-1904, 2017.

62. Best G. Epidemiology and Incidence of Injury in Elite Netball Players – an Injury Audit of the 2016 Netball Superleague Season. *British Journal of Sports Medicine* 51: 297-297, 2017.

63. Beutler A, Cooper, LW, Kirkendall, DT and Garrett, WE. Electromyographic Analysis of Single-Leg Closed Chain Exercises: Implications for Rehabilitation after Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* 37: 13-18, 2002.

67. Blazevich A, and Gill, ND. Reliability of Unfamiliar, Multijoint, Uni- and Bilateral Strength Tests: Effects of Load and Laterality. *Journal of Strength and Conditioning Research* 20: 226-230, 2006.

117. Comfort P and McMahon JJ. Reliability of Maximal Back Squat and Power Clean Performances in Inexperienced Athletes. *Journal of Strength and Conditioning Research* 29: 3089-3096, 2015.

119. Comfort P, Udall R, and Jones PA. The Effect of Loading on Kinematic and Kinetic Variables During the Midthigh Clean Pull. *Journal of Strength and Conditioning Research* 26: 1208-1214, 2012.

124. Cormack SJ, Newton, R.U., McGuigian, M.R. and Doyle, T.L.A. Reliability of Measures Obtained During Single Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.

143. Cronin J, Hing, RD and McNair, PJ. Reliability and Validity of a Linear Position Transducer for Measuring Jump Performance. *Journal of Strength and Conditioning Research* 18: 590-593, 2004.

232. Gonzalo-Skok O, Tous-Fajardo J, Suarez-Arrones L, Arjol-Serrano JL, Casajús JA, and Mendez-Villanueva A. Single-Leg Power Output and between-Limb Imbalances in Team-Sports Players: Unilateral Vs. Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance* 12: 106-114, 2016.

256. Hansen KT, Cronin JB, and Newton MJ. The Reliability of Linear Position Transducer and Force Plate Measurement of Explosive Force–Time Variables During a Loaded Jump Squat in Elite Athletes. *Journal of Strength and Conditioning Research* 25: 1447-1456, 2011.

259. Harris N, Cronin, JB, Taylor, K-L, Boris, J, and Sheppard, J. Understanding Position Transducer Technology for Strength and Conditioning Practioners. *Strength and Conditioning Journal* 32: 66-79, 2010.

261. Hart NH, Nimphius S, Spiteri T, and Newton RU. Leg Strength and Lean Mass Symmetry Influences Kicking Performance in Australian Football. *Journal of Sports Science and Medicine* 13: 157, 2014.

267. Hefzy M and Harrison L. Co-Activation of the Hamstrings and Quadriceps During the Lunge Exercise. *Biomedical Sciences Instrumentation* 33: 360-365, 1997.

283. Hopkins W. Spreadsheets for Analysis of Validity and Reliability. *Sportscience* 19: 36-42, 2015.

285. Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Medicine* 30: 1-15, 2000.

288. Hopkins WG, Hawley JA, and Burke LM. Design and Analysis of Research on Sport Performance Enhancement. *Medicine and Science in Sports and Exercise* 31: 472-485, 1999.

291. Hori N, Newton RU, Kawamori N, McGuigan MR, Kraemer WJ, and Nosaka K. Reliability of Performance Measurements Derived from Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency. *Journal of Strength and Conditioning Research* 23: 874-882, 2009.

298. Howe L, Goodwin J, and Blagrove R. The Integration of Unilateral Strength Training for the Lower Extremity within an Athletic Performance Programme. *Professional Strength and Conditioning Journal* 33: 19-24, 2014.

377. McBride JM, Triplett-McBride, T., Davie, A. and Newton, R.U. A Comparison of Strength and Power Characteristics between Power Lifters, Olympic Lifters and Sprinters. *Journal of Strength and Conditioning Research* 13: 58-66, 1999.

385. McCurdy K, Langford, G.A., Cline, A.L., Doscher, M. and Hoff, R. The Reliability of 1- and 3rm Tests of Unilateral Strength in Trained and Untrained Men and Women. *Journal of Sports Science and Medicine* 3: 190-196, 2004.

386. McCurdy K, O'Kelley, E., Kutz, M., Langford, G., Ernest, J. and Torres, M. Comparison of Lower Extremity Emg between the 2-Leg Squat and Modified Single Leg Squat in Female Athletes. *Journal of Sport Rehabilitation* 19: 57-70, 2010.

393. McGrath TM, Waddington G, Scarvell JM, Ball NB, Creer R, Woods K, and Smith D. The Effect of Limb Dominance on Lower Limb Functional Performance–a Systematic Review. *Journal of Sports Sciences* 34: 289-302, 2016.

426. Myer GD, Martin Jr L, Ford KR, Paterno MV, Schmitt LC, Heidt Jr RS, Colosimo A, and Hewett TE. No Association of Time from Surgery with Functional Deficits in Athletes after Anterior Cruciate Ligament Reconstruction: Evidence for Objective Return-to-Sport Criteria. *American Journal of Sports Medicine* 40: 2256-2263, 2012.

445. Orchard JW, Seward H, and Orchard JJ. Results of 2 Decades of Injury Surveillance and Public Release of Data in the Australian Football League. *American Journal of Sports Medicine* 41: 734-741, 2013.

455. Pyne DB. Interpreting the Results of Fitness Testing. Presented at International Science and Football Symposium, 2003.

464. Ritti-Dias RM, Avelar A, Salvador EP, and Cyrino ES. Influence of Previous Experience on Resistance Training on Reliability of One-Repetition Maximum Test. *Journal of Strength and Conditioning Research* 25: 1418-1422, 2011.

480. Santana JC. Single-Leg Training for 2-Legged Sports: Efficacy of Strength Development in Athletic Performance. *Strength and Conditioning Journal* 23: 35, 2001.

493. Sheppard J, Cronin, JB, Gabbett, TJ, McGuigan MR. Relative Importance of Strength, Power and Anthropometric Measures to Jump Performance of Elite Volleyball Players. *Journal of Strength and Conditioning Research* 22: 758-765, 2008.

510. Soares-Caldeira LF, Ritti-Dias RM, Okuno NM, Cyrino ES, Gurjão ALD, and Ploutz-Snyder LL. Familiarization Indexes in Sessions of 1-Rm Tests in Adult Women. *Journal of Strength and Conditioning Research* 23: 2039-2045, 2009.

511. Speirs DE, Bennett M, Finn CV, and Turner AP. Unilateral Vs Bilateral Squat Training for Strength, Sprints and Agility in Academy Rugby Players. *Journal of Strength and Conditioning Research* 30: 386-392, 2015.

551. Urquhart B, Moir GL, Graham SM, and Connaboy C. The Reliability of 1rm Split-Squat Performance and the Efficacy of Assessing Both Bilateral. *Journal of Strength and Conditioning Research* 29: 1991-1998, 2015.

563. Williams S, Trewartha G, Kemp S, and Stokes K. A Meta-Analysis of Injuries in Senior Men's Professional Rugby Union. *Sports Medicine* 43: 1043-1055, 2013.

572. Wong P and Hong Y. Soccer Injury in the Lower Extremities. *British Journal of Sports Medicine* 39: 473-482, 2005.

4

Chapter Four

Reliability and Validity of Methods to Determine Barbell Displacement in Heavy Back Squats: Implications for Velocity Based Training

As accepted for publication in the

Journal of Strength and Conditioning Research, 2018.

Pages 70-81 are not included in this version of the thesis.

5

Chapter Five

Reliability of Squat Kinetics in Well-Trained Rugby Players: Implications for Monitoring Training

As submitted for second revision to the
Journal of Strength and Conditioning Research, 2019.

Pages 83-97 are not included in this version of the thesis.

You can view this publication's record in Research Online here:
https://ro.ecu.edu.au/ecuworkspost2013/6525/

SUMMARY

Part Two presented three papers establishing methodological rigor central to the primary research question of this thesis:

- The 1RM step-up test is reliable test (CV% = 2.0 – 5.3; ICC = 0.82 – 0.98) capable of detecting important changes in performance of approximately 5%.
- Well-trained participants are capable of familiarising to the 1RM step-up testing protocol within four sessions.
- The location of tracking barbell displacement should be centralised as much as practically possible as the combination of laterality, the pliant nature of a weightlifting barbell and magnitude of external load can influence the validity of displacement (LPT: CV% = 2.1 – 3.0; Overall mean bias % = 0.9 – 1.5; RHS: CV% = 3.3 – 7.5; Overall mean bias % = 7.3 – 11.2; LHS: CV% = 2.7 – 3.4; Overall mean bias % = 4.9 – 7.3).
- Peak and mean ground reaction force from the left, right or sum of left and right legs during heavy back squats is highly reliable. (CV% = 2.3 – 4.8; ICC = 0.87 – 0.96).

PART THREE

PREFACE

Part Three comprises three technical papers pertaining to reliability of key biomechanical variables of squat and step-up performance. Importantly, these papers provide confidence when interpreting biomechanical variables of interest when examining a primary thesis purpose: a comparison of the force application and movement patterns of bilateral and unilateral resistance training. Complementing Chapter Five, these papers combine to form an assessment of the reliability of key variables currently unreported in the literature in well-trained participants in heavy squat and step-up performance. The following chapters include:

Chapter Six
Reliability of back squat kinematics.

Chapter Seven
Reliability of step-up kinetics.

Chapter Eight
Reliability of step-up kinematics.

6

Chapter Six

TECHNICAL PAPER:

RELIABILITY OF BACK SQUAT KINEMATICS

INTRODUCTION

The squat is arguably the most widely prescribed and researched resistance exercise with applications ranging from activities of daily life, to injury rehabilitation and elite athlete training (18, 198, 321, 359, 374, 466, 478, 591). Laboratory measured variables of angle and velocity of movement are reported in numerous studies to describe characteristics of the squat (165, 188, 190, 191, 488) or compare the squat to other exercises (189, 240, 512, 536, 576). Despite the abundance of squat analyses, the documentation of reliability pertaining to key characteristic variables for the back squat are infrequent. Whilst studies have commonly reported knee flexion angles, bar displacement and velocity and temporal phase information, the reliability of these measures is often unpublished. Therefore, the purpose of this technical paper is to identify and report the reliability of kinematic variables of squat performance in highly trained rugby union players, to permit subsequent analysis and characterisation.

METHODS

Experimental Design. A cross-sectional research design was utilised to determine the kinematics during the squat in trained participants (Figure 6.1). Fifteen participants attended two testing sessions, separated by seven to ten days. The first session established one repetition maximum (1RM) strength of the squat and the second session involved assessment of the squat under the following experimental conditions. Participants performed two sets of two repetitions of the back squat at 70, 80 and 90% of 1RM. Force application and movement patterns were assessed using tri-axial force plates and three-dimensional motion measurement. The focus of this paper is the kinematic reliability of the squat (the kinetic results having been presented in a previous chapter) and the use of the force plate for this paper is solely for temporal phase identification.

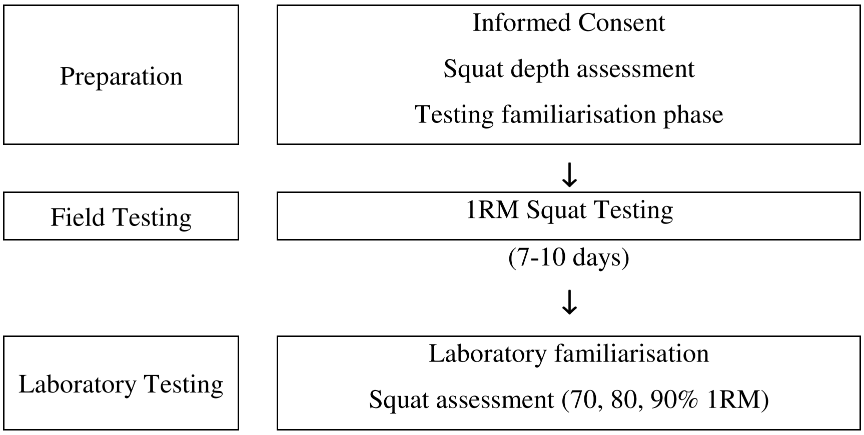


Figure 6.1 Schematic representation of experimental design.

Participants. A combination of 15 academy and professional rugby union players were recruited to participate in this investigation (Table 6.1). All participants were notified of the potential risks involved and gave their written informed consent. This study was approved by the University's Human Research Ethics Committee. All participants were cleared by medical staff to be free of injury or injury history which may have inhibited performance.

Table 6.1 Participant characteristics.

Age (years)	Body mass (kg)	90° Squat 1RM (kg)	Relative squat (1RM:BW)
24.1 ± 3.0	103.0 ± 9.5	194.7 ± 26.9	1.88 ± 0.16

Data presented as mean ± SD for all variables

Data Acquisition and Analysis Procedures *One Repetition Maximum Testing*. The 1RM protocol was applied for assessment of maximal strength (377). This protocol involved participants completing a series of warm-up sets (four repetitions at 50% of estimated 1RM, three repetitions at 70%, two repetitions at 80% and one repetition at 90%) each separated by three minutes recovery. Following the warm-up, maximal single repetition attempts separated by a minimum of five minutes recovery were performed until a 1RM was obtained. Verbal encouragement was provided throughout the testing. The 90º knee flexion depth was assessed by goniometer and verified via video analysis during the familiarisation phase. During maximal testing, the knee angle was monitored by each participant squatting with a 20kg Olympic barbell (Australian Barbell Company, Victoria, Australia) and Olympic weight plates (Eleiko, Halmstad, Sweden) to an elastic band attached horizontally across a power rack (York Fitness, Rocklea, Queensland, Australia.) at their individually determined depth. An accredited strength and conditioning coach and at least one assistant observed each test for spotting, technique and depth monitoring. The repetition was deemed a fail if the participant could not achieve the required depth or could not return to the upright position.

Resistance Exercise Assessment. Session two involved performance of submaximal squats at three loads with measurement of force and movement kinematics (Figure 6.2). A standardised general body warm-up consisted of moderate intensity stationary cycling, self-directed stretching and mobility exercises, followed by the performance of a specific warm-up progression. Tested exercise technique was monitored according to the 1RM protocols and trials not meeting these criteria were repeated. During all resistance assessments, ground reaction force and movement patterns were assessed using tri-axial force plates and three-dimensional motion analysis.

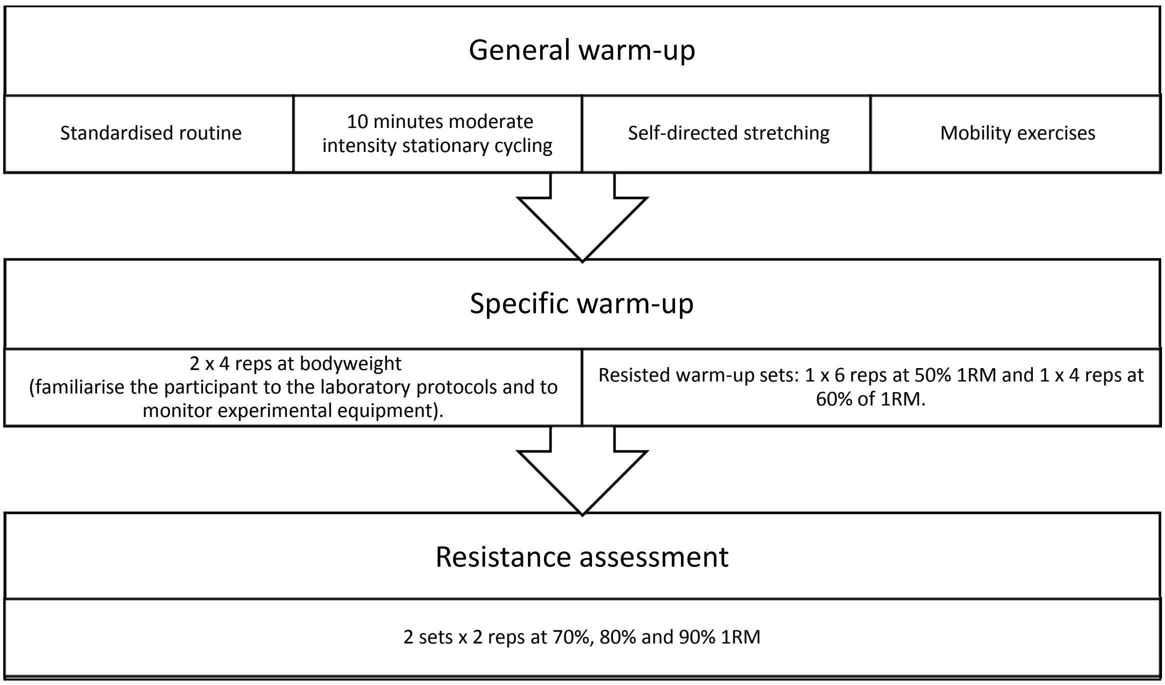


Figure 6.2 Flow chart representation of participant testing session two.

Three-Dimensional Motion Analysis. During all resistance exercise assessments, a 10-camera digital optical motion analysis system (Vicon MX, Vicon, Oxford, UK) was used to record whole body three-dimensional movement patterns at 250Hz. A previously validated, whole-body model was used to capture and analyse movement patterns using Nexus software (Nexus 1.0) (152). The model was a defined, 37 retro-reflective marker set and series of subject measurements to examine the three-dimensional joint kinematics. A control space of approximately 25 square meters to a height of approximately three meters, surrounding two in-ground force plates, was calibrated using the manufacturers recommended technique of wand calibration (538). Force and motion analysis data were captured simultaneously and aligned using a fifth-order spline interpolation to up-sample the motion analysis data to 1,000Hz. All trials were processed according to previous standards in Vicon Nexus 2.3 using a customised pipeline incorporating a zero-lag fourth order 18Hz low pass Butterworth filter (515). All data was analysed using customised calculations in Microsoft Excel 2013.

Temporal Phase Definitions. The commencement of the squat eccentric phase was defined by a 5% reduction in bilateral GRF (494), concluding at minimum marker displacement of the 7th cervical vertebra (C7). The concentric phase was defined, from the end of the eccentric phase to maximum C7 displacement. The use of C7 as a reliable marker of displacement has been previously established (Chapter Four).

Statistical Analysis. The inter-trial reliability was calculated using intraclass correlation coefficient (ICC) and typical error expressed as a percentage of coefficient of variation (CV%), including ±90% confidence limits calculated using a customised Excel spreadsheet (286). The smallest worthwhile change (SWC) was calculated at 0.2 times between-participant pure standard deviation (SD). For CV%, values below a threshold of 10% were deemed acceptable (19, 124, 143). A test was considered capable of detecting the SWC if the CV% was less than the SWC (455).

RESULTS

Reliability assessments of kinematic derived variables are presented in Tables 6.2-6.5. High intra-subject reliability was observed in several variables across all intensities, including maximum knee angle, concentric displacement and peak velocity. The CV% for the squat concentric phase length was also under 10% whilst the ICC improved as bar mass increased (ICC = 0.38-0.78). The eccentric phase of the squat was observed to have the greatest variability (CV% = 13.2-15.2) (Table 6.2). Both the eccentric and concentric measures of displacement for the squat were acceptable (CV% = 4.3-8.6; ICC = 0.55-0.81) (Table 6.3). The typical error for maximum knee flexion during the squat was less than 5.2% with large or very large ICC values (Table 6.4). The typical error for squat average or peak velocity was 7.4% or less, whilst ICC values ranged from moderate to very large (ICC = 0.78-0.89) (Table 6.5). None of the variables could be used to detect the SWC.

Table 6.2 Reliability of duration phases in the squat.

Variable	Load (%1RM)	Mean duration (ms)	CV% (CL)	ICC (CL)	SWC%
Eccentric time	70%	1,185 (238)	13.8 (11.0-19.2)	0.52 (0.22-0.77)	2.6
	80%	1,274 9294)	13.3 (10.6-17.9)	0.66 (0.41-0.85)	3.4
	90%	1,426 (310)	15.2 (12.1-21.3)	0.54 (0.25-0.79)	3.0
Concentric time	70%	861 (84)	8.2 (6.5-11.3)	0.38 (0.07-0.68)	1.2
	80%	984 (110)	6.8 (5.4-9.0)	0.66 (0.41-0.85)	1.7
	90%	1,229 (252)	9.9 (8.0-13.8)	0.77 (0.56-0.91)	3.3

Data presented as mean (SD), CV (90% CL), ICC (90% CL) and SWC%. **CV%:** coefficient of variation; **CL:** confidence limit; **ICC:** intraclass correlation coefficient; **SWC%**: 0.2 times the between-subject pure SD. **Eccentric time:** duration of the eccentric phase from 5% reduction in bilateral GRF to minimal C7 displacement. **Concentric time:** duration from minimum C7 displacement to maximal C7 displacement; **%1RM:** percentage of one repetition maximum.

Table 6.3 Reliability of maximum C7 displacement in the squat.

Variable	Load (%1RM)	Mean displacement (mm)	CV% (CL)	ICC (CL)	SWC%
Eccentric displacement	70%	452 (48)	7.2 (5.8-10.0)	0.60 (0.31-0.82)	1.6
	80%	438 (35)	4.3 (3.5-5.8)	0.75 (0.54-0.89)	1.4
	90%	432 (40)	4.5 (3.6-6.1)	0.81 (0.62-0.92)	1.7
Concentric displacement	70%	527 (62)	8.6 (6.9-11.9)	0.55 (0.26-0.79)	1.7
	80%	522 (51)	4.6 (3.7-6.1)	0.81 (0.64-0.92)	1.8
	90%	514 (49)	4.3 (3.5-6.0)	0.83 (0.65-0.93)	1.7

Data presented as mean (SD), CV (90% CL), ICC (90% CL) and SWC%. **CV%:** coefficient of variation; **CL:** confidence limit; **ICC:** intraclass correlation coefficient; **SWC%**: 0.2 times the between-subject pure SD. **Concentric displacement:** relative displacement from minimum displacement to the completion of the concentric phase. **Eccentric displacement:** relative displacement from commencement of the eccentric phase to minimum displacement.

Table 6.4 Reliability of maximum knee angle in the squat.

Load (%1RM)	Leg	Mean of knee flexion (degrees)	CV% (CL)	ICC (CL)	SWC%
70%	Left	94.4 (6.7)	4.2 (3.4-5.9)	0.69 (0.43-0.87)	1.2
	Right	95.8 (6.9)	5.2 (4.2-7.2)	0.53 (0.23-0.78)	1.0
80%	Left	92.5 (6.0)	2.3 (1.8-3.1)	0.90 (0.78-0.96)	1.2
	Right	93.9 (5.4)	2.7 (2.2-3.6)	0.80 (0.62-0.92)	1.0
90%	Left	91.7 (5.8)	2.9 (2.3-3.9)	0.83 (0.65-0.93)	1.2
	Right	93.6 (5.6)	3.0 (2.4-4.1)	0.78 (0.58-0.91)	1.0

Data presented as mean (SD), CV (90% CL), ICC (90% CL) and SWC%. **CV%:** coefficient of variation; **CL:** confidence limit; **ICC:** intraclass correlation coefficient; **SWC%**: 0.2 times the between-subject pure SD.

Table 6.5 Reliability of C7 velocity in the squat.

Variable	Load	Velocity (m/s)	CV% (CL)	ICC (CL)	SWC%
Average velocity - concentric phase	70%	0.61 (0.07)	5.5 (4.5-7.6)	0.78 (0.60-0.91)	2.0
	80%	0.54 (0.06)	5.3 (4.3-7.2)	0.85 (0.70-0.94)	2.3
	90%	0.43 (0.07)	7.4 (5.9-10.2)	0.86 (0.72-0.95)	3.4
Peak velocity - concentric phase	70%	1.28 (0.16)	6.1 (4.9-8.4)	0.83 (0.66-0.93)	2.5
	80%	1.21 (0.15)	5.9 (4.7-7.8)	0.83 (0.67-0.93)	2.4
	90%	1.12 (0.11)	3.7 (2.9-5.1)	0.89 (0.76-0.96)	1.9

Data presented as mean (SD), CV (90% CL), ICC (90% CL) and SWC%. **CV%:** coefficient of variation; **CL:** confidence limit; **ICC:** intraclass correlation coefficient; **SWC%**: 0.2 times the between-subject pure SD. **Average velocity:** concentric phase: average velocity derived from C7 displacement during the concentric phase. **Peak Velocity:** maximum value of instantaneous velocity, derived from C7 displacement.

DISCUSSION

In this chapter we report acceptable levels of kinematic reliability for back squat concentric phase duration, maximum knee flexion angle, eccentric and concentric displacement and velocity. An important aspect of this study design is the well-trained nature of the participants and the magnitude of load used (absolute and relative), a theme central to Part Three of this thesis and providing critical context for further analysis.

The temporal phases of the squat, without the intra-trial reliability have been reported in a variety of populations and loading parameters (189, 417, 512). In the current investigation, the eccentric phase duration was of high variability in performance, whilst the concentric phase was shorter in duration and more reliable, suggesting individual variation in strategy during squat descent (Table 6.2). In contrast to this study, previous research investigating maximal or near maximal back squats in powerlifters (compared to rugby union athletes in the current study) have shown shorter eccentric phases compared to concentric. Whilst reliability values have not been reported, there exists inconsistency in the literature regarding temporal phase durations, potentially attributed to methodology of participants and technique, or phase detection definitions (e.g. squat descent indicated by bar descent (512), knee flexion (417) or ground reaction force (current study). This suggests future research should strive to ensure consistency in the definition of temporal marks and establish clear temporal phase assessment.

Based on previous research, the use of C7 motion as a measure of barbell displacement has been demonstrated to be reliable across a range of barbell loads (Chapter Four). Both the eccentric and concentric displacement in the squat were found to have good reliability (Table 6.2) and this is supported in the literature in less trained participants performing free weight full or Smith Machine squat variants (CV = 5% (76); ICC = 0.92 (377)). Similarly, the reliability for knee angle in the current study was 5.2% or less, comparable to previous research assessing full squats in trained participants (76) (Table 6.3).

Derived from displacement data, the peak and average velocity during the concentric phase of the squat were found to have excellent reliability (CV% = 3.7-7.3; ICC = 0.78-0.90) with consistency of performance of peak velocity improving with increasing bar load (Table 6.5). This is similar to previous studies using a position transducer or optical encoder in weighted Smith Machine jumps (ICC: 0.775 – 0.90; SEM% < 4%) (377, 456).

CONCLUSION AND PRACTICAL APPLICATIONS

Although kinematic variables are frequently reported, reliability of these measures for heavy back squats in well-trained participants has not been well documented. A strength of the current research is the magnitude of external load, and high training experience of the participants. In this biomechanical study we confirm that although not capable of determining the SWC, kinematic derived peak and average velocity, knee flexion angle and C7 displacement are reliable variables. This suggests that coaches and researchers can confidently interpret these variables in heavily loaded squats.

References

18. Aspe RR and Swinton PA. Electromyographic and Kinetic Comparison of the Back Squat and Overhead Squat. *Journal of Strength and Conditioning Research* 28: 2827-2836, 2014.

19. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217-238, 1998.

76. Brandon R, Howatson, G and Hunter, A. Reliability of a Combined Biomechanical and Surface Electromyographical Analysis System During Dynamic Barbell Squat Exercise. *Journal of Sports Sciences* 29: 1389-1397, 2011.

124. Cormack SJ, Newton, R.U., McGuigian, M.R. and Doyle, T.L.A. Reliability of Measures Obtained During Single Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.

143. Cronin J, Hing, RD and McNair, PJ. Reliability and Validity of a Linear Position Transducer for Measuring Jump Performance. *Journal of Strength and Conditioning Research* 18: 590-593, 2004.

152. Davis III RB, Ounpuu, S., Tyburski, D., and Gage, J.R. A Gait Analysis Data Collection and Reduction Technique. *Human Movement Sciences* 10: 575-587, 1991.

165. Dionisio VC, Almeida GL, Duarte M, and Hirata RP. Kinematic, Kinetic and Emg Patterns During Downward Squatting. *Journal of Electromyography and Kinesiology* 18: 134-143, 2008.

188. Escamilla R, Fleisig, GS, Lowry, TM, Barrentine, SW, and Andrews, JR. A Three-Dimensional Biomechanical Analysis of the Squat During Varying Stance Widths. *Medicine and Science in Sports and Exercise* 33: 984-998, 2001.

189. Escamilla R, Fleisig, GS, Zheng, N, Lander, JE, Barrentine, SW, Andrews, JR, Bergeman, BW and Moorman III, CT. Effect of Technique Variations on Knee Biomechanics During the Squat and Leg Press. *Medicine and Science in Sports and Exercise* 33: 1552-1566, 2001.

190. Escamilla R, Zheng N, Fleisig G, Lander J, Barrentine S, Cutter G, and Andrews J. The Effects of Technique Variations on Knee Biomechanics During the Squat and Leg Press 887. *Medicine and Science in Sports and Exercise* 29: 156, 1997.

191. Escamilla RF. Knee Biomechanics of the Dynamic Squat Exercise. *Medicine and Science in Sports and Exercise* 33: 127-141, 2001.

198. Flanagan S, and Salem, GJ. Bilateral Differences in the Net Joint Torques During the Squat Exercise. *Journal of Strength and Conditioning Research* 21: 1220-1226, 2007.

240. Gullett JC, Tillman, M.D., Gutierrez, G.M. and Chow, J.W. A Biomechanical Comparison of Back and Front Squats in Healthy Train Individuals. *Journal of Strength and Conditioning Research* 23: 284-292, 2008.

286. Hopkins WG. Reliability from Consecutive Pairs of Trials (Excel Spreadsheet). Available from: http://www.sportsci.org/resources/stats/. Accessed 1st May 2017., 2006.

321. Kellis E, Arambatzi F, and Papadopoulos C. Effects of Load on Ground Reaction Force and Lower Limb Kinematics During Concentric Squats. *Journal of Sports Sciences* 23: 1045-1055, 2005.

359. Lynn SK, and Noffal, G.J. Lower Extremity Biomechanics During a Regular and Counterbalanced Squat. *Journal of Strength and Conditioning Research* 26: 2417-2425, 2012.

374. McBride J, Skinner J, Schafer P, Haines T, and Kirby T. Comparison of Kinetic Variables and Muscle Activity During a Squat Vs. A Box Squat. *Journal of Strength and Conditioning Research* 24: 3195-3199, 2010.

377. McBride JM, Triplett-McBride, T., Davie, A. and Newton, R.U. A Comparison of Strength and Power Characteristics between Power Lifters, Olympic Lifters and Sprinters. *Journal of Strength and Conditioning Research* 13: 58-66, 1999.

417. Morrison W and Edwards D. A Temporal Analysis of the Squat Lift at the Australian Power Lifting Championships Melbourne. Presented at ISBS-Conference Proceedings Archive, 1991.

455. Pyne DB. Interpreting the Results of Fitness Testing. Presented at International Science and Football Symposium, 2003.

456. Rahmani A, Dalleau, G., Viale, F., Hautier, C.A. and Lacour, JR. Validity and Reliability of a Kinematic Device for Measuring the Force Developed During Squatting. *Journal of Applied Biomechanics* 16: 26-35, 2000.

466. Robertson D, Wilson J, and St Pierre T. Lower Extremity Muscle Functions During Full Squats. *Journal of Applied Biomechanics* 24: 333-339, 2008.

478. Salem GK, Salinas, R. and Harding V. Bilateral Kinematic and Kinetic Analysis of the Squat Exercise after Anterior Cruciate Ligament Reconstruction. *Archives of Physical Medicine and Rehabilitation* 84: 1211-1216, 2003.

488. Schoenfield BJ. Squatting Kinematics and Kinetics and Their Application to Exercise Performance. *Journal of Strength and Conditioning Research* 24: 3497-2506, 2010.

494. Sheppard J, Doyle, TLA, and Taylor, K-L. A Methodological and Performance Comparison of Free Weight and Smith-Machine Jump Squats. *Journal of Australian Strength and Conditioning* 16: 5-9, 2008.

512. Spencer K and Croiss M. The Effect of Increasing Loading on Powerlifting Movement Form During the Squat and Deadlift. *Journal of Human Sport and Exercise* 10, 2015.

515. Spiteri T, Cochrane JL, Hart NH, Haff GG, and Nimphius S. Effect of Strength on Plant Foot Kinetics and Kinematics During a Change of Direction Task. *European Journal of Sport Science* 13: 646-652, 2013.

536. Swinton PA, Lloyd R, Keogh JW, Agouris I, and Stewart AD. A Biomechanical Comparison of the Traditional Squat, Powerlifting Squat, and Box Squat. *Journal of Strength and Conditioning Research* 26: 1805-1816, 2012.

538. Systems VM. Preparation (Vol 1.2). United Kingdom, 2002.

576. Yavuz HU, Erdağ D, Amca AM, and Aritan S. Kinematic and Emg Activities During Front and Back Squat Variations in Maximum Loads. *Journal of Sports Sciences* 33: 1058-1066, 2015.

591. Zink AJ, Perry AC, Robertson BL, Roach KE, and Signorile JF. Peak Power, Ground Reaction Forces, and Velocity During the Squat Exercise Performed at Different Loads. *Journal of Strength and Conditioning Research* 20: 658-664, 2006.

7

Chapter Seven

TECHNICAL PAPER:

RELIABILITY OF STEP-UP KINETICS

INTRODUCTION

Historically, kinetics of lower body unilateral exercises such as the step-up, lunge or rear foot elevated split squat, have been investigated predominantly for application to rehabilitation or activities of daily living (e.g. stair ascent (473)), seldom in the execution of high-intensity performance in well-trained athletes (116, 324). Muscular activation levels, centre of pressure, joint kinetics and ground reaction forces being commonly investigated. Unilateral exercises are becoming increasingly considered in the sports performance setting for advantages of load prescription and secondary muscle activation (232, 421, 511). Given the increasing prescription of unilateral exercise in elite athlete programs, a greater understanding of the underlying kinetics assists with training program design, providing coaches with knowledge regarding likely targeted physiological and performance criteria. While a sparse number of publications have documented kinetics of the step-up (eccentric and concentric GRF and RFD) none have addressed the reliability associated with reported variables, leaving doubt regarding variability of interpreted measures (195, 574). Further, little is known regarding reliability of kinetic variables associated with the step-up performed by well-trained athletes.

Therefore, the purpose of this paper is to present reliability data of kinetics of the step-up in well-trained rugby union players. The discovery of robust kinetic variables for the step-up may assist with describing the key characteristics of performance. Additionally, given the growing capacity to measure kinetic information in the training environment, determining the reliability of variables may assist coaches to better interpret meaningful information to guide training interventions in the step-up exercise.

METHODS

Experimental Design. In a cross-sectional research design to determine the kinetics of the step-up, fifteen participants attended two testing sessions separated by seven to 10 days. The first session involved assessment of one repetition maximum (1RM) strength in the step-up and the second session involved biomechanical analysis of the step-up. Participants performed two sets of two repetitions of back squat at 70, 80 and 90% of 1RM. Force application and movement patterns were assessed using tri-axial force plates and three-dimensional motion measurement.

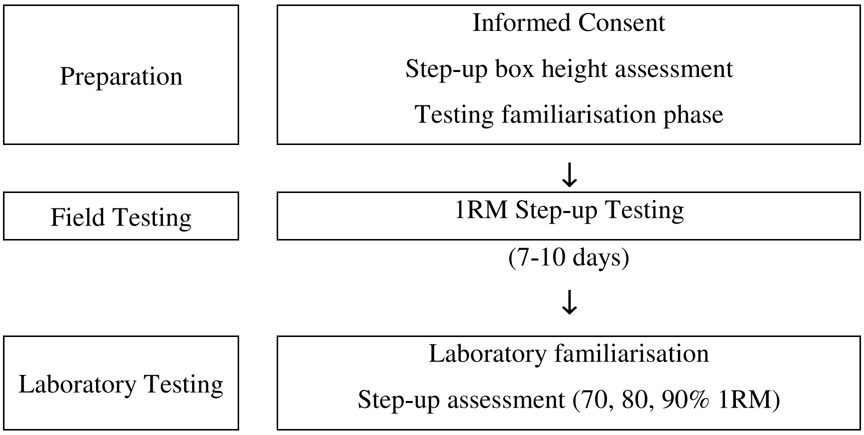


Figure 7.1 Schematic representation of experimental design

*Participants***.** A combination of 15 academy and professional rugby union players were recruited to participate in this investigation (Table 7.1). All participants were notified of the potential risks involved and gave their written informed consent. This study was approved by the University's Human Research Ethics Committee. All participants were cleared by medical staff to be free of injury or injury history which may have inhibited performance.

Table 7.1 Participants characteristics.

Age (years)	Height (cm)	Mass (kg)	Squat 90°1RM (kg)	Relative Squat	Step-up 1RM (kg) (ave)	Relative ave Step-up	Squat:Step-up ratio
24.1 ± 3.0	186.3 ± 6.9	103.6 ± 9.5	194.7 ± 26.9	1.88 ± 0.16	135.3 ± 14.0	1.31 ± 0.12	0.70 ± 0.05

Data presented as mean ± SD for all variables

Data Acquisition and Analysis Procedures. *Step-up Assessments.* The protocol for the allocation of step height and 1RM strength assessment for the step-up has been previously detailed (Chapter Three – Reliability of the One Repetition Maximum Step-up in Academy Level Rugby Union Players).

Step-up Assessment. Upon arrival, participants completed a standardised warm-up consisting of stationary bike riding and lower body mobility exercises. Participants performed two warm-up sets at 50% and 60% 1RM for three and two repetitions respectively. Laboratory testing consisted of two sets of two repetitions at 70%, 80% and 90% of 1RM (left and right leg step-ups), During the step-up, participants stood on one force plate facing the step-up box which was isolated on the second force plate. As well-trained participants, they were requested to perform the concentric phase as "explosively" as possible. Technique was monitored according to the strength testing and was observed by the same accredited strength coach. The step-up was treated as a concentric only movement, starting from foot contact on the box, indicated by an increase of 5N, in line with the threshold detection for commencement of the squat (255).

Ground Reaction Force. Two in-ground tri-axial force plates (9290AD, Kistler Instruments, Winterthur, Switzerland) recording at 1,000Hz captured the kinetics of performance and filtered using a fourth order, low-pass Butterworth digital filter with a cut off frequency of 50 Hz. Calculations were made for each leg with the best trial (mean force) being used in the analysis. The integration of force-time data (trapezoid method) was used to determine total concentric impulse (176, 294). Impulse (Newton seconds (Ns) was calculated for each leg independently during the concentric phase.

Temporal Phase Definitions. The start was determined as foot contact on the box (initiated by the detection of ≥5N of force) to maximum C7 vertical displacement (as determined by motion analysis; 250Hz, Vicon MX, Vicon, Oxford, UK) (Figure 1). The C7 marker has been found reliable for measuring barbell displacement in the squat (Chapter Four – Reliability and Validity of Methods to Determine Barbell Displacement in Heavy Back Squats: Implications for Velocity Based Training). Movement was further divided into a support phase and non-support phase, determined by the presence of ground reaction force through the support leg force plate (the uninvolved step-up leg).

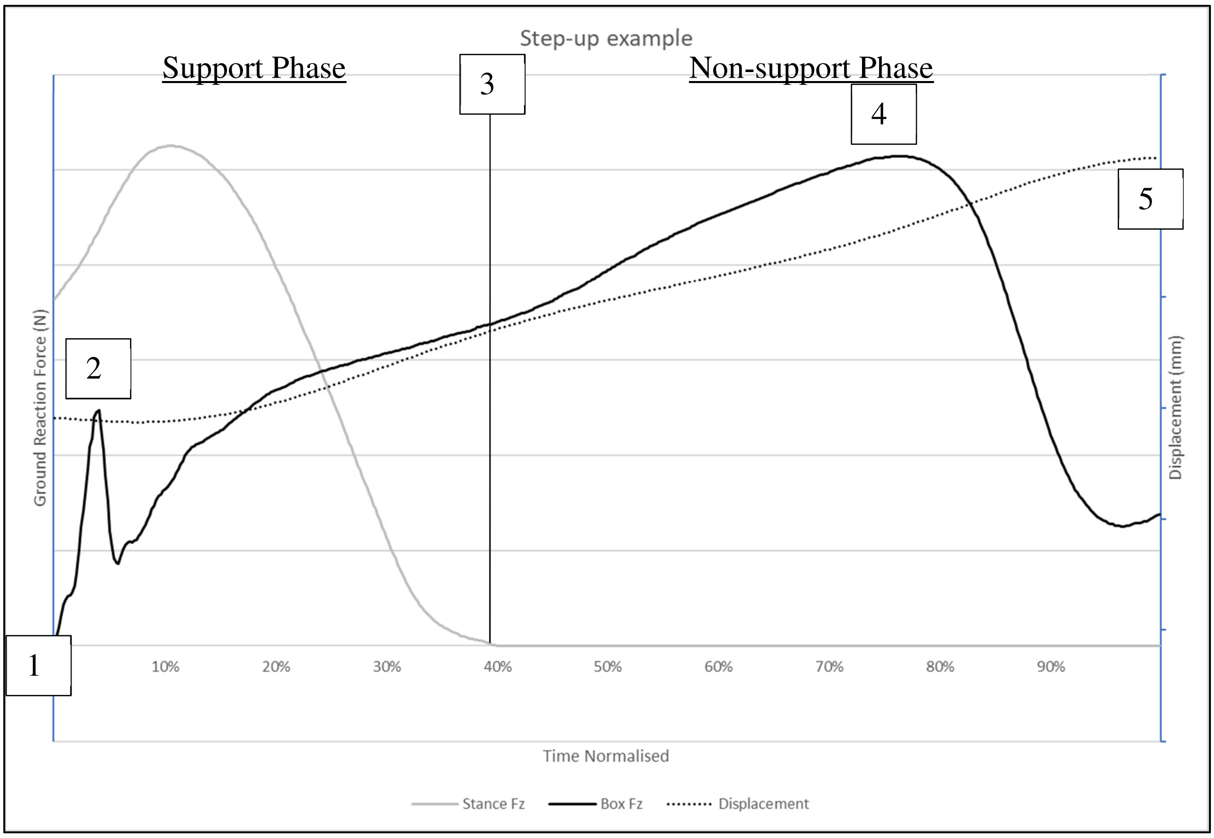


Figure 7.2 Representation of temporal phase of the step-up.

Statistical Analysis. Inter-trial reliability was calculated using intraclass correlation of coefficient (ICC) and the typical error expressed as a percentage of coefficient of variation (CV%), including ±90% confidence limits (286). The smallest worthwhile change (SWC%) was calculated at 0.2 times the between-participant pure SD. For CV%, values below a threshold of 10% were deemed acceptable (19, 124, 143). A test was considered capable of detecting SWC% if the CV% was less than the SWC% (455).

RESULTS

Reliability assessments of kinetic derived variables are presented in Tables 7.2 to 7.4. High intra-subject reliability was observed in several variables across all intensities. The coefficient of variation for ground reaction force (GRF) was very low (less than 6.0%) with very large to nearly perfect correlations across all loads (Tables 7.2 and 7.3). GRF was reliable for all loads for the step-up (left leg and right leg).

Table 7.2 Reliability of peak concentric phase ground reaction force non-support phase for the drive leg left leg and right leg in the step-up.

Load (%1RM)	Leg	Mean of Peak concentric ground reaction force (SD)	CV%	ICC	SWC%
70%	Left	2,248 (297)	4.1 (3.4 – 5.3)	0.92 (0.85 – 0.97)	2.6
	Right	2,212 (238)	4.0 (3.3 – 5.1)	0.89 (0.80 – 0.95)	2.1
80%	Left	2,444 (286)	3.3 (2.7 – 4.2)	0.94 (0.88 – 0.97)	2.3
	Right	2,441 (251)	2.8 (2.3 – 3.6)	0.94 (0.88 – 0.97)	2.0
90%	Left	2,636 (347)	5.5 (4.5 – 7.2	0.85 (0.73 – 0.93)	2.4
	Right	2,631 (282)	3.9 (3.3 – 5.1)	0.89 (0.79 – 0.95)	2.0

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **%1RM** = percentage of one repetition maximum.

Table 7.3 Reliability of mean concentric phase ground reaction force for the drive leg, left leg and right leg in the step-up through concentric phase.

Load (%1RM)	Leg	Mean of average concentric ground reaction force (SD)	CV%	ICC	SWC%
70%	Left	1,356 (170)	3.8 (3.0-5.2)	0.92 (0.83-0.97)	2.4
	Right	1,381 (140)	3.8 (3.0-5.2)	0.88 (0.75-0.95)	1.9
80%	Left	1,495 (182)	2.8 (2.3-3.8)	0.95 (0.90-0.98)	2.4
	Right	1,501 (142)	2.7 (2.2-3.7)	0.93 (0.85-0.97)	1.8
90%	Left	1,628 (219)	3.2 (2.6-4.4)	0.95 (0.88-0.98)	2.5
	Right	1,634 (170)	2.8 (2.3-3.8)	0.94 (0.87-0.98)	2.0

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **%1RM** = percentage of one repetition maximum.

Table 7.4 Reliability of total concentric impulse for the drive leg in the step-up through the non-support phase.

	Load (%1RM)	Leg	Mean total concentric impulse (SD)	CV% (90% CL)	ICC (90% CL)	SWC%
Non-support phase	70%	Left	738 (139)	8.6 (7.1-11.2)	0.83 (0.69-0.92)	3.5
		Right	733 (127)	7.9 (6.5-10.3)	0.82 (0.68-0.92)	3.1
	80%	Left	912 (185)	7.1 (5.6-9.1)	0.90 (0.82-0.96)	3.9
		Right	892 (176)	7.7 (6.5-10.0)	0.86 (0.74-0.93)	3.4
	90%	Left	1,207 (324)	9.0 (7.3-11.9)	0.90 (0.80-0.96)	4.8
		Right	1,161 (274)	10.4 (8.6-13.5)	0.83 (0.69-0.92)	4.1
Support and non-support phase	70%	Left	1,057 (168)	6.3 (5.3-8.3)	0.87 (0.75-0.94)	2.9
		Right	1,063 (165)	6.2 (5.1-8.1)	0.86 (0.74-0.94)	2.8
	80%	Left	1,276 (262)	7.0 (5.8-9.0)	0.89 (0.80-0.95)	3.6
		Right	1,254 (211)	5.3 (4.4-6.8)	0.91 (0.83-0.96)	3.1
	90%	Left	1,597 (358)	6.9 (5.6-9.0)	0.92 (0.84-0.96)	4.1
		Right	1,587 (316)	7.4 (6.1-9.5)	0.88 (0.78-0.95)	3.7

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **Total concentric impulse (Ns)**: integration of force-time data (trapezoid method); **Non-support phase:** period of concentric phase with GRF detected solely under the step-up box; **CV Support and non-support phase:** GRF from foot contact on box to maximum concentric displacement; **%1RM** = percentage of one repetition maximum.

DISCUSSION

The results confirm that measures of GRF in the concentric phase of the step-up are highly reliable, indicated by low CV% and high ICC. Total concentric impulse during the step-up also demonstrated acceptable measures of reliability. Despite the reliability, none of the reported measures were capable of detecting the SWC. However, this acceptable reliability permits confident interpretation of these variables contributing to neuromuscular performance in the step-up.

The reporting of kinetic variables and reliability, in heavy step-ups has escaped rigorous assessment. Fauth et al (195) reported the GRF for the eccentric and concentric phases of step-ups performed by NCAA Division I female athletes. Similarly, Wurm (2010) reported step-up GRF from a population of recreationally trained men (574). Neither study reported the reliability of the GRF, nor distinguished unilateral characteristics. However, reliability measures in unilateral lower body performance has been detailed.

Recently, testing a combination of predominantly professional male rugby league players, Dos'Santos et al (171) reported excellent within session ICC (0.89-0.96) and %CV (4.3-5.9) in peak force using a unilateral isometric mid-thigh pull. Similarly, Comfort et al. reported highly reliable ICC's (0.991) for GRF during the concentric phase of bodyweight single leg squats in recreationally trained males (116). These findings are similar to the current investigation where the ICC ranged from 0.85-0.95 with all CV's under 5.5%.

Unilateral exercises and tests have been reported beneficial for detection of asymmetry, with reporting of reliability confined to single leg jumping tasks. Impulse is the product of force and time and explains, rather than describes, movement (327). Unilateral impulse has been reported in vertical jump with mixed reliability (123, 519). This is the first paper to report the reliability of impulse in a weighted step-up in highly trained individuals. The reliability for the total concentric impulse during phases of the step-up was reliable at all loads (6.2 – 10.4%) with the ICC range between 0.82 to 0.92.

Conclusion and Practical Applications

In conclusion, the high reliability of kinetic variables presented in this investigation demonstrate consistency of performance by these well-trained participants. Of importance, from the highly reliable GRF data it can be concluded that well-trained participants are capable of consistent performance of maximal efforts in heavily loaded unilateral strength exercises. Given the increasing prescription of unilateral resistance exercises for elite athletes, high reliability permits subsequent comparison and interpretation of meaningful differences in the underlying neuromuscular capacities reflected in kinetic outcomes involving the step-up. Additionally, the ability to consistently perform heavy unilateral exercises can provide practitioners with confidence that well-trained participants can achieve a repeatable training stimulus.

REFERENCES

19. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217-238, 1998.

116. Comfort P, Jones PA, Smith LC, and Herrington L. Joint Kinetics and Kinematics During Common Lower Limb Rehabilitation Exercises. *Journal of Athletic Training* 50: 1011-1018, 2015.

123. Cordova ML and Armstrong CW. Reliability of Ground Reaction Forces During a Vertical Jump: Implications for Functional Strength Assessment. *Journal of Athletic Training* 31: 342, 1996.

124. Cormack SJ, Newton, R.U., McGuigian, M.R. and Doyle, T.L.A. Reliability of Measures Obtained During Single Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.

143. Cronin J, Hing, RD and McNair, PJ. Reliability and Validity of a Linear Position Transducer for Measuring Jump Performance. *Journal of Strength and Conditioning Research* 18: 590-593, 2004.

171. Dos' Santos T, Thomas C, Jones PA, and Comfort P. Assessing Muscle-Strength Asymmetry Via a Unilateral-Stance Isometric Midthigh Pull. *International Journal of Sports Physiology and Performance* 12: 505-511, 2017.

176. Dugan E, Doyle, TLA, Humphries, B, Hasson, C and Newton, RU. Determining the Optimal Load for Jump Squats: A Review of Methods and Calculations. *Journal of Strength and Conditioning Research* 19: 665-674, 2004.

195. Fauth M, Garcwau, L, Lutsch, B, Gray, A, Szalkowski, C, Wurm, B and Ebben, WP. Kinetic Analysis of Lower Body Resistance Training Exercises. Presented at XXVIII Congress of the International Society of Biomechanics in Sports, 2010.

232. Gonzalo-Skok O, Tous-Fajardo J, Suarez-Arrones L, Arjol-Serrano JL, Casajús JA, and Mendez-Villanueva A. Single-Leg Power Output and between-Limb Imbalances in Team-Sports Players: Unilateral Vs. Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance* 12: 106-114, 2016.

255. Hales ME, Johnson BF, and Johnson JT. Kinematic Analysis of the Powerlifting Style Squat and the Conventional Deadlift During Competition: Is There a Cross-over Effect between Lifts? *Journal of Strength and Conditioning Research* 23: 2574-2580, 2009.

286. Hopkins WG. Reliability from Consecutive Pairs of Trials (Excel Spreadsheet). Available from: http://www.sportsci.org/resources/stats/. Accessed 1st May 2017., 2006.

294. Hori N, Newton, R.U., Nosaka, K. and McGuigan, M.R. Comparison of Different Methods of Determining Power Output in Weightlifting Exercises. *Strength and Conditioning Journal* 28: 34-40, 2006.

324. Kim D, Unger J, Lanovaz JL, and Oates AR. The Relationship of Anticipatory Gluteus Medius Activity to Pelvic and Knee Stability in the Transition to Single-Leg Stance. *American Academy of Physical Medicine and Rehabilitation* 8: 138-144, 2016.

327. Knudson DV. Correcting the Use of the Term "Power" in the Strength and Conditioning Literature. *Journal of Strength and Conditioning Research* 23: 1902-1908, 2009.

421. Mullican K and Nijem R. Are Unilateral Exercises More Effective Than Bilateral Exercises? *Strength and Conditioning Journal* 38: 68-70, 2016.

455. Pyne DB. Interpreting the Results of Fitness Testing. Presented at International Science and Football Symposium, 2003.

473. Saad M, Felicio, LR, de Lourdes, C, Liporaci, RF and Beviaqua-Grossi, D. Analysis of the Center of Pressure Displacement, Ground Reaction Force and Muscular Acticity During Step Exericses. *Journal of Electromyography and Kinesiology* 21: 712-718, 2011.

511. Speirs DE, Bennett M, Finn CV, and Turner AP. Unilateral Vs Bilateral Squat Training for Strength, Sprints and Agility in Academy Rugby Players. *Journal of Strength and Conditioning Research* 30: 386-392, 2015.

519. Stålbom M, Holm DJ, Cronin J, and Keogh J. Reliability of Kinematics and Kinetics Associated with Horizontal Single Leg Drop Jump Assessment. A Brief Report. *Journal of Sports Science and Medicine* 6: 261, 2007.

574. Wurm B, Garceau L, Zanden T, Fauth M, and Ebben W. Ground Reaction Force and Rate of Force Development During Lower Body Resistance Training Exercises. Presented at ISBS-Conference Proceedings Archive, 2010.

8

Chapter Eight

TECHNICAL PAPER:

RELIABILITY OF STEP-UP KINEMATICS

INTRODUCTION

The step-up exercise is commonly associated with stair ascent and rehabilitation settings. In these environments, biomechanical information such as knee angle and temporal phases have been documented (63, 134, 163, 281). Additionally, the movements are generally performed with low, if any, external mass, atypical of an athletic resistance training program. Recent training investigations have demonstrated comparative improvements in strength with either bilateral or unilateral resistance training (232, 511). However, with growing interest in unilateral exercise prescription (65, 74, 298, 421), much is unknown regarding key kinematic variables important to understanding of unilateral performance, specifically the step-up.

Therefore, the purpose of this investigation was to determine the reliability of the kinematic variables of resisted step-up performance in well-trained athletes. Given the growing application of kinematic assessment in the training environment, information regarding reliability of variables associated performance, may be of assistance to coaches working with athletes.

METHODS

Experimental Design. Fifteen participants attended two testing sessions, separated by seven to ten days. The first testing session involved assessment of one repetition maximum (1RM) strength in the step-up exercise. The second testing session involved the biomechanical assessment of the step-up movement in the laboratory (Figure 8.1). Participants performed two sets of two repetitions of step-up at 70, 80 and 90% of 1RM. Force application and movement pattern were assessed using tri-axial force plates and three-dimensional motion measurement.

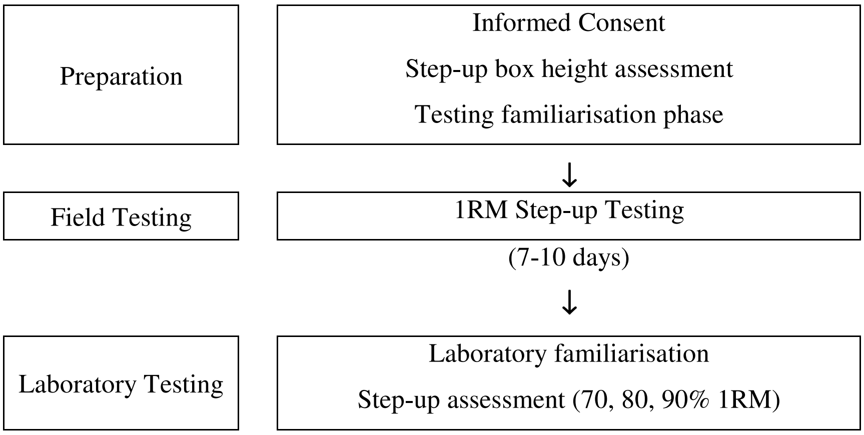


Figure 8.1 Schematic representation of experimental design

Participants. A combination of 15 academy and professional rugby union players were recruited to participate in this investigation (Table 8.1). All participants were notified of the potential risks involved and gave their written informed consent. This study was approved by the University's Human Research Ethics Committee. All participants were cleared by medical staff to be free of serious lower limb injury in the previous six months or injury history which may have inhibited performance.

Table 8.1 Participants characteristics.

Age (years)	Height (cm)	Mass (kg)	Squat 90°1RM (kg)	Relative Squat	Step-up 1RM (kg) (ave)	Relative ave Step-up	Squat:Step-up ratio
24.1 ± 3.0	186.3 ± 6.9	103.6 ± 9.5	194.7 ± 26.9	1.88 ± 0.16	135.3 ± 14.0	1.31 ± 0.12	0.70 ± 0.05

Data presented as mean ± SD for all variables

Data Acquisition and Analysis Procedures.

The assessment of step-up height (Chapter 3), the laboratory testing protocol (Chapter 7), the three-dimensional motion analysis (Chapter 6) and temporal phase definitions (Chapter 7) pertinent to this study have been previously detailed in this thesis.

Statistical Analysis. The inter-trial reliability was calculated using intraclass correlation of coefficient (ICC) and typical error expressed as a percentage of coefficient of variation (CV%), including ±90% confidence limits (286). The SWC% was calculated at 0.2 times the between-participant pure SD. For CV%, values below a threshold of 10% were deemed acceptable (19, 124, 143). A test was considered capable of detecting the SWC% if CV% was less than SWC% (455).

RESULTS

Reliability assessments of kinematic derived variables are presented in Tables 8.1-8.5. High intra-subject reliability was observed in several variables across all intensities, including maximum knee angle, concentric displacement and peak velocity. The typical error for maximum knee flexion during the step-up was less than 5.2% with large or very large ICC values (Table 8.1). With regards to temporal phase analyses, CV% remained under 10% for all step-up variables and ICC values fluctuated between large and very large (ICC = 0.60-0.90). There was excellent reliability for concentric displacement (CV% = 4.3-8.6; ICC = 0.55-0.81); Table 8.5), and both peak velocity from foot contact (CV% = 6.2-10.4; ICC = 0.56-0.85) and average velocity from toe-off (CV% = 5.5-13.2; ICC = 0.53-0.83).

Table 8.2 Reliability of maximum knee angle in the step-up

Phase	Load (%1RM)	Leg	Mean of knee flexion in degrees (SD)	CV% (CL)	ICC (CL)	SWC%
Knee angle at step contact	70%	Left	95.8 (7.0)	2.8 (2.2-3.9)	0.89 (0.77-0.95)	1.4
		Right	97.1 (6.9)	3.0 (2.5-3.9)	0.85 (0.72-0.93)	1.3
	80%	Left	96.0 (7.1)	2.8 (2.3-3.5)	0.88 (0.79-0.95)	1.4
		Right	97.2 (5.9)	2.9 (2.4-3.7)	0.80 (0.64-0.90)	1.1
	90%	Left	96.1 (8.4)	3.3 (2.7-4.2)	0.89 (0.77-0.95)	1.7
		Right	98.0 (6.5)	2.5 (2.1-3.2)	0.88 (0.78-0.95)	1.2
Maximum Knee Angle	70%	Left	101.1 (6.2)	3.2 (2.6-4.1)	0.77 (0.60-0.89)	1.1
		Right	100.1 (5.5)	2.9 (2.4-3.7)	0.76 (0.58-0.88)	0.9
	80%	Left	100.3 (5.8)	2.3 (1.9-2.9)	0.87 (0.76-0.94)	1.1
		Right	99.9 (4.9)	3.0 (2.5-3.8)	0.67 (0.46-0.83)	0.8
	90%	Left	101.3 (6.2)	2.4 (2.0-3.0)	0.87 (0.76-0.94)	1.1
		Right	100.7 (5.6)	2.3(2.0-3.0)	0.85 (0.72-0.93)	1.0

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD; **Knee angle at step contact**: knee angle of leg on step at the moment of GRF measurement under step. **Maximum knee angle**: the greatest knee angle from the time of foot contact until maximal C7 displacement; %1RM = percentage of one repetition maximum.

Table 8.3 Reliability of duration phases for the step-up.

Variable	Load (%1RM)	Limb	Mean of duration (SD)	CV% (CL)	ICC (CL)	SWC%
Duration of stance phase (%time of rep)	70%	Left	40% (5%)	6.5 (5.4-8.4)	0.75 (0.56-0.88)	2.0
		Right	40% (4%)	7.4 (6.1-9.5)	0.63 (0.41-0.82)	1.8
	80%	Left	38% (5%)	6.5 (5.4-8.3)	0.80 (0.65-0.91)	2.4
		Right	39% (5%)	7.7 (6.4-10.0)	0.68 (0.47-0.84)	2.0
	90%	Left	37% (6%)	9.7 (8.0-12.7)	0.74 (0.54-0.87)	2.9
		Right	38% (5%)	6.5 (5.4-8.4)	0.82 (0.67-0.92)	2.5
Time of toe off (ms)	70%	Left	315 (51)	7.6 (6.3-9.9)	0.82 (0.67-0.92)	2.9
		Right	309 (38)	6.9 (5.7-8.8)	0.75 (0.57-0.88)	2.2
	80%	Left	324 (41)	4.7 (3.9-6.0)	0.89 (0.79-0.95)	2.4
		Right	325 (40)	5.6 (4.6-7.2)	0.85 (0.73-0.93)	2.5
	90%	Left	365 (53)	5.1 (4.2-6.7)	0.90 (0.81-0.95)	2.8
		Right	367 (51)	6.7 (5.6-8.6)	0.84 (0.70-0.92)	2.8
Total time (ms)	70%	Left	778 (70)	6.1 (5.0-7.9)	0.60 (0.37-0.80)	1.4
		Right	780 (96)	6.9 (5.7-9.0)	0.69 (0.48-0.85)	1.9
	80%	Left	848 (98)	5.6 (4.7-7.2)	0.77 (0.60-0.89)	0.5
		Right	832 (85)	3.7 (3.1-4.7)	0.88 (0.78-0.95)	1.8
	90%	Left	997 (142)	8.4 (6.9-10.9)	0.68 (0.47-0.84)	2.2
		Right	965 (120)	5.4 (4.5-6.9)	0.83 (0.70-0.92)	2.2

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **Duration of stance phase**: the time of contact of support leg from lead foot contact on step, until GRF of support leg not detected. **Time of toe off**: the time at which the support leg was removed from force plate during drive phase. **Total time**: duration from lead foot contact on step to maximum C7 displacement; **%1RM** = percentage of one repetition maximum.

Table 8.4 Reliability of maximum C7 displacement in the step-up

Variable	Load (%1RM)	Leg	Mean displacement in mm (SD)	CV% (CL)	ICC (CL)	SWC%
Concentric displacement	70%	Left	504 (33)	2.6 (2.2-3.4)	0.86 (0.75-0.94)	1.2
		Right	493 (38)	3.9 (3.2-5.0)	0.78 (0.62-0.90)	1.4
	80%	Left	498 (36)	2.4 (2.0-3.1)	0.91 (0.83-0.96)	1.4
		Right	488 (36)	2.1 (1.8-2.8)	0.93 (0.86-0.97)	1.4
	90%	Left	491 (36)	2.1 (1.7-2.7)	0.93 (0.87-0.97)	1.4
		Right	487 (36)	2.6 (2.2-3.3)	0.90 (0.81-0.95)	1.4

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **Concentric displacement**: displacement from minimum C7 displacement to the maximum C7.

Table 8.5 Reliability of C7 velocity for the step-up.

Variable	Load (%1RM)	Limb	Mean Velocity in m/s (SD)	CV% (CL)	ICC (CL)	SWC%
Average velocity – from toe off to maximum displacement	70%	Left	0.72 (0.09)	9.2 (7.6-12.0)	0.53 (0.27-0.75)	1.8
		Right	0.70 (0.11)	12.1 (10.0-15.8)	0.61 (0.37-0.80)	2.7
	80%	Left	0.63 (0.10)	8.0 (6.7-10.4)	0.83 (0.69-0.92)	3.2
		Right	0.64 (0.08)	5.5 (4.4-7.5)	0.85 (0.72-0.93)	2.4
	90%	Left	0.51 (0.10)	13.2 (10.9-17.4)	0.70 (0.50-0.85)	3.6
		Right	0.54 (0.09)	10.1 (8.4-13.1)	0.70 (0.50-0.85)	2.8
Peak Velocity – pre-toe off	70%	Left	1.07 (0.14)	5.2 (4.3-6.7)	0.88 (0.78-0.95)	2.6
		Right	1.04 (0.12)	5.6 (4.7-7.2)	0.81 (0.66-0.91)	2.1
	80%	Left	1.01 (0.13)	4.1 (3.5-5.3)	0.92 (0.86-0.97)	2.6
		Right	0.98 (0.13)	3.6 (3.0-4.7)	0.94 (0.89-0.98)	2.7
	90%	Left	0.95 (0.13)	5.4 (4.4-7.0)	0.89 (0.80-0.95)	2.8
		Right	0.92 (0.14)	4.7 (3.9-6.0)	0.93 (0.864-0.97)	3.0
Peak Velocity – post-toe off	70%	Left	0.91 (0.13)	10.0 (8.3-13.3)	0.58 (0.33-0.78)	2.1
		Right	0.90 (0.14)	7.8 (6.5-10.2)	0.80 (0.64-0.91)	2.8
	80%	Left	0.84 (0.12)	6.3 (5.3-8.1)	0.85 (0.72-0.93)	2.7
		Right	0.86 (0.12)	6.2 (5.2-8.0)	0.82 (0.68-0.92)	2.4
	90%	Left	0.73 (0.14)	9.5 (7.9-12.6)	0.82 (0.67-0.92)	3.7
		Right	0.76 (0.11)	10.4 (8.6-13.5)	0.56 (0.31-0.77)	2.1

Data presented as mean ± SD for all variables, **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD. **%1RM** = percentage of one repetition maximum. **Average velocity – from toe off to maximum displacement**: the average velocity of the concentric phase from the toe-off to maximum C7 displacement. **Peak velocity – pre-toe off**: peak velocity during ground contact support phase of step-up. **Peak velocity – post-toe off**: peak velocity during concentric phase after support leg removed from ground contact.

DISCUSSION

There were high levels of reliability during step-up for measures of step-leg knee flexion angle, vertical displacement during the concentric phase and temporal phase durations. This acceptable reliability permits confident interpretation of these variables contributing to neuromuscular performance in the step-up. Further, these findings present insight into repeatable aspects of the motion, despite the unstable nature of the unilateral exercise.

During the preparation phase of the research design, each participant was allocated a step-up box height that permitted a 90° knee angle at foot contact. However, in the experimental data capture session, the magnitude of the bar load was substantially greater than during familiarisation, resulting in average knee angles at foot contact between 95-101°. Despite the increased knee angle, there was a high within-session reliability at foot contact, and maximum knee angle achieved during the step-up motion (CV% = 2.3-3.3%; ICC = 0.0.67-0.89; Table 8.2), regardless of the magnitude of external load, demonstrating comparable reliability with squat knee flexion angles (CV% 2.3-5.2; ICC 0.53-0.90; Chapter Six, Table 6.4). The reliability of resisted step-ups have so far escaped scrutiny, with investigations reporting knee angle in sub-maximal unilateral movements such as single leg squats (within-session ICC of 0.97) (116) and/or single leg landings (ICC 0.83-0.97) (387).

Our analysis of the step-up, similar to a deadlift analysis, observed only the upward, or ascent phase for analysis (255). Further, as per Flanagan et al. (199) who investigated joint torque contributions in lightly weighted step-ups, the concentric phase was defined as initiating with one foot on the box, the other on the floor and concluding with both feet on the box. Additionally, it is also important to acknowledge the contribution of the support, or non-propulsive leg, to the movement. The concentric portion of the step-up can be characterised by two sub-phases, representing the contact phase of the support foot during step ascent. Good measures of reliability were observed for the time of toe off (when the support foot was removed from the floor – CV% = 4.7-7.6%; ICC = 0.75-0.90; Table 8.4), the duration of the support phase as a percentage of the total concentric phase time (CV% = 6.5-9.7%; ICC = 0.63-0.82; Table 8.4), and total time of the movement (CV% = 3.7-8.4%; ICC = 0.60-0.88; Table 8.4). These results further can be interpreted as demonstrated consistency of execution of heavy resisted step-up in this group and ability to characterise temporal phase performance of the step-up. Whilst Flanagan et al (199) did not further dissect the propulsion phase, the authors did note contribution of the uninvolved limb to the step-up movement and recommended this phase be considered in future step-up investigations.

The C7 marker was selected as a valid and reliable representation of barbell displacement based on previous research (Chapter Four). Reliability for concentric phase of the step-up was favourable (CV% = 2.1-3.9%; ICC = 0.78-0.93; Table 8.4). To the authors knowledge, this is the first study investigating reliability of step-ups tracking the C7 marker using motion analysis. Traditionally, barbell displacement has been found to be very reliable via linear position transducers in variations of squats and weightlifting derivatives (38, 293, 492). The reliability of bar displacement in unilateral exercises has not been previously analysed, as such, results of this study are an insight of the capacity to reliably measure concentric displacement in step-up performance.

Velocity in unilateral resistance exercises has seldom been reported and reliability analysis limited to single leg jumping variants (408). In the current study, velocity measures were derived from integration of C7 displacement-time data. A range of reliability was found in average velocity (CV% = 5.5-13.2%; ICC = 0.53-0.94; Table 8.5) and peak velocity post-toe-off (CV% = 6.2-10.4%; ICC = 0.56-0.85; Table 8.5). However, peak velocity pre-toe-off was quite reliable (CV% = 3.6-5.6%; ICC = 0.81-0.94; Table 8.5). Perhaps given the reliable displacement and temporal phases within the step-up, the less reliable post-toe-off velocity measures may be an indication of subtle technical variability in the unstable unilateral exercise.

CONCLUSION AND PRACTICAL APPLICATIONS

Several kinematic variables of the step-up are highly reliable permitting confident interpretation and comparison of key characteristics. Knee angle, temporal phases and concentric displacement were very reliable demonstrating consistency of performance. Velocity measures post-toe-off were of lesser reliability. It may be speculated that the unstable nature of the unilateral performance influenced repeatability of the step-up motion during the single leg drive phase. However, confidence can be gained from the consistent knee angle and displacement values permitting confident interpretation of step-up performance characteristics.

REFERENCES

19. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217-238, 1998.

38. Banyard HG, Nosaka K, Sato K, and Haff GG. Validity of Various Methods for Determining Velocity, Force and Power in the Back Squat. *International Journal of Sports Physiology and Performance*: 1-25, 2017.

63. Beutler A, Cooper, LW, Kirkendall, DT and Garrett, WE. Electromyographic Analysis of Single-Leg Closed Chain Exercises: Implications for Rehabilitation after Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* 37: 13-18, 2002.

65. Bishop C, Brierley S, Read P, and Turner A. The Single Leg Squat: When to Prescribe This Exercise. *Professional Strength and Conditioning*: 17-26, 2016.

74. Botton CE, Radaelli R, Wilhelm EN, Rech A, Brown LE, Pinto RS, Fullerton C, Botton CE, Felizardo R, and Botânico BJ. Neuromuscular Adaptations to Unilateral Vs. Bilateral Strength Training in Women. *Journal of Strength and Conditioning Research* 30: 1924-1932, 2015.

116. Comfort P, Jones PA, Smith LC, and Herrington L. Joint Kinetics and Kinematics During Common Lower Limb Rehabilitation Exercises. *Journal of Athletic Training* 50: 1011-1018, 2015.

124. Cormack SJ, Newton, R.U., McGuigian, M.R. and Doyle, T.L.A. Reliability of Measures Obtained During Single Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.

134. Costigan PA, Deluzio KJ, and Wyss UP. Knee and Hip Kinetics During Normal Stair Climbing. *Gait and Posture* 16: 31-37, 2002.

143. Cronin J, Hing, RD and McNair, PJ. Reliability and Validity of a Linear Position Transducer for Measuring Jump Performance. *Journal of Strength and Conditioning Research* 18: 590-593, 2004.

163. Desloovere K, Wong, P., Swings, L., Callewaert, B., Vandenneucker, H. and Leardini, A. Range of Motion and Repeatability of Knee Kinematics for 11 Clinically Relevant Motor Tasks. *Gait and Posture* 23: 597-602, 2010.

199. Flanagan S, Kessans, KM and Salem, GJ. Quantifying Bilateral Joint Contributions During Three Variations of the Step Exercises. *Journal of Sport Rehabilitation* 15: 255-265, 2006.

232. Gonzalo-Skok O, Tous-Fajardo J, Suarez-Arrones L, Arjol-Serrano JL, Casajús JA, and Mendez-Villanueva A. Single-Leg Power Output and between-Limb Imbalances in Team-Sports Players: Unilateral Vs. Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance* 12: 106-114, 2016.

255. Hales ME, Johnson BF, and Johnson JT. Kinematic Analysis of the Powerlifting Style Squat and the Conventional Deadlift During Competition: Is There a Cross-over Effect between Lifts? *Journal of Strength and Conditioning Research* 23: 2574-2580, 2009.

281. Holsgaard Larsen A, Puggaarg, L., Hamalainen, U. and Aagaard, P. Comparison of Ground Reaction Forces and Antagonist Muscle Coactivation During Stair Walking with Ageing. *Journal of Electromyography and Kinesiology* 18: 568-580, 2008.

286. Hopkins WG. Reliability from Consecutive Pairs of Trials (Excel Spreadsheet). Available from: http://www.sportsci.org/resources/stats/. Accessed 1st May 2017., 2006.

293. Hori N, Newton, R.U., Andrews, W.A., Kawamori, N., McGuigan, M.R. and Nosaka, K. Comparison of Four Different Methods to Measure Power Output During the Hang Power Clean and the Weighted Jump Squat. *Journal of Strength and Conditioning Research* `21: 314-320, 2007.

298. Howe L, Goodwin J, and Blagrove R. The Integration of Unilateral Strength Training for the Lower Extremity within an Athletic Performance Programme. *Professional Strength and Conditioning Journal* 33: 19-24, 2014.

387. McCurdy K, Walker J, Saxe J, and Woods J. The Effect of Short-Term Resistance Training on Hip and Knee Kinematics During Vertical Drop Jumps. *Journal of Strength and Conditioning Research* 26: 1257-1264, 2012.

408. Meylan C, McMaster T, Cronin J, Mohammad NI, and Rogers C. Single-Leg Lateral, Horizontal, and Vertical Jump Assessment: Reliability, Interrelationships, and Ability to Predict Sprint and Change-of-Direction Performance. *Journal of Strength and Conditioning Research* 23: 1140-1147, 2009.

421. Mullican K and Nijem R. Are Unilateral Exercises More Effective Than Bilateral Exercises? *Strength and Conditioning Journal* 38: 68-70, 2016.

455. Pyne DB. Interpreting the Results of Fitness Testing. Presented at International Science and Football Symposium, 2003.

492. Sheppard J, Cormack, S, Taylor, K, McGuigan, MR and Newton, RU. Assessing the Force-Velocity Characteristics of the Leg Extensors in Well-Trained Athletes: The Incremental Load Power Profile. *Journal of Strength and Conditioning Research* 22: 1320 - 1326, 2008.

511. Speirs DE, Bennett M, Finn CV, and Turner AP. Unilateral Vs Bilateral Squat Training for Strength, Sprints and Agility in Academy Rugby Players. *Journal of Strength and Conditioning Research* 30: 386-392, 2015.

SUMMARY

Concluding the methodology for this thesis, Part Three comprised three technical papers outlining reliable kinetic and kinematics of the squat and step-up confirming:

- Kinematic derived peak velocity (CV% = 3.7 – 6.1; ICC = 0.83 – 0.89) and mean velocity (CV% = 5.3 – 7.4; ICC = 0.78 – 0.86), knee flexion angle (CV% = 2.3 – 5.2; ICC = 0.53 – 0.90) and C7 concentric displacement (CV% = 4.3 – 8.6; ICC = 0.55 – 0.83) are reliable variables in heavily loaded back squat performance in well-trained participants.
- Peak and mean ground reaction force of the left or right legs in the step-up is highly reliable (Peak: CV% = 2.8 – 5.5; ICC = 0.85 – 0.94; Mean: CV% = 2.7 – 3.8; ICC = 0.88 – 0.95).
- Several kinematic variables in the step-up demonstrated high reliability indicating consistent performance. Knee angle at step contact (CV% = 2.5 – 3.3; ICC = 0.80 – 0.89), temporal phases and duration (CV% = 3.7 – 9.7; ICC = 0.63 – 0.90) and concentric displacement (CV% = 2.1 – 3.9; ICC = 0.86 – 0.93).
- Peak velocity in the non-support phase of the step-up was reliable (CV% = 6.2 – 10.4; ICC = 0.56 – 0.85). Average velocity in the step-up was less reliable (CV% = 5.5 – 13.2; ICC = 0.53 – 0.85).

As a complement, Parts Two and Three substantiate the methodology, confirming reliable variables of performance for confident interpretation of a central thesis question – a comparison of the force application and movement patterns between bilateral and unilateral resistance training exercises in highly trained athletes.

PART FOUR

PREFACE

Having established sound methodological practices, Part Four specifically addresses the research questions: a comparison of the force application and movement patterns between the squat and step-up; and an examination of the efficacy of squat or step-up training for maximum strength and performance improvements in sprint and change of direction ability. Chapter Nine specifically addresses the primary research question with a biomechanical comparison of squat and step-up performance in well-trained athletes. Chapters Ten and Eleven target the secondary research question and present a comprehensive three-arm randomised controlled design training study. Incorporated in a rugby academy pre-season, two intervention groups were distinguished by the volume-load matched prescription of squats (bilateral training) or step-ups (unilateral training). Groups were assessed for maximum strength (both bilateral and unilateral), sprint speed and change of direction. The following chapters include:

<u>Chapter Nine</u>

Kinetics and kinematics of the squat and step-up in well-trained rugby players (as accepted for publication: Appleby BB, Newton RU, and Cormack SJ, 2018 *JSCR).*

<u>Chapter Ten</u>

Specificity and transfer of lower body strength – The influence of bilateral and unilateral lower body resistance training (as accepted for publication: Appleby BB, Cormack SJ, and Newton RU; JSCR, 2019, 33 (2), 318-326*).*

<u>Chapter Eleven</u>

Unilateral and bilateral lower body resistance training does not transfer equally to sprint and change of direction performance (as accepted for publication: Appleby BB, Cormack SJ, and Newton RU, 2018 *JSCR).*

9

Chapter Nine

KINETICS AND KINEMATICS OF THE SQUAT AND STEP-UP IN WELL-TRAINED RUGBY PLAYERS

As accepted for publication in the
Journal of Strength and Conditioning Research, 2018.

Pages 135-151 are not not available in this version of the thesis.

To view this publications record in Research Online, please go here:

https://ro.ecu.edu.au/ecuworkspost2013/6469/

Chapter Ten

SPECIFICITY AND TRANSFER OF LOWER BODY STRENGTH – THE INFLUENCE OF BILATERAL AND UNILATERAL LOWER BODY RESISTANCE TRAINING

As accepted for publication in the
Journal of Strength and Conditioning Research,
2019, 33 (2), 318-326.

.

Pages 153-170 are not not available in this version of the thesis.

To view this publications record in Research Online, please go here:
https://ro.ecu.edu.au/ecuworkspost2013/5881/

11

Chapter Eleven

UNILATERAL AND BILATERAL LOWER BODY RESISTANCE TRAINING DOES NOT TRANSFER EQUALLY TO SPRINT AND CHANGE OF DIRECTION PERFORMANCE.

As accepted for publication in the

Journal of Strength and Conditioning Research, 2018.

Pages 172-192 are not not available in this version of the thesis.

To view this publications record in Research Online, please go here:
https://ro.ecu.edu.au/ecuworkspost2013/6530/

Summary

Part Four specifically addressed the research questions:

1 – a comparison of the force application and movement patterns between bilateral (squat) and unilateral resistance training (step-up) in highly-trained athletes.

- Peak and average GRF was higher for the step-up than squat during the concentric phase at all relative intensities.
- The squat demonstrated superior peak velocity at all intensities compared to the step-up suggesting the squat may have a wider application for coaches utilising velocity-based training.

2 – An examination of the efficacy of bilateral (squat) and unilateral (step-up) resistance training for maximum strength and power development in sprinting and change of direction:

- Lower body strength can be developed using unilateral or bilateral resistance training and expressed in improved performance of the non-trained variation.
- Both unilateral and bilateral strength was shown to transfer to improved sprint acceleration performance, supporting research demonstrating increases in strength facilitating short distance sprint improvements.
- Yet, despite similar strength improvements the bilateral group demonstrated superior COD ability. However, this may be attributed to the contraction specificity between the two exercises and not the unilateral or bilateral nature.
- The results of the training study support training based on targeting the underlying neuromuscular demands of the target performance, and not the similarity in appearance to the target performance.

PART FIVE

12

Chapter Twelve

GENERAL THESIS SUMMARY AND CONCLUSIONS

An important consideration in resistance training program design is the transfer of adaptation to subsequent athletic performance, such as sprint acceleration or COD (396, 583). Historically, lower body strength had been primarily developed using bilateral exercise with unilateral training included as supplementary exercises often for specific rehabilitation purposes or targeting athlete performance development based on the rationale of more sport specific movement (389, 511). However, the absence of biomechanical comparison of bilateral and unilateral exercise utilised by well-trained athletes, and rigorous training intervention research, is a gap in our current understanding of sport specific resistance training applications. As such, a series of studies forming this thesis sought to explore biomechanics and training efficacy and efficiency of bilateral or unilateral resistance training in relatively well-developed athletes. This chapter shall summarise key thesis components, practical applications and suggestions for future research.

Attention to meticulous methodological rigour underpinning this thesis was first presented in Chapter Three. Maximal strength testing is an important field-based athlete assessment protocol (402). Whilst reliability of the rear foot elevated split squat has been reported (385, 511) it was critical to determine reliability of the step-up test, central to the thesis research direction. Ten trained participants were familiarised to the 1RM step-up over four sessions, prior to a test-retest assessment. It was found that the 1RM step-up was highly reliable for the assessment of unilateral strength. This was essential for subsequent investigations. Furthermore, it was concluded that the 1RM step-up test could confidently detect meaningful strength changes of approximately 5%, a finding of practical relevance to coaches who may confidently incorporate the test to measure single leg strength, asymmetry and rehabilitation progression in athletes.

Methodology was further substantiated with a novel investigation of the validity and reliability of measures of barbell displacement. Barbell velocity is a variable of practical importance when comparing resistance training exercises, the calculation of which is dependent upon accurate displacement data (38, 138, 226, 293). The next project was a validation of kinematic methods of tracking barbell displacement in heavily loaded back squats. Using the 7th cervical vertebra (C7) as a representation of barbell centre, the displacement of this marker was compared to the displacement of barbell ends and a linear position transducer attached to the barbell. This investigation offered unique insight regarding the influence of barbell load, the attachment site of barbell displacement tracking and the deformation characteristics of a heavily loaded barbell during squat performance. It was determined that calculations of barbell displacement can be overestimated as the barbell tracking position moves laterally. Further, increases in barbell load can exacerbate displacement due to the bar whip present in flexible barbell design. It is recommended that coaches incorporating barbell velocity as a means of monitoring resistance training chose the centre of the barbell for measurement of displacement to maximise reliability. This methodology was incorporated in the determination of barbell displacement in subsequent laboratory analyses.

An essential thesis intention was to determine the force applications and movement patterns of the squat and step-up. In order to compare and contrast the underlying mechanics it was important to determine key kinetic and kinematic variables. Despite long practical implementation and research investigation, seldom has reliability of kinetics and kinematics been reported for heavy back squats, particularly in well-trained participants (38, 230). Therefore, it was important to first establish the rigor of the laboratory testing protocol assessing biomechanical variables in the squat and step-up. This was presented in Chapters Five to Eight and provided an indication of stable performance of multiple maximal effort squat and step-up repetitions, providing confidence in future key comparisons. Utilising inground force plates and three-dimensional motion analysis, well-trained, participants highly familiar with the movements, performed a series of squats and step-ups at 70 to 90% of 1RM. Concentric variables such as barbell displacement, knee flexion angle at the commencement of the concentric phase and peak and mean GRF were found reliable. These variables were incorporated in subsequent discussion comparing the two exercises. Particular practical importance was the reliability in left and right GRF in both the squat and the step-up. With increasing access to field based bilateral force plates, routine assessment of bilateral asymmetry may be interpreted with confidence.

With methodological approaches established, the kinetic and kinematic variables underlying performance of the squat and step-up were compared. Critically, Chapter Nine demonstrated higher peak and average concentric GRF per leg for the step-up compared to the squat. Total concentric impulse was also higher for the step-up, however the comparison was unclear at 90%1RM. This may have been attributed to the longer concentric duration of the squat allowing a greater duration of maximal force. Barbell velocity is a result of the propulsive force. The squat was faster than the step-up with large differences between exercises at all loads. At a comparable relative intensity, the squat was performed substantially faster. Furthermore, across the 70% to 90% 1RM load range, the squat demonstrated a larger spread in velocity which may present practical implications for coaches utilising velocity-based training. The differences in average concentric velocity were unclear. Underlying the importance of these findings were the well-trained capacity of the participants and magnitude of external load. How these differences in fundamental kinetic and kinematic variables manifest in an applied training environment were subsequently investigated.

Concluding the analysis of the effect of unilateral or bilateral resistance training on the development of lower body strength, and the resulting transfer to athletic performance, a training study was implemented. Critical insight regarding the development of lower body strength using either squat or step-up and the transfer of strength to sprint acceleration and COD capacity was presented. There were several key methodological components of this study: a 6-week pre-study phase incorporating familiarisation, reliability and baseline testing; an 8-week training intervention with two groups stratified by training age and relative 1RM squat; a parallel comparison group; mature subjects with an average five-year training experience; no supplementary lower body strength training or plyometric training; and a 3-week maintenance phase. Presented in Chapter Ten, meaningful improvements in lower body strength were achieved using either step-up or squat, and importantly, the strength developed could be expressed in the 1RM strength testing of the non-trained variant (ie, step-up training improved 1RM squat and vice versa). This has substantial practical application as coaches may be confident in incorporating unilateral resistance training for the development or maintenance of lower body strength using the step-up where the incorporation of the squat may be prohibitive (such as through injury, the training environment or training variation).

The investigation was expanded to assess the influence on sprint acceleration and change of direction (COD) performance. It was revealed that whilst both the squat and step-up groups demonstrated a small ES improvement in 20m sprint acceleration neither was superior in transfer to speed. This finding supported the importance of strength on sprint acceleration performance. However, of interest was the difference between the two groups with respect to COD. Whilst both groups improved COD, the magnitude of adaptation was less for the unilateral group than the bilateral group. Given the similar improvements in strength and sprint acceleration, it was speculated that different COD adaptations were influenced by concentric and eccentric differences between the two resistance exercises, rather than the unilateral or bilateral nature of each. The first component of COD is a breaking force to arrest momentum in the initial direction (353, 518). This breaking force requires eccentric contractions, a stimulus that was absent in the performance of the step-up exercise but present in the squat. It was perhaps this stimulus that was the source of difference between the adaptation in COD between the groups, a theory that requires further investigation. This study highlights the importance of training targeting the underlying physiological stimulus for adaptation and not the exercise selected on the appearance of the target performance. Whilst the step-up exercise produced strength and sprint improvements, practitioners using the step-up may need to consider additional eccentric exercise to facilitate improvements in COD.

CONCLUSIONS

Based on the results of this thesis, the following conclusions can be drawn:

1. Maximal unilateral strength can be reliably assessed with the 1RM step-up exercise after four familiarisation sessions in trained, yet unfamiliar, athletes (Chapter Three).
2. Barbell load and location of barbell displacement measurement systems can influence displacement values. Attachment points should be centralised as much as practically possible, particularly with respect to heavy barbell loads which can exaggerate displacement due to barbell whip (Chapter Four).
3. High single leg GRF is generated during the step-up. These forces are moderately higher than GRF through each leg in the squat. This demonstrates a comparable level of strength stimulus of the step-up to squat and its capacity for strength development (Chapter Nine).
4. The development and transfer of maximal strength can be achieved using the squat or step-up. This strength can be exhibited in the non-trained variation (Chapter Ten).
5. Adaptations from maximal strength training using bilateral or unilateral resistance training positively transfer to sprint acceleration (Chapter Eleven).
6. Despite similar transfer of lower body strength, the underlying neuromuscular mechanism of the strength training stimulus is critical. This was realised in different magnitudes of COD improvement between the squat and step-up groups. These findings further highlight that the adaptation and transfer of strength is dependent upon

the underlying physiological stimulus (e.g. eccentric versus concentric) and not the outward appearance of the exercise (Chapter Eleven).

PRACTICAL APPLICATIONS

A number of practical applications from this thesis include:

1. The 1RM step-up exercise is a reliable testing tool, capable of detecting change in performance. Coaches working with athletes can incorporate this exercise as part of their periodised resistance training plan, utilising the exercise for both training and assessment. The unilateral nature of the test permits detection of lower limb asymmetry. Regular incorporation may assist coaches monitor asymmetry and regulate lower limb rehabilitation plans.
2. Practitioners of velocity-based training or researchers assessing barbell kinematics in heavily loaded back squats are encouraged to centralise the marker tracking position to minimise the influence of barbell whip and load which can lead to overestimations of barbell displacement, and subsequent velocity.
3. Coaches using force as a measure of performance can be confident in the reliability of individual leg peak and mean concentric GRF captured bilaterally in both squats and step-ups.
4. Stable performance and measurement of kinetic variables in multiple sets of maximal effort squat and step-up can be reliably obtained. In the practical training environment, provided adequate rest (minimum three minutes) coaches with high athlete to force plate ratios can rotate athletes through a testing station capturing ground reaction force effectively with minimal disruption to training.
5. The step-up exercise can be effectively used to improve lower body strength and maintain strength during periods where bilateral resistance training may be problematic, such as through injury or environmental constraints.
6. Both squat and step-up resistance training transfer to improved maximal lower body strength and sprint acceleration.
7. A three-week period of one strength session per week is sufficient to maintain strength, using squat or step-up. However, the effects on the magnitude of change in speed was unclear due to individual variation in responses. Practitioners are encouraged to monitor strength and speed for meaningful differences in adaptation to determine the minimum required dose for identified athletes.

8. Coaches are encouraged to program based on the underlying physiological stimulus that drives adaptation and not the outward appearance of the target performance.

RECOMMENDATIONS FOR FUTURE RESEARCH

Findings of this thesis have provided insight into specificity of resistance training and the transfer of adaptation to athletic performance. However, the literature review and thesis results suggest further research opportunities:

EMG analysis between unilateral and bilateral resistance training: In Chapter Nine, the kinetics and kinematics of the squat and step-up were compared. Whilst EMG investigations of the squat have been performed (93, 108, 358, 576), information regarding contraction patterns of the step-up as utilised in athletic resistance training is limited (504), particularly in well-trained participants using heavy loads. Unilateral exercises such as forward step, lateral step and lunge or split squat variations have been investigated from a rehabilitation perspective performed with no or very low external resistance (22, 179, 185, 236). Knowledge of the motor unit recruitment patterns of unilateral resistance exercise during heavy load may benefit rehabilitation progressions and sport specific training. This may be addressed using a similar research design to Chapter Nine incorporating electromyography of prime movers and stabilisers, such as adductor longus.

EMG analysis of change of direction performance and relationship to single leg training: Differences in the magnitude of improvement in COD between squat and step-up training were observed. It was speculated that the difference in transfer was due to the eccentric component of the squat rather than the differences in bilateral or unilateral resistance training. The magnitude of breaking force in COD has been detailed (515, 516, 518), and little has been reported regarding contraction mechanisms of COD (517), in particular their resemblance to resistance training. Contraction specificity is an important principle of resistance training. Future studies may examine the transfer of contraction type between resistance training and the athletic task to facilitate the design of more effective resistance training programs. Research design could utilise force plate and EMG capture during a series of pre-planned COD movements and compare to unilateral resistance training EMG and force plate information as well as individual muscle actions.

Unilateral and bilateral resistance training and the transfer to jumping: Sprinting and COD were the selected performance tasks in this thesis due to their familiarity to the participants. Unilateral jumping is a prominent athletic task and whilst research has shown strong relationships between bilateral resistance training and counter movement jumps (373, 568, 569), comparison of unilateral resistance training has been seldom performed, particularly in well-trained participants. Future research may investigate the relationship between unilateral resistance training and unilateral jump performance. Research design could incorporate two groups, familiarised in both unilateral and bilateral resistance training and bilateral and unilateral jump performance. Each group could be stratified according to jump performance and training age to minimise the confounding influences of jumping ability and principle of diminished returns.

The effect of unilateral resistance training on muscle hypertrophy: An important adaptation of resistance training in athletic populations is the increase or maintenance of muscle mass (15, 223). Bilateral resistance training exercises have a well-documented benefit in muscle hypertrophy and maintenance (85, 254). Unilateral exercise has predominantly investigated with an emphasis on cross-education and is thus less well researched from a hypertrophy perspective (64, 562). Furthermore, study design often utilises single joint exercises foreign to elite training programs or untrained participants (64, 562). Whilst the results of this thesis demonstrated positive improvements in muscle strength, differences in lean tissue changes during the training study were not reported. Future research may incorporate a similar design to Chapter 10 and incorporate lower body lean tissue assessments (DEXA scan).

REFERENCES

15. Argus C, Gill, N, Keogh, J, Hopkins, WG and Beaven, CM. Effects of a Short-Term Pre-Season Training Programme on the Body Composition and Anaerobic Performance of Professional Rugby Union Players. *Journal of Sports Sciences* 28: 679-686, 2010.

22. Ayotte NW, Stetts, D.M., Keenan, G. and Greenway, E.H. Electromyographical Analysis of Selected Lower Extremity Muscles During 5 Unilateral Weight-Bearing Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 37: 48-55, 2007.

38. Banyard HG, Nosaka K, Sato K, and Haff GG. Validity of Various Methods for Determining Velocity, Force and Power in the Back Squat. *International Journal of Sports Physiology and Performance*: 1-25, 2017.

64. Beyer KS, Fukuda DH, Boone CH, Wells AJ, Townsend JR, Jajtner AR, Gonzalez AM, Fragala MS, Hoffman JR, and Stout JR. Short-Term Unilateral Resistance Training Results in Cross Education of Strength without Changes in Muscle Size, Activation, or Endocrine Response. *Journal of Strength and Conditioning Research* 30: 1213-1223, 2016.

85. Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, Ragg KE, Ratamess NA, Kraemer WJ, and Staron RS. Muscular Adaptations in Response to Three Different Resistance-Training Regimens: Specificity of Repetition Maximum Training Zones. *European Journal of Applied Physiology* 88: 50-60, 2002.

93. Caterisano A, Moss, RE, Pellinger, TK, Woodruff, K, Lewis, VC, Booth, W and Khadra, T. The Effect of Back Squat Depth on the Emg Activity of 4 Superficial Hip and Thigh Muslces. *Journal of Strength and Conditioning Research* 16: 428-432, 2002.

108. Clark D, Lambert, MI, and Hunter, AM. Muscle Activation in the Loaded Free Barbell Squat: A Brief Review. *Journal of Strength and Conditioning Research* 26: 1169-1178, 2012.

138. Crewther B, Kilduff, LP, Cunningham, DJ, Cook, C, Owen, N and Yang, G-Z. Validating Two Systems for Estimating Force and Power. *International Journal of Sports Medicine* 32, 2011.

179. Dwyer MK, Boudreau SN, Mattacola CG, Uhl TL, and Lattermann C. Comparison of Lower Extremity Kinematics and Hip Muscle Activation During Rehabilitation Tasks between Sexes. *Journal of Athletic Training* 45: 181-190, 2010.

185. Ekstrom R, Donatelli, RA and Carp, KC. Electromyographic Analysis of Core, Trunk, Hip and Thigh Muscles During 9 Rehabilitation Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 37: 754-762, 2007.

223. Gamble P. Physical Preparation for Elite-Level Rugby Union Football. *Strength and Conditioning Journal* 26: 10-23, 2004.

226. Garnacho-Castaño MV, López-Lastra S, and Maté-Muñoz JL. Reliability and Validity Assessment of a Linear Position Transducer. *Journal of Sports Science and Medicine* 14: 128, 2015.

230. Glassbrook DJ, Helms ER, Brown SR, and Storey AG. A Review of the Biomechanical Differences between the High-Bar and Low-Bar Back-Squat. *Journal of Strength and Conditioning Research* 31: 2618-2634, 2017.

236. Graham V, Gehlsen, GM and Edwards, JA. Electroymyographic Evaluation of Closed and Open Kinetic Chain Knee Rehabilitation Exercises. *Journal of Athletic Training* 28: 23-30, 1993.

254. Hakkinen K, Pakarinen, A, Alen, M, Kauhanen, H and Komi, PV. Neuromuscular and Hormonal Adaptations in Athletes to Strength Training in Two Years. *Journal of Applied Physiology* 65: 2406-2412, 1988.

293. Hori N, Newton, R.U., Andrews, W.A., Kawamori, N., McGuigan, M.R. and Nosaka, K. Comparison of Four Different Methods to Measure Power Output During the Hang Power Clean and the Weighted Jump Squat. *Journal of Strength and Conditioning Research* `21: 314-320, 2007.

353. Lockie RG, Schultz AB, Callaghan SJ, and Jeffriess MD. The Effects of Traditional and Enforced Stopping Speed and Agility Training on Multidirectional Speed and Athletic Function. *Journal of Strength and Conditioning Research* 28: 1538-1551, 2014.

358. Luera MJ, Stock MS, and Chappell AD. Electromyographic Amplitude Vs. Concentric and Eccentric Squat Force Relationships for Monoarticular and Biarticular Thigh Muscles. *Journal of Strength and Conditioning Research* 28: 328-338, 2014.

373. McBride J, Kirby, TJ, Haines, TL, and Skinner, J. Relationship between Relative Net Vertical Impulse and Jump Height in Jump Squats Performed to Various Squat Depths and with Various Loads. *International Journal of Sports Physiology and Performance* 5: 484-496, 2010.

385. McCurdy K, Langford, G.A., Cline, A.L., Doscher, M. and Hoff, R. The Reliability of 1- and 3rm Tests of Unilateral Strength in Trained and Untrained Men and Women. *Journal of Sports Science and Medicine* 3: 190-196, 2004.

389. McCurdy KW, Langford, G.A., Doscher, M.W., Wiley, L.P. and Mallard, K.G. The Effects of Short-Term Unilateral and Bilateral Lower-Body Resistance Training on Measures of Strength and Power. *Journal of Strength and Conditioning Research* 19: 9-15, 2005.

396. McGuigan MR, Wright GA, and Fleck SJ. Strength Training for Athletes: Does It Really Help Sports Performance? *International Journal of Sports Physiology and Performance* 7: 2-5, 2012.

402. McMaster DT, Gill N, Cronin J, and McGuigan M. A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine* 44: 603-623, 2014.

504. Simenz CJ, Garceau LR, Lutsch BN, Suchomel TJ, and Ebben WP. Electromyographical Analysis of Lower Extremity Muscle Activation During Variations of the Loaded Step-up Exercise. *Journal of Strength and Conditioning Research* 26: 3398-3405, 2012.

511. Speirs DE, Bennett M, Finn CV, and Turner AP. Unilateral Vs Bilateral Squat Training for Strength, Sprints and Agility in Academy Rugby Players. *Journal of Strength and Conditioning Research* 30: 386-392, 2015.

515. Spiteri T, Cochrane JL, Hart NH, Haff GG, and Nimphius S. Effect of Strength on Plant Foot Kinetics and Kinematics During a Change of Direction Task. *European Journal of Sport Science* 13: 646-652, 2013.

516. Spiteri T, Newton RU, Binetti M, Hart NH, Sheppard JM, and Nimphius S. Mechanical Determinants of Faster Change of Direction and Agility Performance in Female Basketball Athletes. *Journal of Strength and Conditioning Research* 29: 2205-2214, 2015.

517. Spiteri T, Newton RU, and Nimphius S. Neuromuscular Strategies Contributing to Faster Multidirectional Agility Performance. *Journal of Electromyography and Kinesiology* 25: 629-636, 2015.

518. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, and Newton RU. Contribution of Strength Characteristics to Change of Direction and Agility Performance in Female Basketball Athletes. *Journal of Strength and Conditioning Research* 28: 2415-2423, 2014.

562. Wilkinson SB. Hypertrophy with Unilateral Resistance Exercise Occurs without Increases in Endogenous Anabolic Hormone Concentration. *European Journal of Applied Physiology* 98: 546, 2006.

568. Wirth K, Hartmann H, Sander A, Mickel C, Szilvas E, and Keiner M. The Impact of Back Squat and Leg-Press Exercises on Maximal Strength and Speed-Strength Parameters. *Journal of Strength and Conditioning Research* 30: 1205-1212, 2016.

569. Wisloff U, Castagna, C., Helgerud, J., Jones, R., and Hoff, J. Strong Correlation of Maximal Squat Strength with Sprint Performance and Vertical Jump Height in Elite Soccer Players. *British Journal of Sports Medicine* 38: 285-288, 2004.

576. Yavuz HU, Erdağ D, Amca AM, and Aritan S. Kinematic and Emg Activities During Front and Back Squat Variations in Maximum Loads. *Journal of Sports Sciences* 33: 1058-1066, 2015.

583. Young WB. Transfer of Strength and Power Training to Sports Performance. *International Journal of Sports Physiology and Performance* 1: 74-83, 2006.

Thesis References

1. Aagaard P. Training-Induced Changes in Neural Function. *Exercise and Sport Sciences Reviews* 31: 61-67, 2003.

2. Aagaard P, Simonsen E, Andersen J, Magnusson S, Bojsen-Møller F, and Dyhre-Poulsen P. Antagonist Muscle Coactivation During Isokinetic Knee Extension. *Scandinavian Journal of Medicine and Science in Sports* 10: 58-67, 2000.

3. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Increased Rate of Force Development and Neural Drive of Human Skeletal Muscle Following Resistance Training. *Journal of applied physiology* 93: 1318-1326, 2002.

4. Abernethy P, Wilson, G., and Logan P. Strength and Power Assessment: Issues, Controversies and Challenges. *Sports Medicine* 19: 401-417., 1995.

5. Adams K, O'Shea JP, O'Shea KL, and Climstein M. The Effect of Six Weeks of Squat, Plyometric and Squat-Plyometric Training on Power Production. *Journal of Applied Sport Science Research* 6: 36-41, 1992.

6. Agel J, Rockwood T, and Klossner D. Collegiate Acl Injury Rates across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 through 2012-2013). *Clinical Journal of Sport Medicine* 26: 518-523, 2016.

7. Akima H, Kuno, S., Takahashi, H., Fukunaga, T. and Katasuta, S. The Use of Magnetic Resonance Images to Investigate the Influence of Recruitment on the Relationship between Torque and Cross-Sectional Area in Human Muscle. *European Journal of Applied Physiology* 83: 475-480, 2000.

8. Alegre LM, Ferri-Morales A, Rodriguez-Casares R, and Aguado X. Effects of Isometric Training on the Knee Extensor Moment–Angle Relationship and Vastus Lateralis Muscle Architecture. *European Journal of Applied Physiology* 114: 2437-2446, 2014.

9. Andersen V, Fimland M, Brennset Ø, Haslestad L, Lundteigen M, Skalleberg K, and Saeterbakken A. Muscle Activation and Strength in Squat and Bulgarian Squat on Stable and Unstable Surface. *International Journal of Sports Medicine* 35: 1196-1202, 2014.

10. Andersen V, Fimland MS, Gunnarskog A, Jungård G-A, Slåttland R-A, Vraalsen ØF, and Saeterbakken AH. Core Muscle Activation in One-Armed and Two-Armed Kettlebell Swing. *Journal of Strength and Conditioning Research* 30: 1196-1204, 2016.

11. Antonio J. Nonuniform Response of Skeletal Muscle to Heavy Resistance Training: Can Bodybuilders Induce Regional Muscle Hypertrophy? *Journal of Strength Conditioning Research* 14: 102, 2000.

12. Appleby B, Newton, RU, and Cormie, P. Changes in Strength over a Two Year Period in Professional Rugby Union Players. *Journal of Strength and Conditioning Research* 26: 2538-2546, 2012.

13. Appleby BB, Banyard, H., Cormie, P., Cormack, S.J. and Newton R.U. Validity and Reliability of Methods to Determine Barbell Displacement in Heavy Back Squats: Implications for Velocity Based Training. *Journal of Strength and Conditioning Research* (in press), 2018.

14. Argus C, Gill, N, Keogh, J, Hopkins, WG and Beaven, CM. Changes in Strength, Power, and Steroid Hormones During a Professional Rugby Union Competition. *Journal of Strength and Conditioning Research* 23: 1583-1592, 2009.

15. Argus C, Gill, N, Keogh, J, Hopkins, WG and Beaven, CM. Effects of a Short-Term Pre-Season Training Programme on the Body Composition and Anaerobic Performance of Professional Rugby Union Players. *Journal of Sports Sciences* 28: 679-686, 2010.

16. Argus C, Gill, N, Keogh, J, McGuigan, MR, and Hopkins, WG. Effects of Two Contrast Training Programs on Jump Performance in Rugby Union Players During a Competition Phase. *International Journal of Sports Physiology and Performance* 7: 68-75, 2012.

17. Argus CK, Gill ND, Keogh JW, and Hopkins WG. Acute Effects of Verbal Feedback on Upper-Body Performance in Elite Athletes. *Journal of Strength and Conditioning Research* 25: 3282-3287, 2011.

18. Aspe RR and Swinton PA. Electromyographic and Kinetic Comparison of the Back Squat and Overhead Squat. *Journal of Strength and Conditioning Research* 28: 2827-2836, 2014.

19. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217-238, 1998.

20. Augustsson RS and Svantesson U. Reliability of the 1 Rm Bench Press and Squat in Young Women. *European Journal of Physiotherapy* 15: 118-126, 2013.

21. Austin D, Gabbett T, and Jenkins D. The Physical Demands of Super 14 Rugby Union. *Journal of Science and Medicine in Sport* 14: 259-263, 2011.

22. Ayotte NW, Stetts, D.M., Keenan, G. and Greenway, E.H. Electromyographical Analysis of Selected Lower Extremity Muscles During 5 Unilateral Weight-Bearing Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 37: 48-55, 2007.

23. Baker D. Periodization of Strength Training for Sports: A Brief Review. *Strength and Conditioning Coach* 1: 15-21, 1993.

24. Baker D. Applying the in-Season Periodization of Strength and Power Training to Football. *Strength and Conditioning Journal* April: 18-24, 1998.

25. Baker D. Comparison of Upper-Body Strength and Power between Professional and College-Aged Rugby League Players. *Journal of Strength and Conditioning Research* 15: 30-35, 2001.

26. Baker D. The Effects of an in-Season of Concurrent Training on the Maintenance of Maximal Strength and Power in Professional and College-Aged Rugby League Football Players. *Journal of Strength and Conditioning Research* 15: 172-177, 2001.

27. Baker D. Differences in Strength and Power among Junior-High, Senior-High, College-Aged, and Elite Professional Rugby League Players. *Journal of Strength and Conditioning Research* 16: 581-585, 2002.

28. Baker D. Six-Year Changes in Upper-Body Maximum Strength and Power in Experienced Strength-Power Athletes. *Journal of Australian Strength and Conditioning* 16: 4-10, 2006.

29. Baker D. Six-Year Changes in Upper-Body Maximum Strength and Power in Experienced Strength-Power Athletes. *Journal of Australian Strength and Conditioning* 16: 4-10, 2008.

30. Baker D, and Nance, S. The Relation between Running Speed and Measures of Strength and Power in Professional Rugby League Players. *Journal of Strength and Conditioning Research* 13: 230-235, 1999.

31. Baker D, and Newton, R. Comparison of Lower Body Strength, Power, Acceleration, Speed, Agility and Sprint Momentum to Describe Playing Rank among Professional Rugby League Players. *Journal of Strength and Conditioning Research* 22: 153-158, 2008.

32. Baker D, and Newton, R. Observation of 4-Year Adaptations in Lower Body Maximal Strength and Power Output in Professional Rugby League Players. *Journal of Australian Strength and Conditioning* 16: 3-10, 2008.

33. Baker D, Wilson, G. and Carlyon, B. Generality Versus Specificity: A Comparison of Dynamic and Isometric Measures of Strength and Speed-Strength. *European Journal of Applied Physiology* 68: 350-355, 1994.

34. Baker DG. 10-Year Changes in Upper Body Strength and Power in Elite Professional Rugby League Players—the Effect of Training Age, Stage, and Content. *Journal of Strength and Conditioning Research* 27: 285-292, 2013.

35. Ball NB and Zanetti S. Relationship between Reactive Strength Variables in Horizontal and Vertical Drop Jumps. *Journal of Strength and Conditioning Research* 26: 1407-1412, 2012.

36. Balshaw TG, Massey GJ, Maden-Wilkinson TM, Tillin NA, and Folland JP. Training-Specific Functional, Neural, and Hypertrophic Adaptations to Explosive-Vs. Sustained-Contraction Strength Training. *Journal of Applied Physiology* 120: 1364-1373, 2016.

37. Banyard HG, Nosaka K, and Haff GG. Reliability and Validity of the Load-Velocity Relationship to Predict the 1rm Back Squat. *Journal of Strength and Conditioning Research* 31: 1897-1904, 2017.

38. Banyard HG, Nosaka K, Sato K, and Haff GG. Validity of Various Methods for Determining Velocity, Force and Power in the Back Squat. *International Journal of Sports Physiology and Performance*: 1-25, 2017.

39. Baratta R, Solomonow, M., Zhou, B.H., Letson, EE.D., Chuinard, R. and D'Ambrosia, R. Muscular Coactivation: The Role of the Antagonist Musculature in Maintaining Knee Stability. *American Journal of Sports Medicine* 16: 113-122, 1988.

40. Barber OR, Thomas C, Jones PA, McMahon JJ, and Comfort P. Reliability of the 505 Change-of-Direction Test in Netball Players. *International Journal of Sports Physiology and Performance* 11: 377-380, 2016.

41. Barker M, Wyatt TJ, Johnson RL, Stone MH, O'bryant HS, Poe C, and Kent M. Performance Factors, Psychological Assessment, Physical Characteristics, and Football Playing Ability. *Journal of Strength and Conditioning Research* 7: 224-233, 1993.

42. Barnes JL, Schilling BK, Falvo MJ, Weiss LW, Creasy AK, and Fry AC. Relationship of Jumping and Agility Performance in Female Volleyball Athletes. *Journal of Strength and Conditioning Research* 21: 1192, 2007.

43. Barr MJ, Sheppard JM, Gabbett TJ, and Newton RU. Long-Term Training-Induced Changes in Sprinting Speed and Sprint Momentum in Elite Rugby Union Players. *Journal of Strength and Conditioning Research* 28: 2724-2731, 2014.

44. Barr MJ, Sheppard JM, and Newton RU. Sprinting Kinematics of Elite Rugby Players. *Journal of Australian Strength and Conditioning* 21: 14-20, 2013.

45. Batterham AM and Hopkins WG. Making Meaningful Inferences About Magnitudes. *International Journal of Sports Physiology and Performance* 1: 50-57, 2006.

46. Batterham AMaHWG. A Decision Tree for Controlled Trials. *Sportscience* 9: 33-39, 2005.

47. Bazyler CD. The Use of the Isometric Squat as a Measure of Strength and Explosiveness. *Journal of Strength and Conditioning Research* 29: 1386, 2015.

48. Bazyler CD, Bailey CA, Chiang C-Y, Sato K, and Stone MH. The Effects of Strength Training on Isometric Force Production Symmetry in Recreationally Trained Males. *Journal of Trainology* 3: 6-10, 2014.

49. Behm D, Anderson, K and Curnew, RS. Muscle Force and Activation under Stable and Unstable Conditions. *Journal of Strength and Conditioning Research* 16: 416-422, 2002.

50. Behm D and Colado JC. The Effectiveness of Resistance Training Using Unstable Surfaces and Devices for Rehabilitation. *International Journal of Sports Physical Therapy* 7: 226, 2012.

51. Behm D, Drinkwater, EJ, Willardson, JM and Cowley, PM. The Role of Instability Rehabilitative Resistance Training for the Core Musculature. *Strength and Conditioning Journal* 33: 72-81, 2011.

52. Behm DG. Neuromuscular Implications and Applications of Resistance Training. *Journal of Strength and Conditioning Research* 9: 264-274, 1995.

53. Behm DG. The Role of Instability with Resistance Training. *Journal of Strength and Conditioning Research* 20: 716, 2006.

54. Behm DG, and Sale, D.G. Velocity Specificity of Resistance Training. *Sports Medicine* 15: 374-388, 1993.

55. Behm DG, Drinkwater EJ, Willardson JM, and Cowley PM. The Use of Instability to Train the Core Musculature. *Applied Physiology, Nutrition, and Metabolism* 35: 91-108, 2010.

56. Behm DG, Leonard, A.M., Young, W.B., Bonsey, A.C. and MacMinnon, S.N. Trunk Muscle Electromyographic Activity with Unstable and Unilateral Exercises. *Journal of Strength and Conditioning Research* 19: 193-201, 2005.

57. Behm DG, Muehlbauer T, Kibele A, and Granacher U. Effects of Strength Training Using Unstable Surfaces on Strength, Power and Balance Performance across the Lifespan: A Systematic Review and Meta-Analysis. *Sports Medicine* 45: 1645-1669, 2015.

58. Bellon C, Leigh S, and Suchomel T. A Comparison of Muscle Activation of the Lower Back and Legs between a Back Squat and a Rear Foot Elevated Split Squat. Presented at Conference Papers from the 8th Annual Coaches and Sport Science College December 13-14, 2013, 2013.

59. Berger RA. Effects of Dynamic and Static Training on Vertical Jumping Ability. *Research Quarterly American Association for Health, Physical Education and Recreation* 34: 419-424, 1963.

60. Besier TF, Lloyd DG, Cochrane JL, and Ackland TR. External Loading of the Knee Joint During Running and Cutting Maneuvers. *Medicine and Science in Sports and Exercise* 33: 1168-1175, 2001.

61. Besier TF, Lloyd, D.G. and Ackland, T.R. Muscle Activation Strategies at the Knee During Running and Cutting Maneuvers. *Medicine and Science in Sports and Exercise* 35: 119-127, 2003.

62. Best G. Epidemiology and Incidence of Injury in Elite Netball Players – an Injury Audit of the 2016 Netball Superleague Season. *British Journal of Sports Medicine* 51: 297-297, 2017.

63. Beutler A, Cooper, LW, Kirkendall, DT and Garrett, WE. Electromyographic Analysis of Single-Leg Closed Chain Exercises: Implications for Rehabilitation after Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* 37: 13-18, 2002.

64. Beyer KS, Fukuda DH, Boone CH, Wells AJ, Townsend JR, Jajtner AR, Gonzalez AM, Fragala MS, Hoffman JR, and Stout JR. Short-Term Unilateral Resistance Training Results in Cross Education of Strength without Changes in Muscle Size, Activation, or Endocrine Response. *Journal of Strength and Conditioning Research* 30: 1213-1223, 2016.

65. Bishop C, Brierley S, Read P, and Turner A. The Single Leg Squat: When to Prescribe This Exercise. *Professional Strength and Conditioning*: 17-26, 2016.

66. Black W, and Roundy, E. Comparisons of Size, Strength, Speed and Power in Ncaa Division 1-a Football Players. *Journal of Strength and Conditioning Research* 8: 80-85, 1994.

67. Blazevich A, and Gill, ND. Reliability of Unfamiliar, Multijoint, Uni- and Bilateral Strength Tests: Effects of Load and Laterality. *Journal of Strength and Conditioning Research* 20: 226-230, 2006.

68. Blazevich AJ, Cannavan D, Coleman DR, and Horne S. Influence of Concentric and Eccentric Resistance Training on Architectural Adaptation in Human Quadriceps Muscles. *Journal of Applied Physiology* 103: 1565-1575, 2007.

69. Blazevich AJ, Gill, N.D., Bronks, R. and Newton, R.U. Training-Specific Muscle Architecture Adaptation after 5-Wk Training in Athletes. *Medicine and Science in Sports and Exercise* 35: 2013-2022, 2003.

70. Bloomquist K, Langberg H, Karlsen S, Madsgaard S, Boesen M, and Raastad T. Effect of Range of Motion in Heavy Load Squatting on Muscle and Tendon Adaptations. *European Journal of Applied Physiology*, 2013.

71. Bogdanis G. Comparison between Unilateral and Bilateral Plyometric Training on Single and Double Leg Jumping Performance and Strength. *Journal of Strength and Conditioning Research*, 2017.

72. Bolger R, Lyons M, Harrison AJ, and Kenny IC. Sprinting Performance and Resistance-Based Training Interventions: A Systematic Review. *Journal of Strength and Conditioning Research* 29: 1146-1156, 2015.

73. Boren K, Conrey C, Le Coguic J, Paprocki L, Voight M, and Robinson TK. Electromyographic Analysis of Gluteus Medius and Gluteus Maximus During Rehabilitation Exercises. *International Journal of Sports Physical Therapy* 6: 206-223, 2011.

74. Botton CE, Radaelli R, Wilhelm EN, Rech A, Brown LE, Pinto RS, Fullerton C, Botton CE, Felizardo R, and Botânico BJ. Neuromuscular Adaptations to Unilateral Vs. Bilateral Strength Training in Women. *Journal of Strength and Conditioning Research* 30: 1924-1932, 2015.

75. Boudreau SN, Dwyer, M.K., Mattacola, C.G., Lettermann, C., Uhl, T.L. and McKeon, J.M. Hip-Muscle Activation During the Lunge, Single-Leg Squat, and Step-up-and-over Exercises. *Journal of Sport Rehabilitation* 18: 91-103, 2009.

76. Brandon R, Howatson, G and Hunter, A. Reliability of a Combined Biomechanical and Surface Electromyographical Analysis System During Dynamic Barbell Squat Exercise. *Journal of Sports Sciences* 29: 1389-1397, 2011.

77. Brask B, Lueke, R.H. and Soderberg, G.L. Electromyographic Analysis of Selected Muscles During the Lateral Step-up Exercise. *Physical Therapy* 64: 324-329, 1984.

78. Brechue W, Mayhew, JL and Piper, FC. Characteristics of Sprint Performance in College Football Players. *Journal of Strength and Conditioning Research* 24: 1169-1178, 2010.

79. Bressel E. Effect of Instruction, Surface Stability, and Load Intensity on Trunk Muscle Activity. *Journal of Electromyography and Kinesiology* 19: 500, 2009.

80. Bryanton MA, Kennedy MD, Carey JP, and Chiu LZ. Effect of Squat Depth and Barbell Load on Relative Muscular Effort in Squatting. *Journal of Strength and Conditioning Research* 26: 2820-2828, 2012.

81. Bryne P, Moody JA, Cooper S-M, and Kinsella S. Reliability of Sprint Acceleration Performance and Three Repetition Maximum Back Squat Strength in Hurling Players. *ARC Journal of Research in Sports Medicine* 2: 9-15, 2018.

82. Buckthorpe M, Erskine RM, Fletcher G, and Folland JP. Task-Specific Neural Adaptations to Isoinertial Resistance Training. *Scandinavian Journal of Medicine and Science in Sports* 25: 640-649, 2015.

83. Buttifant D, Graham K, and Cross K. 55 Agility and Speed in Soccer Players Are Two Different Performance Parameters. *Science and football IV* 4: 329, 2001.

84. Calatayud J, Martin F, Colado JC, Benítez JC, Jakobsen MD, and Andersen LL. Muscle Activity During Unilateral Vs. Bilateral Battle Rope Exercises. *Journal of Strength and Conditioning Research* 29: 2854-2859, 2015.

85. Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, Ragg KE, Ratamess NA, Kraemer WJ, and Staron RS. Muscular Adaptations in Response to Three Different Resistance-Training Regimens: Specificity of Repetition Maximum Training Zones. *European Journal of Applied Physiology* 88: 50-60, 2002.

86. Canavan P, Garrett, GE, and Armstrong, LE. Kinematic and Kinetic Relationships between an Olympic-Style Lift and the Vertical Jump. *Journal of Strength and Conditioning Research* 10: 127-130, 1996.

87. Carlock JM, Smith, S.L., Hartman, M.J., Morris, R.T., Ciroslan, D.A., Pierce, K.C., Newton, R.U., Harman, E.A., Sands, W.A. and Stone, M.H. The Relationship between Verical Jump Power Estimates and Weightlifting Ability: A Field Test Approach. *Journal of Strength and Conditioning Research* 18: 534-539, 2004.

88. Carolan B and Cafarelli E. Adaptations in Coactivation after Isometric Resistance Training. *Journal of Applied physiology* 73: 911-917, 1992.

89. Carr C, McMahon JJ, and Comfort P. Relationships between Jump and Sprint Performance in First-Class County Cricketers. *Journal of Trainology* 4: 1-5, 2015.

90. Carroll KM, Sato K, Bazyler CD, Triplett NT, and Stone MH. Increases in Variation of Barbell Kinematics Are Observed with Increasing Intensity in a Graded Back Squat Test. *Sports* 5: 51, 2017.

91. Carroll TJ. Neural Adaptations to Resistance Training. *Sports Medicine* 31: 829, 2001.

92. Castillo-Rodriguez A, Fernadez-Garcia, J.C., Chinchilla-Minguet, J.L., and Carnero, E.A. Relationship between Muscular Strength and Sprints with Changes of Direction. *Journal of Strength and Conditioning Research* 26: 725-732, 2012.

93. Caterisano A, Moss, RE, Pellinger, TK, Woodruff, K, Lewis, VC, Booth, W and Khadra, T. The Effect of Back Squat Depth on the Emg Activity of 4 Superficial Hip and Thigh Muslces. *Journal of Strength and Conditioning Research* 16: 428-432, 2002.

94. Chandler TJ, and Stone, M.H. The Squat Exercise in Athletic Conditioning: A Review of the Literature. *National Strength and Conditioning Association Journal* 13: 52-58, 1991.

95. Chaouachi A, Brughelli, M., Chamari, K., Levin, G.T., Abdelkrim, N.B., Laurencelle, L. and Castagna, C. Lower Limb Maximal Dynamic Strength and Agility Determinants in Elite Basketball Players. *Journal of Strength and Conditioning Research* 23: 1570-1577, 2009.

96. Chapman AR, Vicenzino, B., Blanch, P., and Hodges, P.W. Patterns of Leg Muscle Recruitment Vary between Novice and Highly Trained Cyclists. *Journal of Electromyography and Kinesiology* 18: 359-371, 2008.

97. Chau T, Young S, and Redekop S. Managing Variability in the Summary and Comparison of Gait Data. *Journal of NeuroEngineering and Rehabilitation* 2: 1-20, 2005.

98. Chaudhari AM, Hearn BK, and Andriacchi TP. Sport-Dependent Variations in Arm Position During Single-Limb Landing Influence Knee Loading: Implications for Anterior Cruciate Ligament Injury. *American Journal of Sports Medicine* 33: 824-830, 2005.

99. Chauhan E, Bridge C, Hammond B, and Marques-Bruna P. Surface Electromyography Analysis of the Free, Smith Machine and Split Squats Performed by Strength-Trained Males. *Journal of Fitness Research* 5: 68-79, 2016.

100. Chelly MS, Cherif, N., Amar, M.B., Hermassi, S., Fathloun, M., Bouhlel, E., Tabka, Z. and Shephard, R.J. Relationships of Peak Leg Power, 1 Maximal Repetition Half Back Squat and Leg Muscle Volume to 5m Sprint Performance of Junior Soccer Players. *Journal of Strength and Conditioning Research* 24: 266-271, 2010.

101. Chelly MS, Fathloun M, Cherif N, Amar MB, Tabka Z, and Van Praagh E. Effects of a Back Squat Training Program on Leg Power, Jump, and Sprint Performances in Junior Soccer Players. *Journal of Strength and Conditioning Research* 23: 2241-2249, 2009.

102. Chelly MS, Hermassi, S. and Shephard, R.J. Relationships between Power and Strength of the Upper and Lower Limb Muscles and Throwing Velocity in Male Handball Players. *Journal of Strength and Conditioning Research* 24: 1480-1487, 2010.

103. Chelly SM, and Denis, C. Leg Power and Hopping Stiffness: Relationship with Sprint Running Performance. *Medicine and Science in Sports and Exercise* 33: 326-333, 2001.

104. Chiu LZ. Mechanical Properties of Weightlifting Bars. *Journal of Strength and Conditioning Research* 24: 2390-2399, 2010.

105. Chiu LZ, Schilling BK, Fry AC, and Salem GJ. The Influence of Deformation on Barbell Mechanics During the Clean Pull. *Sports Biomechanics* 7: 260-273, 2008.

106. Choe KH, Coburn JW, Costa PB, and Pamukoff DN. Hip and Knee Kinetics During a Back Squat and Deadlift. *Journal of Strength and Conditioning Research*, 2018.

107. Chui LZF. Sitting Back in the Squat. *Strength and Conditioning Journal* 31: 25-27, 2009.

108. Clark D, Lambert, MI, and Hunter, AM. Muscle Activation in the Loaded Free Barbell Squat: A Brief Review. *Journal of Strength and Conditioning Research* 26: 1169-1178, 2012.

109. Coburn JW, Housh TJ, Malek MH, Weir JP, Cramer JT, Beck TW, and Johnson GO. Neuromuscular Responses to Three Days of Velocity-Specific Isokinetic Training. *Journal of Strength and Conditioning Research* 20: 892-898, 2006.

110. Cochrane JL, Lloyd DG, Besier TF, Elliott BC, Doyle TL, and Ackland TR. Training Affects Knee Kinematics and Kinetics in Cutting Maneuvers in Sport. *Medicine and Science in Sports and Exercise* 42: 1535-1544, 2010.

111. Colby S, Francisco, A., Yu, B., Kirkendall, D., Finch, M. and Garrett Jr, W. Electromyographic and Kinematic Analysis of Cutting Maneuvers. *American Journal of Sports Medicine* 28: 234-240, 2000.

112. Collen FM, Baer, G.D. and Ashburn, A.M. Stepping onto a Single Step: A Kinematic Study. *Physiotherapy Research International* 10: 81-92, 2005.

113. Comfort P. Within- and between-Session Reliability of Power, Force, and Rate of Force Development During the Power Clean. *Journal of Strength and Conditioning Research* 27: 1210-1214, 2013.

114. Comfort P, Bullock, N, and Pearson, S.J. A Comparison of Maximal Squat Strength and 5-, 10- and 20-Meter Sprint Times in Athletes and Recreationally Trained Men. *Journal of Strength and Conditioning Research* 26: 937-940, 2012.

115. Comfort P, Haigh, A, and Matthews, M.J. Are Changes in Maximal Squat Strength During Preseason Training Reflected in Changes in Sprint Performance in Rugby League Players? *Journal of Strength and Conditioning Research* 26: 772-776, 2012.

116. Comfort P, Jones PA, Smith LC, and Herrington L. Joint Kinetics and Kinematics During Common Lower Limb Rehabilitation Exercises. *Journal of Athletic Training* 50: 1011-1018, 2015.

117. Comfort P and McMahon JJ. Reliability of Maximal Back Squat and Power Clean Performances in Inexperienced Athletes. *Journal of Strength and Conditioning Research* 29: 3089-3096, 2015.

118. Comfort P, Stewart A, Bloom L, and Clarkson B. Relationships between Strength, Sprint and Jump Performance in Well Trained Youth Soccer Players. *Journal of Strength and Conditioning Research*, 2014.

119. Comfort P, Udall R, and Jones PA. The Effect of Loading on Kinematic and Kinetic Variables During the Midthigh Clean Pull. *Journal of Strength and Conditioning Research* 26: 1208-1214, 2012.

120. Condello G, Schultz K, and Tessitore A. Assessment of Sprint and Change-of-Direction Performance in College Football Players. *International Journal of Sports Physiology and Performance* 8: 211-212, 2013.

121. Contreras B, Vigotsky AD, Schoenfeld BJ, Beardsley C, and Cronin J. A Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyography Amplitude in the Parallel, Full, and Front Squat Variations in Resistance-Trained Females. *Journal of applied biomechanics* 32: 16-22, 2016.

122. Cools A, Declercq, GA, Cambier, DC, Mahieu, NN and Witvrouw, EE. Trapezius Activity and Intramuscular Balance During Isometric Exercise in Overhead Athletes with Impingement Symptoms. *Scandianvian Journal of Medicine and Science in Sports* 17: 25-33, 2007.

123. Cordova ML and Armstrong CW. Reliability of Ground Reaction Forces During a Vertical Jump: Implications for Functional Strength Assessment. *Journal of Athletic Training* 31: 342, 1996.

124. Cormack SJ, Newton, R.U., McGuigian, M.R. and Doyle, T.L.A. Reliability of Measures Obtained During Single Repeated Countermovement Jumps. *International Journal of Sports Physiology and Performance* 3: 131-144, 2008.

125. Cormie P. A Series of Investigations into the Effect of Strength Level on Muscular Power in Athletic Movements. 2009.

126. Cormie P, Deane, R, and McBride, JM. Methodological Concerns for Determining Power Output in the Jump Squat. *Journal of Strength and Conditioning Research* 21: 424-430, 2007.

127. Cormie P, McBride, J.M. and McCaulley, G.O. Power-Time, Force-Time, and Velocity-Time Curve Analysis of the Countermovement Jump - Impact of Training. *Journal of Strength and Conditioning Research* 23: 177-186, 2009.

128. Cormie P, McBride, JM, and McCaulley, GO. Validation of Power Measurement Techniques in Dynamic Lower Body Resistance Exercise. *Journal of Applied Biomechanics* 23, 2007.

129. Cormie P, McBride, JM, and McCaulley, GO. Power-Time, Force-Time, and Velocity-Time Curve Analysis During the Jump Squat: Impact of Load. *Journal of Applied Biomechanics* 24: 112-120, 2008.

130. Cormie P, McGuigan MR, and Newton RU. Influence of Strength on Magnitude and Mechanisms of Adaptation to Power Training. *Medicine and Science in Sports and Exercise* 42: 1566-1581, 2010.

131. Cormie P, McGuigan, M.R. and R.U.Newton. Developing Maximal Neuromuscular Power: Part 1 - Biological Basis of Maximal Power Production. *Sports Medicine* 41: 17-38, 2011.

132. Cormie P MM, and Newton R.U. Adaptations in Athletic Performance after Ballistic Power Versus Strength Training. *Medicine and Science in Sports and Exercise* 42: 1582-1598, 2010.

133. Cortina JM. What Is Coefficient Alpha? An Examination of Theory and Applications. *Journal of Applied Psychology* 78: 98, 1993.

134. Costigan PA, Deluzio KJ, and Wyss UP. Knee and Hip Kinetics During Normal Stair Climbing. *Gait and Posture* 16: 31-37, 2002.

135. Cotter JA, Chaudhari AM, Jamison ST, and Devor ST. Knee Joint Kinetics in Relation to Commonly Prescribed Squat Loads and Depths. *J Strength Cond Res* 27: 1765-1774, 2013.

136. Cowell JF, Cronin J, and Brughelli M. Eccentric Muscle Actions and How the Strength and Conditioning Specialist Might Use Them for a Variety of Purposes. *Strength and Conditioning Journal* 34: 33-48, 2012.

137. Cressey EM, West CA, Tiberio DP, Kraemer WJ, and Maresh CM. The Effects of Ten Weeks of Lower-Body Unstable Surface Training on Markers of Athletic Performance. *The Journal of Strength & Conditioning Research* 21: 561-567, 2007.

138. Crewther B, Kilduff, LP, Cunningham, DJ, Cook, C, Owen, N and Yang, G-Z. Validating Two Systems for Estimating Force and Power. *International Journal of Sports Medicine* 32, 2011.

139. Croisier J-L, Forthomme, B., Namurios, M-H, Vanderthommen, M. and Crielaard, J-M. Hamstring Muscle Strain Recurrence and Strength Performance Disorders. *American Journal of Sports Medicine* 30: 199 - 203, 2002.

140. Cronin J, and Hansen, K.T. Strength and Power Predictors of Sports Speed. *Journal of Strength and Conditioning Research* 19: 349-357, 2005.

141. Cronin J, and Hansen, K.T. Resisted Sprint Training for the Acceleration Phase of Sprinting. *Strength and Conditioning Journal* 28: 42-51, 2006.

142. Cronin J, and Sleivert, G. Challenges in Understanding the Influence of Maximal Power Training on Improving Athletic Performance. *Sports Medicine* 35: 213-234, 2005.

143. Cronin J, Hing, RD and McNair, PJ. Reliability and Validity of a Linear Position Transducer for Measuring Jump Performance. *Journal of Strength and Conditioning Research* 18: 590-593, 2004.

144. Cronin J, McNair, P.J. and Marshall, R.N. Developing Explosive Power: A Comparison of Technique and Training. *Journal of Science and Medicine in Sport* 4: 59-70, 2001.

145. Cronin J, McNair, P.J. and Marshall, R.N. The Effects of Bungy Weight Training on Muscle Function and Functional Performance. *Journal of Sports Sciences* 21: 59-71, 2003.

146. Cronin JB. Timing Light Height Affects Sprint Times. *Journal of Strength and Conditioning Research* 22: 318, 2008.

147. Cross MR, Brughelli M, Brown SR, Samozino P, Gill ND, Cronin JB, and Morin J-B. Mechanical Properties of Sprinting in Elite Rugby Union and Rugby League. *International journal of sports physiology and performance* 10: 695-702, 2015.

148. Crossley K, Zhang, W, Schache, AG, Bryant, A and Cowan, SM. Performance on the Single-Leg Squat Task Indicates Hip Abductor Muscle Function. *American Journal of Sports Medicine* 39: 866-873, 2011.

149. Daneshmandi HH, S.A. and Afsharnejad, T. Intermuscular and Intramuscular Neural Adaptations of Trained and Contralateral Untrained Limb Following Unilateral Resistance Training. *International Journal of Fitness* 3: 1-10, 2007.

150. Darainy M and Ostry DJ. Muscle Cocontraction Following Dynamics Learning. *Experimental Brain Research* 190: 153-163, 2008.

151. Davis DS, Barnette, B.J., Kiger, J.T., Mirasola, J.J. and Young, S.M. Physical Characteristics That Predict Functional Performance in Division I College Football Players. *Journal of Strength and Conditioning Research* 19: 115-120, 2004.

152. Davis III RB, Ounpuu, S., Tyburski, D., and Gage, J.R. A Gait Analysis Data Collection and Reduction Technique. *Human Movement Sciences* 10: 575-587, 1991.

153. Dawson B, Hopkinson, R., Appleby, B., Stewart, G. and Roberts, C. Player Movement Patterns and Game Activities in the Australian Football League. *Journal of Science and Medicine in Sport* 7: 278-291, 2004.

154. de Hoyo Moises M. Comparative Effects of in-Season Full-Back Squat, Resisted Sprint Training, and Plyometric Training on Explosive Performance in U-19 Elite Soccer Players. *Journal of Strength and Conditioning Research* 30: 368-377, 2016.

155. De Souza E, Tricoli V, Paulo A, Silva-Batista C, Cardoso R, Brum PC, Bacurau A, Laurentino G, Neves-Jr M, and Aihara A. Multivariate Analysis in the Maximum Strength Performance. *International journal of sports medicine* 33: 970-974, 2012.

156. Dedinsky R, Baker L, Imbus S, Bowman M, and Murray L. Exercises That Facilitate Optimal Hamstring and Quadriceps Co-Activation to Help Decrease Acl Injury Risk in Healthy Females: A Systematic Review of the Literature. *International journal of sports physical therapy* 12: 3, 2017.

157. DeForest BA, Cantrell GS, and Schilling BK. Muscle Activity in Single-Vs. Double-Leg Squats. *International Journal of Exercise Science* 7: 302, 2014.

158. Delaney JA, Scott, T.J., Ballard, D.A., Duthie, G.M., Hickmans, J.A., Lockie, R.G. and Dascombe, B.J. Contributing Factors to Change-of-Direction Ability in Professional Rugby League Players. *The Journal of Strength & Conditioning Research* 29: 2688-2696, 2015.

159. Delecluse C. Influence of Strength Training on Sprint Running Performance: Current Findings and Implications for Training. *Sports Medicine* 24: 147-156, 1997.

160. Delecluse C, Van Coppenolle, H., Willems, E., Van Leemputte, M., Diels, R. and Goris, M. . Influence of High-Resistance and High-Velocity Training on Sprint Performance. *Medicine and Science in Sports and Exercise* 27: 1203-1209, 1995.

161. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, and Munro BJ. Changing Sidestep Cutting Technique Reduces Knee Valgus Loading. *American Journal of Sports Medicine* 37: 2194-2200, 2009.

162. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, and Russo KA. The Effect of Technique Change on Knee Loads During Sidestep Cutting. *Medicine & Science in Sports & Exercise* 39: 1765-1773, 2007.

163. Desloovere K, Wong, P., Swings, L., Callewaert, B., Vandenneucker, H. and Leardini, A. Range of Motion and Repeatability of Knee Kinematics for 11 Clinically Relevant Motor Tasks. *Gait and Posture* 23: 597-602, 2010.

164. Di Salvo V, Baron R, Gonzalez-Haro C, Gormasz C, Pigozzi F, and Bachl N. Sprinting Analysis of Elite Soccer Players During European Champions League and Uefa Cup Matches. *J Sports Sci* 28: 1489-1494, 2010.

165. Dionisio VC, Almeida GL, Duarte M, and Hirata RP. Kinematic, Kinetic and Emg Patterns During Downward Squatting. *Journal of Electromyography and Kinesiology* 18: 134-143, 2008.

166. Distefano L, Blackburn, JT, Marshall, SW, and Padua, DA. Gluteal Muscle Activation During Common Theraputic Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 39: 532-540, 2009.

167. Donnelly CJ, Lloyd DG, Elliott BC, and Reinbolt JA. Optimizing Whole-Body Kinematics to Minimize Valgus Knee Loading During Sidestepping: Implications for Acl Injury Risk. *Journal of biomechanics* 45: 1491-1497, 2012.

168. Donnelly DV. The Effect of the Direction of Gaze on the Kinematics of the Squat Exercise. *Journal of Strength and Conditioning Research* 20: 145, 2006.

169. Dos' Santos T. Mechanical Determinants of Faster Change of Direction Speed Performance in Male Athletes. *Journal of Strength and Conditioning Research* 31: 696, 2017.

170. Dos' Santos T, Thomas C, Jones PA, and Comfort P. Assessing Asymmetries in Change of Direction Speed Performance; Application of Change of Direction Deficit. *Journal of strength and conditioning research*, 2018.

171. Dos' Santos T, Thomas C, Jones PA, and Comfort P. Assessing Muscle-Strength Asymmetry Via a Unilateral-Stance Isometric Midthigh Pull. *International Journal of Sports Physiology and Performance* 12: 505-511, 2017.

172. Drinkwater E, Galna, B, McKenna, MJ, Hunt, PH and Pynes, DB. Validation of an Optical Encoder During Free Weight Resistance Movements and Analysis of Bench Press Sticking Point Power During Fatigue. *Journal of Strength and Conditioning Research* 21: 510-517, 2007.

173. Drinkwater EJ, Moore NR, and Bird SP. Effects of Changing from Full Range of Motion to Partial Range of Motion on Squat Kinetics. *The Journal of Strength & Conditioning Research* 26: 890-896, 2012.

174. Duchateau J, and Nainaut, K. Isometric or Dynamic Training: Differential Effects on Mechanical Properties of a Human Muscle. *Journal of Applied Physiology* 56: 396-301, 1984.

175. Duchateau J and Baudry S. Training Adaptation of the Neuromuscular System. *Neuromuscular aspects of sport performance* 17: 216-253, 2010.

176. Dugan E, Doyle, TLA, Humphries, B, Hasson, C and Newton, RU. Determining the Optimal Load for Jump Squats: A Review of Methods and Calculations. *Journal of Strength and Conditioning Research* 19: 665-674, 2004.

177. Duthie GM, Pyne, D and Hooper, S. Time Motion Analysis of 2001 and 2002 Super 12 Rugby. *Journal of Sports Sciences* 23: 523-530, 2005.

178. Duthie GM, Pyne, D., Marsh, D.J. and Hooper, S. Sprint Patterns in Ruby Union Players During Competition. *Journal of Strength and Conditioning Research* 20: 208-214, 2006.

179. Dwyer MK, Boudreau SN, Mattacola CG, Uhl TL, and Lattermann C. Comparison of Lower Extremity Kinematics and Hip Muscle Activation During Rehabilitation Tasks between Sexes. *Journal of Athletic Training* 45: 181-190, 2010.

180. Ebben W, Carroll R, and Simenz C. Strength and Conditioning Practices of National Hockey League Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research* 18: 889-897, 2004.

181. Ebben W, Feldmann, CR, Dayne, A, Mitsche, D, Chmiklewski, LM, Alexander, P and Knetgzer, KJ. Using Squat Testing to Predict Training Loads for the Deadlift, Lunge, Step-up, and Leg Extension Exercises. *Journal of Strength and Conditioning Research* 22: 1947-1949, 2008.

182. Ebben W, Hintz, MJ and Simenz, CJ. Strength and Conditioning Practices of Major League Baseball Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research* 19: 538-546, 2005.

183. Ebben WaB, DO. Strength and Conditioning Practices of National Football League Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research* 15: 48-58, 2001.

184. Ebert JR, Edwards PK, Fick DP, and Janes GC. A Systematic Review of Rehabilitation Exercises to Progressively Load the Gluteus Medius. *Journal of sport rehabilitation* 26: 418-436, 2017.

185. Ekstrom R, Donatelli, RA and Carp, KC. Electromyographic Analysis of Core, Trunk, Hip and Thigh Muscles During 9 Rehabilitation Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 37: 754-762, 2007.

186. Emery CA, Roy T-O, Whittaker JL, Nettel-Aguirre A, and Van Mechelen W. Neuromuscular Training Injury Prevention Strategies in Youth Sport: A Systematic Review and Meta-Analysis. *British Journal of Sports Medicine* 49: 865-870, 2015.

187. Enoka R, and Duchateau, J. Muscle Fatigue: What, Why and How It Influences Muscle Function. *Journal of Physiology* 586: 11-23, 2008.

188. Escamilla R, Fleisig, GS, Lowry, TM, Barrentine, SW, and Andrews, JR. A Three-Dimensional Biomechanical Analysis of the Squat During Varying Stance Widths. *Medicine and Science in Sports and Exercise* 33: 984-998, 2001.

189. Escamilla R, Fleisig, GS, Zheng, N, Lander, JE, Barrentine, SW, Andrews, JR, Bergeman, BW and Moorman III, CT. Effect of Technique Variations on Knee Biomechanics During the Squat and Leg Press. *Medicine and Science in Sports and Exercise* 33: 1552-1566, 2001.

190. Escamilla R, Zheng N, Fleisig G, Lander J, Barrentine S, Cutter G, and Andrews J. The Effects of Technique Variations on Knee Biomechanics During the Squat and Leg Press 887. *Medicine and Science in Sports and Exercise* 29: 156, 1997.

191. Escamilla RF. Knee Biomechanics of the Dynamic Squat Exercise. *Medicine and Science in Sports and Exercise* 33: 127-141, 2001.

192. Escamilla RF, Francisco, A.C., Kayes, A.V., Speer, K.P. and Moorman III, C.T. An Electromyographic Analysis of Sumo and Conventional Style Deadlifts. *Medicine and Science in Sports and Exercise* 34: 682-688, 2002.

193. Farrow D, Young, W. and Bruce, L. The Development of a Test of Reactive Agility for Netball: A New Methodology. *Journal of Science and Medicine in Sport* 8: 52-60, 2005.

194. Farup J, Kjølhede T, Sørensen H, Dalgas U, Møller AB, Vestergaard PF, Ringgaard S, Bojsen-Møller J, and Vissing K. Muscle Morphological and Strength Adaptations to Endurance Vs. Resistance Training. *Journal of Strength and Conditioning Research* 26: 398-407, 2012.

195. Fauth M, Garcwau, L, Lutsch, B, Gray, A, Szalkowski, C, Wurm, B and Ebben, WP. Kinetic Analysis of Lower Body Resistance Training Exercises. Presented at XXVIII Congress of the International Society of Biomechanics in Sports, 2010.

196. Fimland MS, Helgerud J, Solstad GM, Iversen VM, Leivseth G, and Hoff J. Neural Adaptations Underlying Cross-Education after Unilateral Strength Training. *Eur J Appl Physiol* 107: 723-730, 2009.

197. Fisher J and Wallin M. Unilateral Versus Bilateral Lower-Body Resistance and Plyometric Training for Change of Direction Speed. *Journal of Athletic Enhancement* 6: 2, 2014.

198. Flanagan S, and Salem, GJ. Bilateral Differences in the Net Joint Torques During the Squat Exercise. *Journal of Strength and Conditioning Research* 21: 1220-1226, 2007.

199. Flanagan S, Kessans, KM and Salem, GJ. Quantifying Bilateral Joint Contributions During Three Variations of the Step Exercises. *Journal of Sport Rehabilitation* 15: 255-265, 2006.

200. Flanagan SP, Kulik JB, and Salem GJ. The Limiting Joint During a Failed Squat: A Biomechanics Case Series. *Journal of Strength and Conditioning Research* 29: 3134-3142, 2015.

201. Flanagan SP and Salem GJ. Lower Extremity Joint Kinetic Responses to External Resistance Variations. *Journal of Applied Biomechanics* 24: 58-68, 2008.

202. Flannagan EaC, TM. The Use of Contact Time and the Reactive Strength Index to Optimise Fast Stretch-Shortening Cycle Training. *Strength and Conditioning Journal* 30: 32-38, 2008.

203. Fletcher I and Jones B. The Effect of Different Warm-up Stretch Protocols on 20 Metre Sprint Performance in Trained Rugby Union Players. *Journal of Strength and Conditioning Research* 18: 885-888, 2004.

204. Foden M, Astley S, Comfort P, McMahon JJ, Matthews MJ, and Jones PA. Relationships between Speed, Change of Direction and Jump Performance with Cricket Specific Speed Tests in Male Academy Cricketers. *Journal of Trainology* 4: 37-42, 2015.

205. Folland J and Williams A. The Adaptations to Strength Training: Morphological and Neurological Contributions to Increased Strength. *Sports Medicine* 37: 145-168, 2007.

206. Folland JP, Hawker K, Leach B, Little T, and Jones DA. Strength Training: Isometric Training at a Range of Joint Angles Versus Dynamic Training. *J Sports Sci* 23: 817-824, 2005.

207. Franchi MV, Longo S, Mallinson J, Quinlan JI, Taylor T, Greenhaff PL, and Narici MV. Muscle Thickness Correlates to Muscle Cross-Sectional Area in the Assessment of Strength Training-Induced Hypertrophy. *Scandinavian journal of medicine & science in sports* 28: 846-853, 2018.

208. French DN, Gomez, A.L., Volek, J.S., Rubin, M.R., Ratamess, N.A., Sharman, M.J., Gotshalk, L.A., Sebastianelli, W.J., Putukian, M., Newton, R.U., Hakkinen, K., Fleck, S.J. and Kraemer, W.J. Longitudinal Tracking of Muscluar Power Changes of Ncaa Division I Collegiate Women Gymnasts. *Journal of Strength and Conditioning Research* 18: 101-107, 2004.

209. Fry A and Kraemer W. Physical Performance Characteristics of American Collegiate Football Players. *Journal of Applied Sport Science Research* 5: 126-138, 1991.

210. Fry AC. Coaching Considerations for the Barbell Squat-Part 2. *National Strength and Conditioning Association Journal* 15: 28-32, 1993.

211. Fry AC. The Role of Resistance Exercise Intensity on Muscle Fibre Adaptations. *Sports medicine* 34: 663-679, 2004.

212. Fry AC, Smith, J.C., and Schilling, B.K. Effect of Knee Position on Hip and Knee Torques During the Barbell Squat. *journal of Strength and Conditioning Research* 17: 629-633, 2003.

213. Fullagar HH, McCunn R, and Murray A. Updated Review of the Applied Physiology of American College Football: Physical Demands, Strength and Conditioning, Nutrition, and Injury Characteristics of America's Favorite Game. *International Journal of Sports Physiology and Performance* 12: 1396-1403, 2017.

214. Gabbett T and Georgieff B. Physiological and Anthropometric Characteristics of Australian Junior National, State, and Novice Volleyball Players. *Journal of Strength and Conditioning Research* 21: 902-908, 2007.

215. Gabbett T, Kelly, J., Ralph, S., and Driscoll, D. Physiological and Anthropometric Characteristics of Junior Elite and Sub-Elite Rugby League Players with Special Reference to Starters and Non-Starters. *Journal of Science and Medicine in Sport* 12: 215-222, 2009.

216. Gabbett TaB, D. Reactive Agility of Rugby League Players. *Journal of Science and Medicine in Sport* 12: 212-214, 2009.

217. Gabbett TJ. Physiological Characteristics of Junior and Senior Rugby League Players. *British Journal of Sports Medicine* 36: 334-339, 2002.

218. Gabbett TJ. Relative Importance of Physiological, Anthropometric, and Skill Qualities to Team Selection in Professional Rugby League. *Journal of Sports Sciences* 29: 1453, 2011.

219. Gabbett TJ. Physical Demands of Professional Rugby League Training and Competition Using Microtechnology. *Journal of Science and Medicine in Sport* 15: 80, 2012.

220. Gabbett TJ, Kelley, N. and Sheppard, J.M. Speed, Change of Direction Speed, and Reactive Agility of Rugby League Players. *Journal of Strength and Conditioning Research* 22: 174-181, 2008.

221. Gabriel D, Kamen, G and Frost, G. Neural Adaptations to Resistive Exercise - Mechanisms and Recommendations for Training Practices. *Sports Medicine* 36: 133-149, 2006.

222. Gallagher S and Marras WS. Tolerance of the Lumbar Spine to Shear: A Review and Recommended Exposure Limits. *Clinical Biomechanics* 27: 973-978, 2012.

223. Gamble P. Physical Preparation for Elite-Level Rugby Union Football. *Strength and Conditioning Journal* 26: 10-23, 2004.

224. Gannon EA, Stokes KA, and Trewartha G. Strength and Power Development in Professional Rugby Union Players over a Training and Playing Season. *International Journal of Sports Physiology and Performance* 11: 381-387, 2016.

225. Gardner GW. Specificity of Strength Changes of the Exercised and Nonexercised Limb Following Isometric Training. *Research Quarterly American Association for Health, Physical Education and Recreation* 34: 98-101, 1963.

226. Garnacho-Castaño MV, López-Lastra S, and Maté-Muñoz JL. Reliability and Validity Assessment of a Linear Position Transducer. *Journal of Sports Science and Medicine* 14: 128, 2015.

227. Garstecki M, Latin, RW and Cuppett, MM. Comparison of Selected Physical Fitness and Performance Variables between Ncaa Division I and Ii Football Players. *Journal of Strength and Conditioning Research* 19: 292-297, 2004.

228. Giboin LS, Weiss B, Thomas F, and Gruber M. Neuroplasticity Following Short-Term Strength Training Occurs at Supraspinal Level and Is Specific for the Trained Task. *Acta Physiologica* 222: e12998, 2018.

229. Glassbrook DJ, Brown SR, Helms ER, Duncan JS, and Storey AG. The High-Bar and Low-Bar Back-Squats: A Biomechanical Analysis. *Journal of Strength and Conditioning Research* PAP, 2017.

230. Glassbrook DJ, Helms ER, Brown SR, and Storey AG. A Review of the Biomechanical Differences between the High-Bar and Low-Bar Back-Squat. *Journal of Strength and Conditioning Research* 31: 2618-2634, 2017.

231. Gonyea WJ, and Sale, D. Physiology of Weight-Lifting Exercise. *Archives of Physical Medicine and Rehabilitation* 63: 235-237, 1982.

232. Gonzalo-Skok O, Tous-Fajardo J, Suarez-Arrones L, Arjol-Serrano JL, Casajús JA, and Mendez-Villanueva A. Single-Leg Power Output and between-Limb Imbalances in Team-Sports Players: Unilateral Vs. Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance* 12: 106-114, 2016.

233. Goodin J. Comparison of External Kinetic and Kinematic Variables between High Barbell Back Squats and Low Barbell Back Squats across a Range of Loads. East Tennessee State University, 2015.

234. Gorostiaga E, Granados C, Ibanez J, and Izquierdo M. Differences in Physical Fitness and Throwing Velocity among Elite and Amateur Male Handball Players. *International journal of sports medicine* 26: 225-232, 2005.

235. Graham JF. Exercise Technique: Dumbbell Squat, Dumbbell Split Squat and Barbell Box Step-Up. *Strength and Conditioning Journal* 33: 76-78, 2011.

236. Graham V, Gehlsen, GM and Edwards, JA. Electroymyographic Evaluation of Closed and Open Kinetic Chain Knee Rehabilitation Exercises. *Journal of Athletic Training* 28: 23-30, 1993.

237. Green BS, Blake C, and Caulfield BM. A Comparison of Cutting Technique Performance in Rugby Union Players. *Journal of Strength and Conditioning Research* 25: 2668-2680, 2011.

238. Green BS, Blake C, and Caulfield BM. A Valid Field Test Protocol of Linear Speed and Agility in Rugby Union. *Journal of Strength and Conditioning Research* 25: 1256-1262, 2011.

239. Gryzlo SM, Patek, R.M., Pink, M. and Perry, J. Electromyographic Analysis of Knee Rehabilitation Exercises. *Journal of Orthopaedic and Sports Physical Therapy* 20: 36-43, 1994.

240. Gullett JC, Tillman, M.D., Gutierrez, G.M. and Chow, J.W. A Biomechanical Comparison of Back and Front Squats in Healthy Train Individuals. *Journal of Strength and Conditioning Research* 23: 284-292, 2008.

241. Haff G. Quantifying Workloads in Resistance Training: A Brief Review. *UK Strength and Conditioning Association* 19: 31-40, 2010.

242. Haff G, Carlock, JM, Hartman, MJ, Kilgore, JL, Kawamori, N, Jackson, JR, Morris, RT, Sands, WA and Stone, MH. Force-Time Curve Characteristics of Dynamic and Isometric Muscle Actions of Elite Women Olympic Weightlifters. *Journal of Strength and Conditioning Research* 19: 741-748, 2005.

243. Haff GG. Roundtable Discussion: Machines Versus Free Weights. *Strength & Conditioning Journal* 22: 18, 2000.

244. Haff GG and Nimphius S. Training Principles for Power. *Strength & Conditioning Journal* 34: 2-12, 2012.

245. Haff GG, Ruben RP, Lider J, Twine C, and Cormie P. A Comparison of Methods for Determining the Rate of Force Development During Isometric Midthigh Clean Pulls. *Journal of Strength and Conditioning Research* 29: 386-395, 2015.

246. Haff GG, Stone, M., O'Bryant, H.S., Harman, E., Dinan, C., Johnson, R. and Han, K-H. Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions. *Journal of Strength and Conditioning Research* 11: 269-272, 1997.

247. Hakkinen H, Komi, P.V. and Kauhanen, H. Electromyographic and Force Production Characteristics of Leg Extensor Muscles of Eltie Weight Lifters During Isometric, Concentric and Various Stretch-Shortening Cycle Exercises. *International Journal of Sports Medicine* 7: 144-151, 1986.

248. Hakkinen K. Neuromuscular and Hormonal Adaptations During Strength and Power Training. *Journal of Sports Medicine* 29: 9-26, 1989.

249. Häkkinen K, Alen M, and Komi P. Changes in Isometric Force-and Relaxation-Time, Electromyographic and Muscle Fibre Characteristics of Human Skeletal Muscle During Strength Training and Detraining. *Acta physiologica scandinavica* 125: 573-585, 1985.

250. Häkkinen K, Kallinen M, Linnamo V, PASTINEN UM, Newton R, and Kraemer W. Neuromuscular Adaptations During Bilateral Versus Unilateral Strength Training in Middle-Aged and Elderly Men and Women. *Acta Physiologica* 158: 77-88, 1996.

251. Hakkinen K and Komi PV. Electromyographic Changes During Strength Training and Detraining. *Medicine and Science in Sports and Exercise* 15: 455-460, 1983.

252. Hakkinen K, Komi, PV, Aleu, M and Kauhanen, H. Emg, Muscle Fibre and Force Production Characteristics During a 1 Year Training Period in Elite Weight-Lifters. *European Journal of Applied Physiology* 56: 419-427, 1987.

253. Häkkinen K, Newton RU, Gordon SE, McCormick M, Volek JS, Nindl BC, Gotshalk LA, Campbell WW, Evans WJ, and Häkkinen A. Changes in Muscle Morphology, Electromyographic Activity, and Force Production Characteristics During Progressive Strength Training in Young and Older Men. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 53: B415-B423, 1998.

254. Hakkinen K, Pakarinen, A, Alen, M, Kauhanen, H and Komi, PV. Neuromuscular and Hormonal Adaptations in Athletes to Strength Training in Two Years. *Journal of Applied Physiology* 65: 2406-2412, 1988.

255. Hales ME, Johnson BF, and Johnson JT. Kinematic Analysis of the Powerlifting Style Squat and the Conventional Deadlift During Competition: Is There a Cross-over Effect between Lifts? *Journal of Strength and Conditioning Research* 23: 2574-2580, 2009.

256. Hansen KT, Cronin JB, and Newton MJ. The Reliability of Linear Position Transducer and Force Plate Measurement of Explosive Force–Time Variables During a Loaded Jump Squat in Elite Athletes. *Journal of Strength and Conditioning Research* 25: 1447-1456, 2011.

257. Harris GR, Stone, M.H., O'Bryant, H.S., Proulx, C.M., and Johnson, R.L. Short-Term Performance Effects of High Power, High Force, or Combined Weight-Training Methods. *Journal of Strength and Conditioning Research* 14: 14-20, 2000.

258. Harris N, Cronin, JB, Hopkins, WG, and Hansen, KT. Squat Jump Training at Maximal Power Loads V Heavy Loads: Effect on Sprint Ability. *Journal of Strength and Conditioning Research* 22: 1742-1749, 2008.

259. Harris N, Cronin, JB, Taylor, K-L, Boris, J, and Sheppard, J. Understanding Position Transducer Technology for Strength and Conditioning Practioners. *Strength and Conditioning Journal* 32: 66-79, 2010.

260. Harris NK, Cronin ,J.B., Hopkins, W.G. and Hansen, K.T. Relationship between Sprint Times and the Strength/Power Outputs of a Machine Squat Jump. *Journal of Strength and Conditioning Research* 22: 691-698, 2008.

261. Hart NH, Nimphius S, Spiteri T, and Newton RU. Leg Strength and Lean Mass Symmetry Influences Kicking Performance in Australian Football. *Journal of Sports Science and Medicine* 13: 157, 2014.

262. Hart NH, Spiteri T, Lockie RG, Nimphius S, and Newton RU. Detecting Deficits in Change of Direction Performance Using the Preplanned Multidirectional Australian Football League Agility Test. *Journal of Strength and Conditioning Research* 28: 3552-3556, 2014.

263. Hartmann H, Wirth K, Mickel C, Keiner M, Sander A, and Yaghobi D. Stress for Vertebral Bodies and Intervertebral Discs with Respect to Squatting Depth. *Journal of Functional Morphology and Kinesiology* 1: 254-268, 2016.

264. Hatfield GL, Charlton JM, Cochrane CK, Hammond CA, Napier C, Takacs J, Krowchuk NM, and Hunt MA. The Biomechanical Demands on the Hip During Progressive Stepping Tasks. *The Journal of Strength & Conditioning Research* 31: 3444-3453, 2017.

265. Hay D, de Souza, VA, and Fukashiro, S. Human Bilateral Deficit During Dynamic Multi-Joint Leg Press Movement, in: *ISB XXth Congress*. Cleveland, Ohio, 2005, p 551.

266. Hedrick A. Manipulating Strength and Conditioning Programs to Improve Athleticism. *Strength & Conditioning Journal* 24: 71-74, 2002.

267. Hefzy M and Harrison L. Co-Activation of the Hamstrings and Quadriceps During the Lunge Exercise. *Biomedical Sciences Instrumentation* 33: 360-365, 1997.

268. Hendy AM. Cross Education and Immobilisation: Mechanisms and Implications for Injury Rehabilitation. *Journal of Science and Medicine in Sport* 15: 94, 2012.

269. Henneman E. Relation between Size of Neurons and Their Susceptibility to Discharge. *Science* 126: 1345-1347, 1957.

270. Henry GJ, Dawson B, Lay BS, and Young WB. Relationships between Reactive Agility Movement Time and Unilateral Vertical, Horizontal and Lateral Jumps. *Journal of strength and conditioning research/National Strength & Conditioning Association*, 2013.

271. Hermassi S. Effects of 8-Week in-Season Upper and Lower Limb Heavy Resistance Training on the Peak Power, Throwing Velocity, and Sprint Performance of Elite Male Handball Players. *Journal of Strength and Conditioning Research* 25: 2424, 2011.

272. Hewett TE, Lindenfeld TN, Riccobene JV, and Noyes FR. The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes. *American Journal of Sports Medicine* 27: 699-706, 1999.

273. Hewit J, Cronin J, Button C, and Hume P. Understanding Deceleration in Sport. *Strength and Conditioning Journal* 33: 47-52, 2011.

274. Hewit JK, Cronin JB, and Hume PA. Kinematic Factors Affecting Fast and Slow Straight and Change-of-Direction Acceleration Times. *Journal of Strength and Conditioning Research* 27: 69-75, 2013.

275. Hickson R, Hidaka K, Foster C, Falduto M, and Chatterton Jr R. Successive Time Courses of Strength Development and Steroid Hormone Responses to Heavy-Resistance Training. *Journal of Applied Physiology* 76: 663-670, 1994.

276. Higbie EJ, Cureton, K.J., Warren III, G.L. and Prior, B.M. Effects of Concentric and Eccentric Training on Muscle Strength, Cross-Sectional Area and Neural Activation. *Journal of Applied Physiology* 81: 2173-2181, 1996.

277. Hoffman J and Kang J. Strength Changes During an in-Season Resistance-Training Program for Football. *The Journal of Strength & Conditioning Research* 17: 109-114, 2003.

278. Hoffman JR, Cooper, J., Wendell, M., and Kang, J. Comparison of Olympic Vs Traditional Power Lifting Training Programs in Football Players. *Journal of Strength and Conditioning Research* 18: 129-135, 2004.

279. Hoffman JR, Fry, A.C., Howard, R., Maresh, C.M., and Kraemer, W.J. Strength, Speed and Endurance Changes During the Course of a Division I Basketball Season. *Journal of Applied Sport Science Research* 5: 144-149, 1991.

280. Hoffman JR, Ratamess, N.A., Klatt, M., Faigenbaum, A.D., Ross, R.E., Transhina, N.M., McCurley, R.C., Kang, J. and Kraemer, W.J. Comparison between Different Off-Season Resistance Training Programs in Division Iii American College Football Players. *Journal of Strength and Conditioning Research* 23: 11-19, 2009.

281. Holsgaard Larsen A, Puggaarg, L., Hamalainen, U. and Aagaard, P. Comparison of Ground Reaction Forces and Antagonist Muscle Coactivation During Stair Walking with Ageing. *Journal of Electromyography and Kinesiology* 18: 568-580, 2008.

282. Hopkins JT, Ingersoll, C.D., Sandrey, M.A. and Bleggi, S.D. An Electromyographic Comparison of 4 Closed Chain Exercises. *Journal of Athletic Training* 34: 353-357, 1999.

283. Hopkins W. Spreadsheets for Analysis of Validity and Reliability. *Sportscience* 19: 36-42, 2015.

284. Hopkins W, Marshall S, Batterham A, and Hanin J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine and Science in Sports and Exercise* 41: 3, 2009.

285. Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Medicine* 30: 1-15, 2000.

286. Hopkins WG. Reliability from Consecutive Pairs of Trials (Excel Spreadsheet). Available from: http://www.sportsci.org/resources/stats/. Accessed 1st May 2017., 2006.

287. Hopkins WG. Spreadsheets for Analysis of Controlled Trials, with Adjustment for a Subject Characteristic. *Sportscience* 10: 46-50, 2006.

288. Hopkins WG, Hawley JA, and Burke LM. Design and Analysis of Research on Sport Performance Enhancement. *Medicine and Science in Sports and Exercise* 31: 472-485, 1999.

289. Hopper DM. Functional Recovery after Anterior Cruciate Ligament Reconstruction: A Longitudinal Perspective. *Archives of Physical Medicine and Rehabilitation* 89: 1535, 2008.

290. Hori N, and Andrews, W.A. Reliability of Velocity, Force and Power Obtained from the Gymaware Optical Encoder During Countermovement Jump with and without External Load. *Journal of Australian Strength and Conditioning* 17: 12-17, 2009.

291. Hori N, Newton RU, Kawamori N, McGuigan MR, Kraemer WJ, and Nosaka K. Reliability of Performance Measurements Derived from Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency. *Journal of Strength and Conditioning Research* 23: 874-882, 2009.

292. Hori N, Newton, R.U. and Stone, M.H. Weightlifting Exercises Enhance Athletic Performance That Requires High-Load Speed Strength. *Strength and Conditioning Journal* 27: 50-55, 2005.

293. Hori N, Newton, R.U., Andrews, W.A., Kawamori, N., McGuigan, M.R. and Nosaka, K. Comparison of Four Different Methods to Measure Power Output During the Hang Power Clean and the Weighted Jump Squat. *Journal of Strength and Conditioning Research* `21: 314-320, 2007.

294. Hori N, Newton, R.U., Nosaka, K. and McGuigan, M.R. Comparison of Different Methods of Determining Power Output in Weightlifting Exercises. *Strength and Conditioning Journal* 28: 34-40, 2006.

295. Hori N, Newton, RU, Andrews, WA, Kawamori, N, McGuigan, MR and Nosaka, K. Does Performance of Hang Power Clean Differentiate Performance of Jumping, Sprinting and Changing of Direction? *Journal of Strength and Conditioning Research* 22: 412-418, 2008.

296. Hornsby WG, Gentles JA, Haff GG, Stone MH, Buckner SL, Dankel SJ, Bell ZW, Abe T, and Loenneke JP. What Is the Impact of Muscle Hypertrophy on Strength and Sport Performance? *Strength and Conditioning Journal* 40: 99-111, 2018.

297. Howard J and Enoka R. Maximum Bilateral Contractions Are Modified by Neurally Mediated Interlimb Effects. *J Appl Physiol* 70: 306-316, 1991.

298. Howe L, Goodwin J, and Blagrove R. The Integration of Unilateral Strength Training for the Lower Extremity within an Athletic Performance Programme. *Professional Strength and Conditioning Journal* 33: 19-24, 2014.

299. Hunter GR, Hilyer, J. and Forster, M.A. Changes in Fitness During 4 Years of Intercollegiate Basketball. *Journal of Strength and Conditioning Research* 7: 26-29, 1993.

300. Hunter JP, Marshall, R.N., and McNair, P.J. Relationships between Ground Reaction Force Impulse and Kinematics of Sprint-Running Acceleration. *Journal of Applied Biomechanics* 21: 31-43, 2005.

301. Hydock D. The Split Position: Sport Specificity with a Barbell. *Strength and Conditioning Journal*: 56-59, 1997.

302. Ireland MJ, Willson, J.D., Ballantyne, B.T., and McClay Davis, I. Hip Strength in Females with and without Patellofemoral Pain. *Journal of Orthopaedic and Sports Physical Therapy* 33: 671-676, 2003.

303. Issurin VB. Training Transfer: Scientific Background and Insights for Practical Application. *Sports Medicine* 43: 675, 2013.

304. Jacobs RR. Intermuscular Coordination in a Sprint Push-Off. *Journal of Biomechanics* 25: 953-965.

305. Jakobi JM and Chilibeck PD. Bilateral and Unilateral Contractions: Possible Differences in Maximal Voluntary Force. *Canadian Journal of Applied Physiology* 26: 12-33, 2001.

306. Jarvis S, Sullivan LO, Davies B, Wiltshire H, and Baker JS. Interrelationships between Measured Running Intensities and Agility Performance in Subelite Rugby Union Players. *Research in Sports Medicine* 17: 217-230, 2009.

307. Jensen RL. Hamstring Electromyographic Response of the Back Squat at Different Knee Angles During Eccentric and Concentric Phases. 2000.

308. JJ. K. Strength, Power, and Speed Qualities in English Junior Elite Rugby League Players. *Journal of Strength and Conditioning Research* 27: 2414-2419, 2013.

309. Johnston RD, Gabbett TJ, Jenkins DG, and Hulin BT. Influence of Physical Qualities on Post-Match Fatigue in Rugby League Players. *Journal of Science and Medicine in Sport* 18: 209-213, 2015.

310. Jones B. Physical Qualities of International Female Rugby League Players by Playing Position. *Journal of Strength and Conditioning Research* 30: 1333, 2016.

311. Jones MT, Ambegaonkar JP, Nindl BC, Smith JA, and Headley SA. Effects of Unilateral and Bilateral Lower-Body Heavy Resistance Exercise on Muscle Activity and Testosterone Responses. *Journal of Strength and Conditioning Research* 26: 1094-1100, 2012.

312. Jones P, Bampouras T, and Marrin K. An Investigation into the Physical Determinants of Change of Direction Speed. *Journal of Sports Medicine and Physical Fitness* 49: 97-104, 2009.

313. Jones PA, and Bampouras, T.M. A Comparison of Isokinetic and Functional Methods of Assessing Bilateral Strength Imbalance. *Journal of Strength and Conditioning Research* 24: 1553-1558, 2010.

314. Jordan MJ, Aagaard P, and Herzog W. Rapid Hamstrings/Quadriceps Strength in Acl-Reconstructed Elite Alpine Ski Racers. *Medicine & Science in Sports & Exercise* 47: 109-119, 2015.

315. Jovanovic MaF, E.P. Researched Applications of Velocity Based Strength Training. *Journal of Australian Strength and Conditioning* 22: 58-69, 2014.

316. Kanehisa H and Miyashita M. Specificity of Velocity in Strength Training. *European Journal of Applied Physiology and Occupational Physiology* 52: 104-106, 1983.

317. Kawamori N, Nosaka K, and Newton RU. Relationships between Ground Reaction Impulse and Sprint Acceleration Performance in Team Sport Athletes. *Journal of Strength and Conditioning Research* 27: 568-573, 2013.

318. Kawamori N, Rossi, S.J., Justice, B.D., Haff, E.E., Pistille, E.E., O'Bryant, H.S., Stone, M.H. and Haff, G.G. Peak Force and Rate of Force Development During Isometric and Dynamic Mid-Thigh Clean Pulls Performed at Various Intensities. *Journal of Strength and Conditioning Research* 20: 488-491, 2006.

319. Kawamori NaN, R.U. Velocity Specificity of Resistance Training: Actual Movement Velocity Versus Intention to Move Explosively. *Strength and Conditioning Journal* 28: 86-91, 2006.

320. Keiner M, Sander A, Wirth K, and Schmidtbleicher D. Long-Term Strength Training Effects on Change-of-Direction Sprint Performance. *Journal of Strength and Conditioning Research* 28: 223-231, 2014.

321. Kellis E, Arambatzi F, and Papadopoulos C. Effects of Load on Ground Reaction Force and Lower Limb Kinematics During Concentric Squats. *Journal of Sports Sciences* 23: 1045-1055, 2005.

322. Keogh J. Lower-Body Resistance Training: Increasing Functional Performacne with Lunges. *Strength and Conditioning Journal* 21: 62-72, 1999.

323. Khuu A, Foch E, and Lewis CL. Not All Single Leg Squats Are Equal: A Biomechanical Comparison of Three Variations. *International Journal of Sports Physical Therapy* 11: 201-211, 2016.

324. Kim D, Unger J, Lanovaz JL, and Oates AR. The Relationship of Anticipatory Gluteus Medius Activity to Pelvic and Knee Stability in the Transition to Single-Leg Stance. *American Academy of Physical Medicine and Rehabilitation* 8: 138-144, 2016.

325. Kipp K, Harris, C.25 and Sabick, M.B. Lower Extremity Biomechanics During Weightlifting Exercise Vary across Joint and Load. *Journal of Strength and Conditioning Research* 25: 1229-1234, 2011.

326. Knapik JJ, Bauman, C.L., Jones, B.H., Harris, J.M. and Vaughan, L. Preseason Strength and Flexibility Imbalances in Female Collegiate Athletes. *American Journal of Sports Medicine* 19: 76-81, 1991.

327. Knudson DV. Correcting the Use of the Term “Power” in the Strength and Conditioning Literature. *Journal of Strength and Conditioning Research* 23: 1902-1908, 2009.

328. Kobayashi Y. Bilateral Asymmetry in Joint Torque During Squat Exercise Performed by Long Jumpers. *Journal of Strength and Conditioning Research* 24: 2826, 2010.

329. Kohmura Y, Aoki K, Yoshigi H, Sakuraba K, and Yanagiya T. Development of a Baseball-Specific Battery of Tests and a Testing Protocol for College Baseball Players. *Journal of Strength and Conditioning Research* 22: 1051-1058, 2008.

330. Kotzamanidis C, Chatzopoulos, D., Michailidis, C., Papalahovou, G. and Patikas, D. The Effect of a Combined High-Intensity Strength and Speed Training Program on the Running and Jumping Abilitiy of Soccer. *Journal of Strength and Conditioning Research* 19: 369-375, 2005.

331. Kraemer WJ, and Newton, R.U. Training for Muscular Power. *Physical Medicine and Rehabilitation Clinics of North America* 11: 341 - 368, 2000.

332. Kraemer WJ, and Ratamess, N.A. Fundamentals of Resistance Training: Progression and Exercise Prescription. *Medicine and Science in Sports and Exercise* 26: 674-688, 2004.

333. Kraemer WJ, Duncan ND, and Volek JS. Resistance Training and Elite Athletes: Adaptations and Program Considerations. *Journal of Orthopaedic & Sports Physical Therapy* 28: 110-119, 1998.

334. Krause DA, Jacons, R.S., Pilger, K.E., Sather, B.R., Sibunka, S.P. and Hollman, J.H. Electromyographic Analysis of the Gluteus Medius in Five Weight-Bearing Exercises. *Journal of Strength and Conditioning Research* 23: 2689-2694, 2009.

335. Kulas AS, Hortobágyi T, and DeVita P. Trunk Position Modulates Anterior Cruciate Ligament Forces and Strains During a Single-Leg Squat. *Clinical biomechanics* 27: 16-21, 2012.

336. Kuruganti U, and Seaman, K. The Bilateral Strength Deficit Is Present in Old, Young and Adolescent Females During Isokinetic Knee Extension and Flexion. *European Journal of Applied Physiology* 97: 322-326, 2006.

337. Kuruganti U and Murphy T. Bilateral Deficit Expressions and Myoelectric Signal Activity During Submaximal and Maximal Isometric Knee Extensions in Young, Athletic Males. *European journal of applied physiology* 102: 721-726, 2008.

338. Kvist J and Gillquist J. Sagittal Plane Knee Translation and Electromyographic Activity During Closed and Open Kinetic Chain Exercises in Anterior Cruciate Ligament-Deficient Patients and Control Subjects. *American Journal of Sports Medicine* 29: 72-82, 2001.

339. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, and Deluzio KJ. Neuromuscular and Lower Limb Biomechanical Differences Exist between Male and Female Elite Adolescent Soccer Players During an Unanticipated Side-Cut Maneuver. *American Journal of Sports Medicine* 35: 1888-1900, 2007.

340. Langford GA and McCurdy KW. Resistance Training for Elementary School Age Children. *Teaching Elementary Physical Education* 16: 39-44, 2005.

341. Langford GA, McCurdy KW, Doscher M, and Teetzel J. Effects of Single-Leg Resistance Training on Measurement of Jumping Performance in Ncaa Division Ii Women Volleyball Players. *International Journal of Volleyball Research* 1: 17, 1999.

342. Lauersen JB, Andersen TE, and Andersen LB. Strength Training as Superior, Dose-Dependent and Safe Prevention of Acute and Overuse Sports Injuries: A Systematic Review, Qualitative Analysis and Meta-Analysis. *British Journal of Sports Medicine*, 2018.

343. Lauersen JB, Bertelsen DM, and Andersen LB. The Effectiveness of Exercise Interventions to Prevent Sports Injuries: A Systematic Review and Meta-Analysis of Randomised Controlled Trials. *British Journal of Sports Medicine*: bjsports-2013-092538, 2013.

344. Lawrence MA and Carlson LA. Effects of an Unstable Load on Force and Muscle Activation During a Parallel Back Squat. *Journal of Strength and Conditioning Research* 29: 2949-2953, 2015.

345. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, and Davis IM. Core Stability Measures as Risk Factors for Lower Extremity Injury in Athletes. *Medicine & Science in Sports & Exercise* 36: 926-934, 2004.

346. Lesmes GR, Costill DL, Coyle EF, and Fink WJ. Muscle Strength and Power Changes During Maximal Isokinetic Training. *Med Sci Sports* 10: 266-269, 1978.

347. Little T and Williams A. Specificity of Acceleration, Maximum Speed and Agility in Professional Soccer Players, in: *Science and Football V*. T Reilly, Cabri, J. and Araujo, D., ed. London: Routledge, 2005, pp 276-283.

348. Lloyd DG. Rationale for Training Programs to Reduce Anterior Cruciate Ligament Injuries in Australian Football. *Journal of Orthopaedic & Sports Physical Therapy* 31: 645-654, 2001.

349. Lockie RG, Callaghan SJ, Berry SP, Cooke ER, Jordan CA, Luczo TM, and Jeffriess MD. Relationship between Unilateral Jumping Ability and Asymmetry on Multidirectional Speed in Team Sport Athletes. *Journal of Strength and Conditioning Research*, 2014.

350. Lockie RG, Murphy AJ, Knight TJ, and Janse de Jonge XA. Factors That Differentiate Acceleration Ability in Field Sport Athletes. *Journal of Strength and Conditioning Research* 25: 2704-2714, 2011.

351. Lockie RG, Murphy AJ, Schultz AB, Knight TJ, and Janse de Jonge XA. The Effects of Different Speed Training Protocols on Sprint Acceleration Kinematics and Muscle Strength and Power in Field Sport Athletes. *Journal of Strength and Conditioning Research* 26: 1539-1550, 2012.

352. Lockie RG, Risso FG, Lazar A, Giuliano DV, Stage AA, Liu TM, Beiley MD, Hurley JM, Torne IA, and Stokes JJ. Between-Leg Mechanical Differences as Measured by the Bulgarian Split-Squat: Exploring Asymmetries and Relationships with Sprint Acceleration. *Sports* 5: 65, 2017.

353. Lockie RG, Schultz AB, Callaghan SJ, and Jeffriess MD. The Effects of Traditional and Enforced Stopping Speed and Agility Training on Multidirectional Speed and Athletic Function. *Journal of Strength and Conditioning Research* 28: 1538-1551, 2014.

354. Lockie RG, Schultz AB, Callaghan SJ, and Jeffriess MD. The Relationship between Dynamic Stability and Multidirectional Speed. *Journal of Strength and Conditioning Research* 30: 3033-3043, 2016.

355. Lockie RG, Schultz AB, Callaghan SJ, Jeffriess MD, and Berry SP. Reliability and Validity of a New Test of Change-of-Direction Speed for Field-Based Sports: The Change-of-Direction and Acceleration Test (Codat). *Journal of Sports Science and Medicine* 12: 88, 2013.

356. Lockie RG, Schultz AB, Jeffriess MD, and Callaghan SJ. The Relationship between Bilateral Differences of Knee Flexor and Extensor Isokinetic Strength and Multi-Directional Speed. *Isokinetics and Exercise Science* 20: 211, 2012.

357. Lorenz D. Targeting the Hips to Help Prevent Anterior Knee Pain. *Strength and Conditioning Journal* 28: 32-37, 2006.

358. Luera MJ, Stock MS, and Chappell AD. Electromyographic Amplitude Vs. Concentric and Eccentric Squat Force Relationships for Monoarticular and Biarticular Thigh Muscles. *Journal of Strength and Conditioning Research* 28: 328-338, 2014.

359. Lynn SK, and Noffal, G.J. Lower Extremity Biomechanics During a Regular and Counterbalanced Squat. *Journal of Strength and Conditioning Research* 26: 2417-2425, 2012.

360. Lyttle AD, Wilson, G.J. and Ostrowski, K.J. Enhancing Performance: Maximal Power Versus Combined Weights and Plyometrics Training. *Journal of Strength and Conditioning Research* 10: 173-179, 1996.

361. MacDougall J, Ward G, Sale D, and Sutton J. Biochemical Adaptation of Human Skeletal Muscle to Heavy Resistance Training and Immobilization. *Journal of Applied Physiology* 43: 700-703, 1977.

362. Makaruk H, Winchester JB, Sadowski J, Czaplicki A, and Sacewicz T. Effects of Unilateral and Bilateral Plyometric Training on Power and Jumping Ability in Women. *Journal of Strength and Conditioning Research* 25: 3311-3318, 2011.

363. Makaruk H, Winchester, JB, Sadowski, J, Czaplicki, A and Sacewicz, T. Effects of Unilateral and Bilateral Plyometric Training on Power and Jumping Ability in Women. *Journal of Strength and Conditioning Research* 25: 3311-3318, 2011.

364. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, and Garrett Jr W. Effectiveness of a Neuromuscular and Proprioceptive Training Program in Preventing Anterior Cruciate Ligament Injuries in Female Athletes: 2-Year Follow-Up. *American Journal of Sports Medicine* 33: 1003-1010, 2005.

365. Mann JB, Ivey PA, Mayhew JL, Schumacher RM, and Brechue WF. Relationship between Agility Tests and Short Sprints: Reliability and Smallest Worthwhile Difference in National Collegiate Athletic Association Division-I Football Players. *Journal of Strength and Conditioning Research* 30: 893-900, 2016.

366. Mann JB, Ivey PA, and Sayers SP. Velocity-Based Training in Football. *Strength and Conditioning Journal* 37: 52-57, 2015.

367. Markovic G. Poor Relationships between Strength and Power Qualities and Agility Performance. *Journal of Sports Medicine and Physical Fitness* 47: 276-283, 2007.

368. Marshall BM. Biomechanical Factors Associated with Time to Complete a Change of Direction Cutting Maneuver. *Journal of Strength and Conditioning Research* 28: 2845, 2014.

369. Maulder PS. Dominant Limb Asymmetry Associated with Prospective Injury Occurrence. *South African Journal for Research in Sport, Physical Education and Recreation* 35: 121-131, 2013.

370. Mausehund L, Skard AE, and Krosshaug T. Muscle Activation in Unilateral Barbell Exercises: Implications for Strength Training and Rehabilitation. *Journal of strength and conditioning research* 4, 2018.

371. Mayhew JL, Piper, F.C., Schwegler, T.M., and Ball, T.E., . Contributions of Speed, Agility and Body Composition to Anaerobic Power Measurement in College Football Players. *Journal of Applied Sport Science Research* 3: 101-106, 1989.

372. McBride J, Cormie, P. and Deane, R. Isometric Squat Force Output and Muscle Activity in Stable and Unstable Conditions. *Journal of Strength and Conditioning Research* 20: 915-918, 2006.

373. McBride J, Kirby, TJ, Haines, TL, and Skinner, J. Relationship between Relative Net Vertical Impulse and Jump Height in Jump Squats Performed to Various Squat Depths and with Various Loads. *International Journal of Sports Physiology and Performance* 5: 484-496, 2010.

374. McBride J, Skinner J, Schafer P, Haines T, and Kirby T. Comparison of Kinetic Variables and Muscle Activity During a Squat Vs. A Box Squat. *Journal of Strength and Conditioning Research* 24: 3195-3199, 2010.

375. McBride JM, Blow, D., Kirby, T.J., Haines, T.L., Dayne, A.M. and Travis-Triplett, N. Relationship between Maximal Squat Strength and Five, Ten, and Forty Yard Sprint Times. *Journal of Strength and Conditioning Research* 23: 1633-1636, 2009.

376. McBride JM LT, Dayne AM, and Haines TL, and Kirby TJ. Effect of Absolute and Relative Loading on Muscle Activity During Stable and Unstable Squatting. *International Journal of Sports Physiology and Performance* 5: 177-183, 2010.

377. McBride JM, Triplett-McBride, T., Davie, A. and Newton, R.U. A Comparison of Strength and Power Characteristics between Power Lifters, Olympic Lifters and Sprinters. *Journal of Strength and Conditioning Research* 13: 58-66, 1999.

378. McBride JM, Triplett-McBride, T., Davie, A. and Newton, R.U. The Effect of Heavy- Vs Light-Load Jump Squats on the Development of Strength, Power and Speed. *Journal of Strength and Conditioning Research* 16: 75-82, 2002.

379. McCaw STaM, D.R. Stance Width and Bar Load Effects on Leg Muscle Activity During the Parallel Squat. *Medicine and Science in Sports and Exercise* 31: 428-436, 1999.

380. McClellan T and Stone WJ. A Survey of Football Strength and Conditioning Programs for Division I Ncaa Universities. *Strength and Conditioning Journal* 8: 34-37, 1986.

381. McCormick BT, Hannon JC, Newton M, Shultz B, Detling N, and Young WB. The Effects of Frontal- and Sagittal-Plane Plyometrics on Change-of-Direction Speed and Power in Adolescent Female Basketball Players. *International Journal of Sports Physiology and Performance* 11, 2015.

382. McCurdy K. Technique, Variation, and Progression of the Rear-Foot-Elevated Split Squat. *Strength and Conditioning Journal* 39: 93, 2017.

383. McCurdy K, Kutz M, O'Kelley E, Langford G, and Ernest J. External Oblique Activity During the Unilateral and Bilateral Free Weight Squat. *Clinical Kinesiology* 64: 16-21, 2010.

384. McCurdy K and Langford G. Comparison of Unilateral Squat Strength between the Dominant and Non-Dominant Leg in Men and Women. *Journal of Sports Science and Medicine* 4: 153-159, 2005.

385. McCurdy K, Langford, G.A., Cline, A.L., Doscher, M. and Hoff, R. The Reliability of 1- and 3rm Tests of Unilateral Strength in Trained and Untrained Men and Women. *Journal of Sports Science and Medicine* 3: 190-196, 2004.

386. McCurdy K, O'Kelley, E., Kutz, M., Langford, G., Ernest, J. and Torres, M. Comparison of Lower Extremity Emg between the 2-Leg Squat and Modified Single Leg Squat in Female Athletes. *Journal of Sport Rehabilitation* 19: 57-70, 2010.

387. McCurdy K, Walker J, Saxe J, and Woods J. The Effect of Short-Term Resistance Training on Hip and Knee Kinematics During Vertical Drop Jumps. *Journal of Strength and Conditioning Research* 26: 1257-1264, 2012.

388. McCurdy KaC, C. Unilateral Support Resistance Training Incorporating the Hip and Knee. *Strength and Conditioning Journal* 25: 45-51, 2003.

389. McCurdy KW, Langford, G.A., Doscher, M.W., Wiley, L.P. and Mallard, K.G. The Effects of Short-Term Unilateral and Bilateral Lower-Body Resistance Training on Measures of Strength and Power. *Journal of Strength and Conditioning Research* 19: 9-15, 2005.

390. Mccurdy KW, Walker JL, Langford GA, Kutz MR, Guerrero JM, and Mcmillan J. The Relationship between Kinematic Determinants of Jump and Sprint Performance in Division I Women Soccer Players. *The Journal of Strength & Conditioning Research* 24: 3200-3208, 2010.

391. McElveen MT, Riemann, B.L., abnd Davies, G.J. Bilateral Comparison of Propulsion Mechanics During Single-Leg Vertical Jumping. *Journal of Strength and Conditioning Research* 24: 375-381, 2010.

392. McEvoy KP and Newton RU. Baseball Throwing Speed and Base Running Speed: The Effects of Ballistic Resistance Training. *Journal of Strength and Conditioning Research* 12: 216-221, 1998.

393. McGrath TM, Waddington G, Scarvell JM, Ball NB, Creer R, Woods K, and Smith D. The Effect of Limb Dominance on Lower Limb Functional Performance–a Systematic Review. *Journal of Sports Sciences* 34: 289-302, 2016.

394. McGuigan M. Resistance Training: Not All Programs Are Created Equal. 2015.

395. McGuigan MR and Wilson BD. Biomechanical Analysis of the Deadlift. *Journal of Strength and Conditioning Research* 10: 250-255, 1996.

396. McGuigan MR, Wright GA, and Fleck SJ. Strength Training for Athletes: Does It Really Help Sports Performance? *International Journal of Sports Physiology and Performance* 7: 2-5, 2012.

397. McKenna J and Muckle A. Rugby Union Players' Resistance Training - an Application of the Transtheoretical Model, in: *Science and Football Iii*. T Reilly, Bangsbo, J. and Hughes, M., ed. London: E and F.N. Spon, 1997, pp 94-97.

398. McLean SG, Huang, X. and van den Bogert, A.J. Association between Lower Extremity Posture at Contact and Peak Knee Valgus Moment During Sidestepping: Implications for Acl Injury. *Clinical Biomechanics* 20: 863-870, 2005.

399. McMahon JJ, Stapley JT, Suchomel TJ, and Comfort P. Relationships between Lower Body Muscle Structure and Isometric Mid-Thigh Pull Peak Force. *Journal of Trainology* 4: 43-48, 2015.

400. McMahon JJ, Turner A, and Comfort P. Relationships between Lower Body Muscle Structure and Maximal Power Clean Performance. *Journal of Trainology* 4: 32-36, 2015.

401. McMaster DT, Gill N, Cronin J, and McGuigan M. The Development, Retention and Decay Rates of Strength and Power in Elite Rugby Union, Rugby League and American Football: A Systematic Review. *Sports Medicine* 43: 367-384, 2013.

402. McMaster DT, Gill N, Cronin J, and McGuigan M. A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine* 44: 603-623, 2014.

403. Meir R, Colla, P and Milligan C. Impact of the 10-Meter Rule Change on Professional Rugby League: Implications for Training. *Strength and Conditioning Journal* 23: 42-46, 2001.

404. Mero A. Force-Time Characteristics and Running Velocity of Male Sprinters During the Acceleration Phase of Sprinting. *Research Quarterly for Exercise and Sport* 59: 94-98, 1988.

405. Mero A, and Kovi, P.A. Force-, Emg-, and Elastic-Velocity Relationships at Submaximal, Maximal and Supramazimal Running Speeds in Sprinters. *European Journal of Applied Physiology* 55: 553-561, 1986.

406. Mero A, and Kovi, P.A. Reaction Time and Electromyographic Activity During a Sprint Start. *European Journal of Applied Physiology* 61: 73-80, 1990.

407. Mero A, Komi PV, and Gregor RJ. Biomechanics of Sprint Running. A Review. *Sports Med* 13: 376-392, 1992.

408. Meylan C, McMaster T, Cronin J, Mohammad NI, and Rogers C. Single-Leg Lateral, Horizontal, and Vertical Jump Assessment: Reliability, Interrelationships, and Ability to Predict Sprint and Change-of-Direction Performance. *Journal of Strength and Conditioning Research* 23: 1140-1147, 2009.

409. Miller MG, Herniman, J.J., Ricard, M.D., Cheatham, C.C., Michael, T.J. The Effects of a 6-Week Plyometric Training Program on Agility. *Journal of Sports Science and Medicine* 5: 459-465, 2006.

410. Milner-Brown H and Lee R. Synchronization of Human Motor Units: Possible Roles of Exercise and Supraspinal Reflexes. *Clinical Neurophysiology* 38: 245-254, 1975.

411. Moffroid MT and Whipple RH. Specificity of Speed of Exercise. *Physical Therapy* 50: 1692-1700, 1970.

412. Moir G, Button C, Glaister M, and Stone MH. Influence of Familiarization on the Reliability of Vertical Jump and Acceleration Sprinting Performance in Physically Active Men. *Journal of strength and conditioning research* 18: 276-280, 2004.

413. Morin J-B, Slawinski J, Dorel S, Couturier A, Samozino P, Brughelli M, and Rabita G. Acceleration Capability in Elite Sprinters and Ground Impulse: Push More, Brake Less? *Journal of biomechanics* 48: 3149-3154, 2015.

414. Morin JB. Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. *Frontiers in Physiology* 6: 404, 2015.

415. Moritani T. Neural Factors Versus Hypertrophy in the Time Course of Muscle Strength Gain. *American Journal of Physical Medicine* 58: 115-130, 1979.

416. Morland B, Bottoms L, Sinclair J, and Bourne N. Can Change of Direction Speed and Reactive Agility Differentiate Female Hockey Players? *International Journal of Performance Analysis in Sport* 13: 510-521, 2013.

417. Morrison W and Edwards D. A Temporal Analysis of the Squat Lift at the Australian Power Lifting Championships Melbourne. Presented at ISBS-Conference Proceedings Archive, 1991.

418. Morrissey MC, Harman EA, and Johnson MJ. Resistance Training Modes: Specificity and Effectiveness. *Medicine and Science in Sports and Exercise* 27: 648-660, 1995.

419. Moss B, Refsnes P, Abildgaard A, Nicolaysen K, and Jensen J. Effects of Maximal Effort Strength Training with Different Loads on Dynamic Strength, Cross-Sectional Area, Load-Power and Load-Velocity Relationships. *European journal of applied physiology and occupational physiology* 75: 193-199, 1997.

420. Mroz Jr TJ. *Prevalence of Bilateral Deficit in Trained Men.* Southeastern Louisiana University, 2013.

421. Mullican K and Nijem R. Are Unilateral Exercises More Effective Than Bilateral Exercises? *Strength and Conditioning Journal* 38: 68-70, 2016.

422. Munn J, Herbert RD, and Gandevia SC. Contralateral Effects of Unilateral Resistance Training: A Meta-Analysis. *Journal of Applied physiology* 96: 1861-1866, 2004.

423. Munro AGaH, L.C. Between-Session Reliability of Four Hop Tests and the Agility T-Test. *Journal of Strength and Conditioning Research* 25: 1470-1477, 2011.

424. Murphy AJ, Lockie RG, and Coutts AJ. Kinematic Determinants of Early Acceleration in Field Sport Athletes. *Journal of sports science & medicine* 2: 144, 2003.

425. Myer GD, Ford, K.R., Palumbo, J.P. and Hewett, T.E. Neuromuscular Training Improves Performance and Lower-Extremity Biomechanics in Female Athletes. *Journal of Strength and Conditioning Research* 19: 51-60, 2005.

426. Myer GD, Martin Jr L, Ford KR, Paterno MV, Schmitt LC, Heidt Jr RS, Colosimo A, and Hewett TE. No Association of Time from Surgery with Functional Deficits in Athletes after Anterior Cruciate Ligament Reconstruction: Evidence for Objective Return-to-Sport Criteria. *American Journal of Sports Medicine* 40: 2256-2263, 2012.

427. Myklebust G, Engebretsen L, Brækken IH, Skjølberg A, Olsen O-E, and Bahr R. Prevention of Anterior Cruciate Ligament Injuries in Female Team Handball Players: A Prospective Intervention Study over Three Seasons. *Clinical journal of sport medicine* 13: 71-78, 2003.

428. Narici MV, Roi G, Landoni L, Minetti A, and Cerretelli P. Changes in Force, Cross-Sectional Area and Neural Activation During Strength Training and Detraining of the Human Quadriceps. *European journal of applied physiology and occupational physiology* 59: 310-319, 1989.

429. Neptune RR, Wright, I.C. and Van Den Bogert, A.J. Muscle Coordination and Funciton During Cutting Movements. *Medicine and Science in Sports and Exercise* 31: 294-302, 1999.

430. Newman MA, Tarpenning, K.M. and Marino, F.E. Relationships between Isokinetic Knee Strength, Single-Sprint Performance and Repeated-Sprint Ability in Football Players. *Journal of Strength and Conditioning Research* 18: 867-872, 2004.

431. Newton R and Dugan E. Application of Strength Diagnosis. *Strength and Conditioning Journal* 24: 50-59, 2002.

432. Newton R, Gerber, A, Nimphius, S, Shim, JK, Doan, BK, Robertson, M, Pearson, DR, Craig, BW, Hakkinen, K and Kraemer, W. Determination of Functional Strength Imbalance of the Lower Extremities. *Journal of Strength and Conditioning Research* 20: 971-977, 2006.

433. Newton R and Kraemer W. Developing Explosive Muscular Power: Implications for a Mixed Methods Training Strategy *Strength and Conditioning Journal* October: 20-31, 1994.

434. Nijem RM and Galpin AJ. Unilateral Versus Bilateral Exercise and the Role of the Bilateral Force Deficit. *Strength and Conditioning Journal* 36: 113-118, 2014.

435. Nimphius S, Callaghan SJ, Spiteri T, and Lockie RG. Change of Direction Deficit: A More Isolated Measure of Change of Direction Performance Than Total 505 Time. *Journal of strength and conditioning research* 30: 3024-3032, 2016.

436. Nimphius S, Callaghan, S.J., Bezodis, N.E. and Lockie, R.G. Change of Direction and Agility Tests: Challenging Our Current Measures of Performance. *Strength and Conditioning Journal* 40: 26, 2018.

437. Nimphius S, Geib G, Spiteri T, and Carlisle D. Change of Direction Deficit" Measurement in Division I American Football Players. *Journal of Australian Strength and Conditioning* 21: 115-117, 2013.

438. Nimphius S, McGuigian, M.R. and Newton, R.U. Relationship between Strength, Power, Speed, and Change of Direction Performance of Female Softball Players. *Journal of Strength and Conditioning Research* 24: 885-895, 2010.

439. Nimphius S, McGuigian, M.R. and Newton, R.U. Changes in Muscle Architecture and Performance During a Competitive Season in Female Softball Players. *Journal of Strength and Conditioning Research* 26: 2655-2666, 2012.

440. Noorkõiv M, Nosaka K, and BLAZEVICH A. Neuromuscular Adaptations Associated with Knee Joint Angle-Specific Force Change. 2014.

441. Nuzzo JL, McBride, J.M., Cormie, P. and McCaulley, G.O. Relationship between Countermovement Jump Performance and Multi-Joint Isometric and Dynamic Tests of Strength. *Journal of Strength and Conditioning Research* 22: 699-707, 2008.

442. Nuzzo JL, McCaulley, G.O., Cormie, P., Cavill, M.J. and McBride, J.M. Trunk Muscle Activity During Stability Ball and Free Weight Exercises. *Journal of Strength and Conditioning Research* 22: 95-102, 2008.

443. Oliver JL and Meyers RW. Reliability and Generality of Measures of Acceleration, Planned Agillity and Reactive Agility. *International Journal of Sports Physiology and Performance* 4: 345-354, 2009.

444. Orchard J, Marsden, J., Lord, S. and Garlick, D. Preseason Hamstring Muscle Weakness Associated with Hamstring Muscle Injury in Australian Footballers. *American Journal of Sports Medicine* 25: 81-85, 1997.

445. Orchard JW, Seward H, and Orchard JJ. Results of 2 Decades of Injury Surveillance and Public Release of Data in the Australian Football League. *American Journal of Sports Medicine* 41: 734-741, 2013.

446. Owen A, Dunlop G, Rouissi M, Chtara M, Paul D, Zouhal H, and Wong DP. The Relationship between Lower-Limb Strength and Match-Related Muscle Damage in Elite Level Professional European Soccer Players. *Journal of sports sciences*: 1-6, 2015.

447. Paoli A, Marcolin, G. and Petrone, N. The Effect of Stance Width on the Electromyographical Activity of Eight Superficial Thigh Muscles During Back Squat with Different Bar Loads. *Journal of Strength and Conditioning Research* 23: 246-250, 2009.

448. Paul DJ. Agility in Team Sports: Testing, Training and Factors Affecting Performance. *Sports Medicine* 46: 421, 2016.

449. Peterson MD, Alvar BA, and Rhea MR. The Contribution of Maximal Force Production to Explosive Movement among Young Collegiate Athletes. *The Journal of Strength & Conditioning Research* 20: 867-873, 2006.

450. Peyer KL, Pivarnik JM, Eisenmann JC, and Vorkapich M. Physiological Characteristics of National Collegiate Athletic Association Division I Ice Hockey Players and Their Relation to Game Performance. *J Strength Cond Res* 25: 1183-1192, 2011.

451. Ploutz LL, Tesch PA, Biro RL, and Dudley GA. Effect of Resistance Training on Muscle Use During Exercise. *Journal of Applied Physiology* 76: 1675-1681, 1994.

452. Poprawski B. Aspects of Strength, Power and Speed in Shot Put Training. *NSCA Journal* 9: 39-41, 1987.

453. Presswood L, Cronin J, Keogh JW, and Whatman C. Gluteus Medius: Applied Anatomy, Dysfunction, Assessment, and Progressive Strengthening. *Strength & Conditioning Journal* 30: 41-53, 2008.

454. Pyne D, Gardner A, Sheehan K, and Hopkins W. Fitness Testing and Career Progression in Afl Football. *Journal of Science and Medicine in Sport* 8: 321-332, 2005.

455. Pyne DB. Interpreting the Results of Fitness Testing. Presented at International Science and Football Symposium, 2003.

456. Rahmani A, Dalleau, G., Viale, F., Hautier, C.A. and Lacour, JR. Validity and Reliability of a Kinematic Device for Measuring the Force Developed During Squatting. *Journal of Applied Biomechanics* 16: 26-35, 2000.

457. Rahmani A, Viale F, Dalleau G, and Lacour J-R. Force/Velocity and Power/Velocity Relationships in Squat Exercise. *European Journal of Applied Physiology* 84: 227-232, 2001.

458. Randell AD, Cronin, J.B., Keogh, J.W.L., and Gill, N.D. Transference of Strength and Power Adaptation to Sports Performance - Horizontal and Vertical Force Production. *Strength and Conditioning Journal* 32: 100-106, 2010.

459. Rasch PJ and Morehouse LE. Effect of Static and Dynamic Exercises on Muscular Strength and Hypertrophy. *J Appl Physiol* 11: 29-34, 1957.

460. Reeder A. Ankle Muscle Activation During Unilateral and Bilateral Lower Body Strength Exercises. University of Akron, 2014.

461. Reiman MP, Bolgla LA, and Lorenz D. Hip Function's Influence on Knee Dysfunction: A Proximal Link to a Distal Problem. *Journal of Sport Rehabilitation* 18: 33, 2009.

462. Requena B, García I, Requena F, de Villarreal ES-S, and Cronin JB. Relationship between Traditional and Ballistic Squat Exercise with Vertical Jumping and Maximal Sprinting. *The Journal of Strength & Conditioning Research* 25: 2193-2204, 2011.

463. Richards J, Thewlis D, Selfe J, Cunningham A, and Hayes C. A Biomechanical Investigation of a Single-Limb Squat: Implications for Lower Extremity Rehabilitation Exercise. *Journal of Athletic Training* 43: 477-482, 2008.

464. Ritti-Dias RM, Avelar A, Salvador EP, and Cyrino ES. Influence of Previous Experience on Resistance Training on Reliability of One-Repetition Maximum Test. *Journal of Strength and Conditioning Research* 25: 1418-1422, 2011.

465. Robbins DW. Relationships between National Football League Combine Performance Measures. *Journal of Strength and Conditioning Research* 26: 226-231, 2012.

466. Robertson D, Wilson J, and St Pierre T. Lower Extremity Muscle Functions During Full Squats. *Journal of Applied Biomechanics* 24: 333-339, 2008.

467. Ronnestad B, Nymark, BS and Raastad, T. Effects of in-Season Strength Maintenance Training Frequency in Professional Soccer Players. *Journal of Strength and Conditioning Research* 25: 2653-2660, 2011.

468. Ronnestad BR, Kvamme NH, Sunde A, and Raastad T. Short-Term Effects of Strength and Plyometric Training on Sprint and Jump Performance in Professional Soccer Players. *Journal of Strength and Conditioning Research* 22: 773-780, 2008.

469. Roos PE. Motor Control Strategies During Double Leg Squat Following Anterior Cruciate Ligament Rupture and Reconstruction: An Observational Study. *Journal of Neuroengineering and Rehabilitation* 11: 19, 2014.

470. Rossi S, Buford, TW, Smith, DB, Kennel, R, Haff, EE and Haff, GG. Bilateral Comparision of Barbell Kinetics and Kinematics During a Weightlifting Competition. *International Journal of Sports Physiology and Performance* 2: 150-158, 2007.

471. Rouissi M, Chtara M, Owen A, Chaalali A, Chaouachi A, Gabbett T, and Chamari K. Effect of Leg Dominance on Change of Direction Ability Amongst Young Elite Soccer Players. *Journal of sports sciences* 34: 542-548, 2016.

472. Rutherford OM, and Jones, D.A. The Role of Learning and Coordination in Strength Training. *European Journal of Applied Physiology* 55: 100-105, 1986.

473. Saad M, Felicio, LR, de Lourdes, C, Liporaci, RF and Beviaqua-Grossi, D. Analysis of the Center of Pressure Displacement, Ground Reaction Force and Muscular Acticity During Step Exericses. *Journal of Electromyography and Kinesiology* 21: 712-718, 2011.

474. Saeterbakken AH and Fimland MS. Muscle Activity of the Core During Bilateral, Unilateral, Seated and Standing Resistance Exercise. *European Journal of Applied Physiology* 112: 1671-1678, 2012.

475. Salaj S and Markovic G. Specificity of Jumping, Sprinting, and Quick Change-of-Direction Motor Abilities. *Journal of Strength and Conditioning Research* 25: 1249-1255, 2011.

476. Sale DG. Neural Adaptation to Resistance Training. *Medicine and Science in Sports and Exercise* 20: S135-S145, 1988.

477. Sale DG. Neural Adaptation to Strength Training, in: *Strength and Power in Sport*. Oxford, UK: Blackwell, 1992.

478. Salem GK, Salinas, R. and Harding V. Bilateral Kinematic and Kinetic Analysis of the Squat Exercise after Anterior Cruciate Ligament Reconstruction. *Archives of Physical Medicine and Rehabilitation* 84: 1211-1216, 2003.

479. Sander A, Keiner M, Wirth K, and Schmidtbleicher D. Influence of a 2-Year Strength Training Programme on Power Performance in Elite Youth Soccer Players. *European Journal of Sport Science*: 1-7, 2012.

480. Santana JC. Single-Leg Training for 2-Legged Sports: Efficacy of Strength Development in Athletic Performance. *Strength and Conditioning Journal* 23: 35, 2001.

481. Sasaki Shogo S. The Relationship between Performance and Trunk Movement During Change of Direction. *Journal of Sports Science Medicine* 10: 112-118, 2011.

482. Sato K and Heise GD. Influence of Weight Distribution Asymmetry on the Biomechanics of a Barbell Back Squat. *The Journal of Strength & Conditioning Research* 26: 342-349, 2012.

483. Sayers MG. Influence of Test Distance on Change of Direction Speed Test Results. *Journal of Strength and Conditioning Research* 29: 2412-2416, 2015.

484. Schaub PA and Worrell TW. Emg Activity of Six Muscles and Vmo: Vl Ratio Determination During a Maximal Squat Exercise. *J Sport Rehabil* 4: 195-202, 1995.

485. Schellenberg F, Taylor WR, and Lorenzetti S. Towards Evidence Based Strength Training: A Comparison of Muscle Forces During Deadlifts, Goodmornings and Split Squats. *BMC Sports Science, Medicine and Rehabilitation* 9: 13, 2017.

486. Schilling BK, Falvo MJ, and Chiu LZ. Force-Velocity, Impulse-Momentum Relationships: Implications for Efficacy of Purposefully Slow Resistance Training. *Journal of Sports Science and Medicine* 7: 299-304, 2008.

487. Schoenfeld B. Strength and Hypertrophy Adaptations between Low- Vs. High-Load Resistance Training: A Systematic Review and Meta-Analysis. *Journal of Strength and Conditioning Research* 31: 3508-3523, 2017.

488. Schoenfield BJ. Squatting Kinematics and Kinetics and Their Application to Exercise Performance. *Journal of Strength and Conditioning Research* 24: 3497-2506, 2010.

489. Schütz P. Joint Angles of the Ankle, Knee, and Hip and Loading Conditions During Split Squats. *Journal of Applied Biomechanics* 30: 373, 2014.

490. Seitz LB, Reyes A, Tran TT, de Villarreal ES, and Haff GG. Increases in Lower-Body Strength Transfer Positively to Sprint Performance: A Systematic Review with Meta-Analysis. *Sports Medicine* 44: 1693-1702, 2014.

491. Sheehy P, Burdett, R.G., Irrgang, J.J. and VanSwearingen, J. An Electromyographic Study of Vastus Medialis Oblique and Vastus Lateralis Activity While Ascending and Descending Stairs. *Journal of Orthopaedic and Sports Physical Therapy* 27: 423-429, 1998.

492. Sheppard J, Cormack, S, Taylor, K, McGuigan, MR and Newton, RU. Assessing the Force-Velocity Characteristics of the Leg Extensors in Well-Trained Athletes: The Incremental Load Power Profile. *Journal of Strength and Conditioning Research* 22: 1320 - 1326, 2008.

493. Sheppard J, Cronin, JB, Gabbett, TJ, McGuigan MR. Relative Importance of Strength, Power and Anthropometric Measures to Jump Performance of Elite Volleyball Players. *Journal of Strength and Conditioning Research* 22: 758-765, 2008.

494. Sheppard J, Doyle, TLA, and Taylor, K-L. A Methodological and Performance Comparison of Free Weight and Smith-Machine Jump Squats. *Journal of Australian Strength and Conditioning* 16: 5-9, 2008.

495. Sheppard JM, Dawes JJ, Jeffreys I, Spiteri T, and Nimphius S. Broadening the View of Agility: A Scientific Review of the Literature. *Journal of Australian Strength and Conditioning* 22: 6-25, 2014.

496. Sheppard JM, Nolan, E. and Newton, R.U. Changes in Strength and Power Qualities over Two Years in Volleyball Players Transitioning from Junior to Senior National Team. *Journal of Strength and Conditioning Research* 26: 152-157, 2012.

497. Sheppard JM, Young, W.B., Doyle, T.L.A., Sheppard, T.A. and Newton, R.U. An Evaluation of a New Test of Reactive Agility and Its Relationship to Sprint Speed and Change of Direction Speed. *Journal of Science and Medicine in Sport* 9: 342-349, 2006.

498. Sheppard JMaY, W.B. Agility Literature Review: Classifications, Training and Testing. *Journal of Sports Sciences* 24: 919-932, 2006.

499. Shima N, Ishida K, Katayama K, Morotome Y, Sato Y, and Miyamura M. Cross Education of Muscular Strength During Unilateral Resistance Training and Detraining. *European journal of applied physiology* 86: 287-294, 2002.

500. Sierer SP, Battaglini CL, Mihalik JP, Shields EW, and Tomasini NT. The National Football League Combine: Performance Differences between Drafted and Nondrafted Players Entering the 2004 and 2005 Drafts. *Journal of Strength and Conditioning Research* 22: 6-12, 2008.

501. Siff MC, and Verkhoshanski, Y. *Supertraining: Strength Training for Sporting Excellence.* Johannesburg, South Africa: University of Witwatersrand, 1998.

502. Signorile JF, Weber, B., Roll, B., Caruso, J.F., Lowensteyn, I. and Perry, A.C. An Electromyographic Comparison of the Squat and Knee Extension Exercises. *Journal of Strength and Conditioning Research* 8: 178-183, 1994.

503. Simenz C, Dugan, CA and Ebben, WP. Strength and Conditioning Practices of National Basketball Association Strength and Conditioning Coaches. *Journal of Strength and Conditioning Research* 19: 495-504, 2005.

504. Simenz CJ, Garceau LR, Lutsch BN, Suchomel TJ, and Ebben WP. Electromyographical Analysis of Lower Extremity Muscle Activation During Variations of the Loaded Step-up Exercise. *Journal of Strength and Conditioning Research* 26: 3398-3405, 2012.

505. Škarabot J, Cronin N, Strojnik V, and Avela J. Bilateral Deficit in Maximal Force Production. *European Journal of Applied Physiology* 116: 2057-2084, 2016.

506. Slater LV. Muscle Activation Patterns During Different Squat Techniques. *Journal of Strength and Conditioning Research* 31: 667, 2017.

507. Sleivert G and Taingahue M. The Relationship between Maximal Jump-Squat Power and Sprint Acceleration in Athletes. *Eur J Appl Physiol* 91: 46-52, 2004.

508. Smart D, Hopkins WG, Quarrie KL, and Gill N. The Relationship between Physical Fitness and Game Behaviours in Rugby Union Players. *European Journal of Sport Science* 14: S8-S17, 2014.

509. Smart DJ and Gill ND. Effects of an Off-Season Conditioning Program on the Physical Characteristics of Adolescent Rugby Union Players. *Journal of Strength and Conditioning Research* 27: 708-717, 2013.

510. Soares-Caldeira LF, Ritti-Dias RM, Okuno NM, Cyrino ES, Gurjão ALD, and Ploutz-Snyder LL. Familiarization Indexes in Sessions of 1-Rm Tests in Adult Women. *Journal of Strength and Conditioning Research* 23: 2039-2045, 2009.

511. Speirs DE, Bennett M, Finn CV, and Turner AP. Unilateral Vs Bilateral Squat Training for Strength, Sprints and Agility in Academy Rugby Players. *Journal of Strength and Conditioning Research* 30: 386-392, 2015.

512. Spencer K and Croiss M. The Effect of Increasing Loading on Powerlifting Movement Form During the Squat and Deadlift. *Journal of Human Sport and Exercise* 10, 2015.

513. Spencer M, Bishop D, Dawson B, and Goodman C. Physiological and Metabolic Responses of Repeated-Sprint Activities. *Sports Medicine* 35: 1025-1044, 2005.

514. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, and Goodman C. Time-Motion Analysis of Elite Field Hockey, with Special Reference to Repeated-Sprint Activity. *J Sports Sci* 22: 843-850, 2004.

515. Spiteri T, Cochrane JL, Hart NH, Haff GG, and Nimphius S. Effect of Strength on Plant Foot Kinetics and Kinematics During a Change of Direction Task. *European Journal of Sport Science* 13: 646-652, 2013.

516. Spiteri T, Newton RU, Binetti M, Hart NH, Sheppard JM, and Nimphius S. Mechanical Determinants of Faster Change of Direction and Agility Performance in Female Basketball Athletes. *Journal of Strength and Conditioning Research* 29: 2205-2214, 2015.

517. Spiteri T, Newton RU, and Nimphius S. Neuromuscular Strategies Contributing to Faster Multidirectional Agility Performance. *Journal of Electromyography and Kinesiology* 25: 629-636, 2015.

518. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, and Newton RU. Contribution of Strength Characteristics to Change of Direction and Agility Performance in Female Basketball Athletes. *Journal of Strength and Conditioning Research* 28: 2415-2423, 2014.

519. Stålbom M, Holm DJ, Cronin J, and Keogh J. Reliability of Kinematics and Kinetics Associated with Horizontal Single Leg Drop Jump Assessment. A Brief Report. *Journal of Sports Science and Medicine* 6: 261, 2007.

520. Staron RSR. Skeletal Muscle Adaptations During Early Phase of Heavy-Resistance Training in Men and Women. *Journal of Applied Physiology* 76: 1247-1255.

521. Stastny P, Lehnert M, Zaatar AM, Svoboda Z, and Xaverova Z. Does the Dumbbell-Carrying Position Change the Muscle Activity in Split Squats and Walking Lunges? *Journal of Strength and Conditioning Research* 29: 3177, 2015.

522. Stodden DF, and Galitski, H.M. Longitudinal Effects of a Collegiate Strength and Conditioning Program in American Football. *Journal of Strength and Conditioning Research* 24: 2300-2308, 2010.

523. Stone M, and Borden, RA. Modes and Methods of Resistance Training. *Strength and Conditioning Journal* 19: 18-24, 1997.

524. Stone M, Collines, D, Plisk, S, Haff, G, and Stone, ME. Training Principles: Evaluation of Modes and Methods of Resistance Training. *Strength and Conditioning Journal* 22: 65-76, 2000.

525. Stone M, Plisk S, and Collins D. Training Principles: Evaluation of Modes and Methods of Resistance Training--a Coaching Perspective. *Sports Biomech* 1: 79-103, 2002.

526. Stone M, Plisk, SS, Stone, ME, Schilling, BK, O'Bryant, HS and Pierce, KC. Athletic Performance Development: Volume Load - 1 Set V Multiple Sets, Training Velocity and Training Variation. *Strength and Conditioning Journal* 20: 22-31, 1998.

527. Stone M, Sanborn, K, O'Bryant, HS, Hartman, M, Stone, ME, Proulx, C, Ward, B and Hruby, J. Maximum Strength-Power-Performance Relationships in Collegiate Throwers. *Journal of Strength and Conditioning Research* 17: 739-745, 2003.

528. Stone M, Stone. M. and Sands, WA. *Principles and Practice of Resistance Training*. Champaign IL: Human Kinetics, 2007.

529. Stone MH, Moir G., Glaister M., and and R. S. How Much Strength Is Necessary? *Physical Therapy in Sport* 3: 88-96, 2002.

530. Stone MH, O'Bryant, H.S., McCoy, L.., Coglianese, R., Lehmkuhl, M. and Shilling, B. Power and Maximum Strength Relationships During Performance of Dynamic and Static Weight Jumps. *Journal of Strength and Conditioning Research* 17: 140-147, 2003.

531. Stone MH, Sands, W.A., Carock, J., Callan, S., Dickie, D., Daigle, K., Cotton, J., Smith, S.L. and Hartman, M. The Importance of Isometric Maximum Strength and Peak Rate-of-Force Development in Sprint Cycling. *Journal of Strength and Conditioning Research* 18: 878-884, 2004.

532. Styles WJ, Matthews MJ, and Comfort P. Effects of Strength Training on Squat and Sprint Performance in Soccer Players. *Journal of Strength and Conditioning Research* 30: 1534-1539, 2016.

533. Suchomel TJ, Nimphius S, and Stone MH. The Importance of Muscular Strength in Athletic Performance. *Sports Medicine*: 1-31, 2016.

534. Sugimoto D, Alentorn-Geli E, Mendiguchía J, Samuelsson K, Karlsson J, and Myer GD. Biomechanical and Neuromuscular Characteristics of Male Athletes: Implications for the Development of Anterior Cruciate Ligament Injury Prevention Programs. *Sports Medicine* 45: 809-822, 2015.

535. Suzuki Y, Ae M, Takenaka S, and Fujii N. Comparison of Support Leg Kinetics between Side-Step and Cross-Step Cutting Techniques. *Sports biomechanics* 13: 144-153, 2014.

536. Swinton PA, Lloyd R, Keogh JW, Agouris I, and Stewart AD. A Biomechanical Comparison of the Traditional Squat, Powerlifting Squat, and Box Squat. *Journal of Strength and Conditioning Research* 26: 1805-1816, 2012.

537. Swinton PA, Lloyd R, Keogh JW, Agouris I, and Stewart AD. Regression Models of Sprint, Vertical Jump, and Change of Direction Performance. *The Journal of Strength & Conditioning Research* 28: 1839-1848, 2014.

538. Systems VM. Preparation (Vol 1.2). United Kingdom, 2002.

539. Tan B. Manipulating Resistance Training Program Variables to Optimize Maximum Strength in Men: A Review. *Journal of Strength and Conditioning Research* 13: 289-304, 1999.

540. Taylor K-L, Cronin, J, Gill, ND, Chapman, DW and Sheppard, J. Source of Variability in Iso-Inertial Jump Assessments. *International Journal of Sports Physiology and Performance* 5: 546-558, 2010.

541. Thepaut-Mathieu C, Van Hoecke J, and Maton B. Myoelectrical and Mechanical Changes Linked to Length Specificity During Isometric Training. *Journal of Applied Physiology* 64: 1500-1505, 1988.

542. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between Isometric Mid-Thigh Pull Variables and Sprint and Change of Direction Performance in Collegiate Athletes. *Journal of trainology* 4: 6-10, 2015.

543. Thomas C, Dos'Santos T, Comfort P, and Jones P. Relationships between Unilateral Muscle Strength Qualities and Change of Direction in Adolescent Team-Sport Athletes. *Sports* 6: 83, 2018.

544. Thomas C, Ismail KT, Simpson R, Comfort P, Jones PA, and Dos'Santos T. Physical Profiles of Female Academy Netball Players by Position. *J Strength Cond Res*, 2017.

545. Toutoungi D, Lu T, Leardini A, Catani F, and O'connor J. Cruciate Ligament Forces in the Human Knee During Rehabilitation Exercises. *Clinical biomechanics* 15: 176-187, 2000.

546. Tredrea M. The Role of Anthropometric, Performance and Psychological Attributes in Predicting Selection into an Elite Development Programme in Older Adolescent Rugby League Players. *Journal of Sports Sciences* 35: 1897, 2017.

547. Tricolli V, Lamas, L., Carnevale, R. and Ugrinowitsch, C. Short-Term Effects on Lower-Body Functional Power Development: Weightlifting Versus Vertical Jump Training Programs. *Journal of Strength and Conditioning Research* 19: 433-437, 2005.

548. Tufano JJ, Conlon J, Nimphius S, Brown LE, Seitz L, Williamson B, and Haff GG. Maintenance of Velocity and Power with Cluster Sets Maintain Velocity and Power During High-Volume Back Squats. *International Journal of Sports Physiology and Performance* 11: 885-892, 2016.

549. Tyler TF, Nicholas SJ, Mullaney MJ, and McHugh MP. The Role of Hip Muscle Function in the Treatment of Patellofemoral Pain Syndrome. *American Journal of Sports Medicine* 34: 630-636, 2006.

550. Tyler TF, Nicholas, S.J., Campbell, R.J. and McHugh, M.P. The Association of Hip Strength and Flexibility with the Incidence of Adductor Muscle Strains in Professional Ice Hockey Players. *American Journal of Sports Medicine* 29: 124-128, 2001.

551. Urquhart B, Moir GL, Graham SM, and Connaboy C. The Reliability of 1rm Split-Squat Performance and the Efficacy of Assessing Both Bilateral. *Journal of Strength and Conditioning Research* 29: 1991-1998, 2015.

552. Van Cutsem M. Changes in Single Motor Unit Behaviour Contribute to the Increase in Contraction Speed after Dynamic Training in Humans. *Journal of Physiology* 513: 295, 1998.

553. van Ingen Schenau GJ. The Constrained Control of Force and Position in Multi-Joint Movements. *Neuroscience* 46: 197, 1992.

554. Vanrenterghem J, Venables E, Pataky T, and Robinson MA. The Effect of Running Speed on Knee Mechanical Loading in Females During Side Cutting. *Journal of Biomechanics* 45: 2444-2449, 2012.

555. Veale JP, Pearce, A.J. and Carlson, J.S. Reliability and Validity of a Reactive Agility Test for Australian Football. *international Journal of Sports Physiology and Performance* 5: 239-248, 2010.

556. Vogt M and Hoppeler HH. Eccentric Exercise: Mechanisms and Effects When Used as Training Regime or Training Adjunct. *Journal of Applied Physiology* 116: 1446-1454, 2014.

557. Volkov NIN. Analysis of the Velocity Curve in Sprint Running. *Medicine and Science in Sports* 11: 332-337, 1979.

558. Weakley JJ, Till K, Darrall-Jones J, Roe GA, Phibbs PJ, Read DB, and Jones BL. The Influence of Resistance Training Experience on the between-Day Reliability of Commonly Used Strength Measures in Male Youth Athletes. *Journal of Strength and Conditioning Research* 31: 2005-2010, 2017.

559. Weir JP, Housh DJ, Housh TJ, and Weir LL. The Effect of Unilateral Concentric Weight Training and Detraining on Joint Angle Specificity, Cross-Training, and the Bilateral Deficit. *Journal of Orthopaedic & Sports Physical Therapy* 25: 264-270, 1997.

560. Weir JP, Housh TJ, and Weir LL. Electromyographic Evaluation of Joint Angle Specificity and Cross-Training after Isometric Training. *Journal of Applied Physiology* 77: 197-201, 1994.

561. Wilderman DR, Ross SE, and Padua DA. Thigh Muscle Activity, Knee Motion, and Impact Force During Side-Step Pivoting in Agility-Trained Female Basketball Players. *J Athl Train* 44: 14-25, 2009.

562. Wilkinson SB. Hypertrophy with Unilateral Resistance Exercise Occurs without Increases in Endogenous Anabolic Hormone Concentration. *European Journal of Applied Physiology* 98: 546, 2006.

563. Williams S, Trewartha G, Kemp S, and Stokes K. A Meta-Analysis of Injuries in Senior Men's Professional Rugby Union. *Sports Medicine* 43: 1043-1055, 2013.

564. Wilson G, Newton, RU, Murphy, AJ and Humphries, BJ. The Optimal Training Load for the Development of Dynamic Athletic Performance. *Medicine and Science in Sports and Exercise* 25: 1279-1286, 1993.

565. Wilson GJ, Murphy AJ, and Walshe A. The Specificity of Strength Training: The Effect of Posture. *European Journal of Applied Physiology and Occupational Physiology* 73: 346-352, 1996.

566. Wilson GJ, Murphy, A.J. and Walshe, A.D. Performance Benefits from Weight and Plyometric Training: Effects of Initial Strength Level. *Coaching and Sport Science Journal* 2: 3-8, 1997.

567. Winter EM, Abt G, Brookes FC, Challis JH, Fowler NE, Knudson DV, Knuttgen HG, Kraemer WJ, Lane AM, and Van Mechelen W. Misuse of "Power" and Other Mechanical Terms in Sport and Exercise Science Research. *Journal of Strength and Conditioning Research* 30: 292-300, 2016.

568. Wirth K, Hartmann H, Sander A, Mickel C, Szilvas E, and Keiner M. The Impact of Back Squat and Leg-Press Exercises on Maximal Strength and Speed-Strength Parameters. *Journal of Strength and Conditioning Research* 30: 1205-1212, 2016.

569. Wisloff U, Castagna, C., Helgerud, J., Jones, R., and Hoff, J. Strong Correlation of Maximal Squat Strength with Sprint Performance and Vertical Jump Height in Elite Soccer Players. *British Journal of Sports Medicine* 38: 285-288, 2004.

570. Wong DP, Tan EC, Chaouachi A, Carling C, Castagna C, Bloomfield J, and Behm DG. Using Squat Testing to Predict Training Loads for Lower-Body Exercises in Elite Karate Athletes. *Journal of Strength and Conditioning Research* 24: 3075-3080, 2010.

571. Wong P-L, Chouachi, A., Dellal, A., and Wisloff, U. Effect of Preseason Concurrent Muscular Strength and High-Intensity Interval Training in Professional Soccer Players. *Journal of Strength and Conditioning Research* 24: 653-660, 2010.

572. Wong P and Hong Y. Soccer Injury in the Lower Extremities. *British Journal of Sports Medicine* 39: 473-482, 2005.

573. Woolford SM, Polglaze, T., Rowsell, G. and Spencer, M. Field Testing Principles and Protocols, in: *Physiological Tests for Elite Athletes, 2e*. R Tanner, C Gore, eds.: Human Kinetics, 2000.

574. Wurm B, Garceau L, Zanden T, Fauth M, and Ebben W. Ground Reaction Force and Rate of Force Development During Lower Body Resistance Training Exercises. Presented at ISBS-Conference Proceedings Archive, 2010.

575. Yavuz HU and Erdag D. Kinematic and Electromyographic Activity Changes During Back Squat with Submaximal and Maximal Loading. *Applied Bionics and Biomechanics* 2017, 2017.

576. Yavuz HU, Erdağ D, Amca AM, and Aritan S. Kinematic and Emg Activities During Front and Back Squat Variations in Maximum Loads. *Journal of Sports Sciences* 33: 1058-1066, 2015.

577. Yetter MaM, G.L. The Acute Effects of Heavy Back and Front Squats on Speed During Forty-Meter Sprint Trials. *Journal of Strength and Conditioning Research* 22: 159-165, 2008.

578. Yeung SS, Suen, A.M.Y., and Yeung, E.W. A Prospective Cohort Study of Hamstring Injuries in Competitive Sprinters: Preseason Muscle Imbalance as a Possible Risk Factor. *British Journal of Sports Medicine* 43: 589-594, 2009.

579. Young W, and Farrow, D. A Review of Agility: Practial Applications for Strength and Conditioning. *Strength and Conditioning Journal* 28: 24-29, 2006.

580. Young W, Benton, D., Duthie, G., and Pryor, J. Resistance Training for Short Sprints and Maximum-Speed Sprints. *Strength and Conditioning Journal* 23: 7-13, 2001.

581. Young W, McLean, B. and Ardagna, J. Relationship between Strength Qualities and Sprinting Performance. *Journal of Sports Medicine and Physical Fitness* 35: 13-19, 1995.

582. Young W, Russell A, Burge P, Clarke A, Cormack S, and Stewart G. The Use of Sprint Tests for Assessment of Speed Qualities of Elite Australian Rules Footballers. *International Journal of Sports Physiology and Performance* 3: 199-206, 2008.

583. Young WB. Transfer of Strength and Power Training to Sports Performance. *International Journal of Sports Physiology and Performance* 1: 74-83, 2006.

584. Young WB, and Pryor, L. Relationship between Pre-Season Anthropometric and Fitness Measures and Indicators of Playing Performance in Elite Junior Australian Rules Football. *Journal of Science and Medicine in Sport* 10: 110-118, 2007.

585. Young WB, Dawson B, and Henry GJ. Agility and Change-of-Direction Speed Are Independent Skills: Implications for Training for Agility in Invasion Sports. *International Journal of Sports Science and Coaching* 10: 159-169, 2015.

586. Young WB, James, R. and Montgomery, I. Is Muscle Power Related to Running Speed with Changes of Direction? *Journal of Sports Medicine and Physical Fitness* 42: 282-288, 2002.

587. Young WB, McDowell, M.H. and Scarlett, B.J. Specificity of Sprint and Agility Training Methods. *Journal of Strength and Conditioning Research* 15: 315-319, 2001.

588. Young WB, Newton, R.U., Doyle, T.L.A., Chapman, D., Cormack, S., Stewart, G. and Dawson, B. Physiological and Anthropometric Characteristics of Starters and Non-Starters and Playing Positions in Elite Australian Rules Football: A Case Study. *Journal of Science and Medicine in Sport* 8: 333-345, 2005.

589. Yu J. Biomechanical Insights into Differences between the Mid-Acceleration and Maximum Velocity Phases of Sprinting. *Journal of Strength and Conditioning Research* 30: 1906, 2016.

590. Zatsiorsky VM, and Kraemer, W.J. *Science and Practice of Strength Training.* Champaign, IL.: Human Kinetics, 2006.

591. Zink AJ, Perry AC, Robertson BL, Roach KE, and Signorile JF. Peak Power, Ground Reaction Forces, and Velocity During the Squat Exercise Performed at Different Loads. *Journal of Strength and Conditioning Research* 20: 658-664, 2006.

APPENDICES

Appendix A

Human Research Ethics Acknowledgement

8223 APPLEBY ethics approval

Research Ethics <research.ethics@ecu.edu.au>

Thu 5/07/2012 2:11 PM

To:Brendyn APPLEBY <bbappleb@our.ecu.edu.au>; 'Brendyn Appleby' <Brendyn.Appleby@rugbywa.com.au>;

Cc:Rob NEWTON <r.newton@ecu.edu.au>; Prue CORMIE <p.cormie@ecu.edu.au>; Research Assessments <researchassessments@ecu.edu.au>;

1 attachments (47 KB)

Conditions of approval.pdf;

Dear Brendyn

Project 8223 APPLEBY
Effects of bilateral and unilateral resistance training on athletic performance

Student Number:

The ECU Human Research Ethics Committee (HREC) has reviewed your application and has granted ethics approval for your research project. In granting approval, the HREC has determined that the research project meets the requirements of the *National Statement on Ethical Conduct in Human Research.*

The approval period is from 6 July 2012 to 31 January 2016.

The Research Assessments Team has been informed and they will issue formal notification of approval. Please note that the submission and approval of your research proposal is a separate process to obtaining ethics approval and that no recruitment of participants and/or data collection can commence until formal notification of both ethics approval and approval of your research proposal has been received.

All research projects are approved subject to general conditions of approval. Please see the attached document for details of these conditions, which include monitoring requirements, changes to the project and extension of ethics approval.

Please feel free to contact me if you require any further information.

Regards
Kim

Kim Gifkins
Research Ethics Officer
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA 6027
Phone: (08) 6304 2170
Fax: (08) 6304 5044
Email: research.ethics@ecu.edu.au

APPENDIX B

INFORMATION LETTER TO PARTICIPANTS AND INFORMED CONSENT FORMS

INFORMATION LETTER TO PARTICIPANTS

This study has been approved by the Edith Cowan University Human Research Ethics Committee

Project Title

The relationship between bilateral and unilateral resistance training exercises to measures of functional athletic performance.

Purpose

Resistance training is a fundamental component of rugby union player development. Strength and conditioning coaches need to implement programs based on sound scientific practice. The relationships bilateral and unilateral resistance training and athletic tasks such as jumping, sprinting and changing direction requires in-depth analysis. The purpose of this research is to discover the relationships and between bilateral and unilateral resistance training exercises and athletic movements such as jumping, sprinting and changing direction capability.

Testing Procedures

As a participant in this investigation, all assessments will be conducted at Edith Cowan University Joondalup campus. It is important to note that all of these tests are no more strenuous that a typical training session. You will be thoroughly instructed on the correct technique and procedure prior to testing, complete adequate warm-up and cool down procedures, be provided adequate hydration and nutrition and be supervised by certified professionals during all testing sessions.

- Body Composition
    - Height will be determined with a wall-mounted stadiometer to the nearest millimetre.
    - Body mass will be measures on electronic scales to the nearest 100 grams.
    - Body composition will be assessed by a dual energy x-ray absorptiometry (DEXA), a test that involves lying still on a platform for approximately seven minutes.
- Power
    - Jumping Exercises: You will be required to perform double and single leg countermovement jumps (CMJ) and drop jumps (DJ). A CMJ requires an athlete to perform a rapid lower movement to a self-selected depth (usually 70-120 degrees of knee angle) and then jump, explosively, upwards as fast as possible with the feet leaving the floor. The DJ requires an athlete to step off a 40 cm box (double leg trials) or a 20cm box (single leg version), perform a rapid countermovement on contact with the ground and then jump, explosively, upwards as fast as possible with the feet leaving the floor. During these jump assessments, subjects will be required to hold a light (400g) fibreglass pole across their upper back, similar to a squat bar position.
- Strength:

- One Repetition Maximum (1RM): this is a dynamic measure of maximal force production that determines the maximum amount of weight an individual can move in one effort. The exercises to be used here include the back squat and step-up.
- Resistance assessment: you will be required to perform the back squat and step-up at sub-maximal loads under laboratory conditions.

- Speed:
  - Maximal speed: involves accelerating in a straight line as fast as possible over 10 metres or 30 metres.
- Change of Direction:
  - 50 Degree cut: subjects will accelerate as fast as possible over 2.5 metres and then change direction (50 degrees) to continue running an additional 2.5 metres. Tests need to be performed to the right and left and are pre-planned.

During jump, strength, sprint and change of direction tests, you will have markers placed on your upper and lower body to film your movements and detect muscle signals. These markers are external and stuck on your skin with double sided tape.

Risks

There are no inherent risks involved with this investigation. However, as with all physical testing, there is the risk of muscle pulls or strains. With lower body resistance exercises, there is a risk of injury to the lower back. Typically, an injury occurs as a result of poor movement technique. As such, all participants will be thoroughly instructed and familiarised with the correct technique by trained professionals. Furthermore, with any exercise test, there is the risk of delayed onset muscle soreness. This will be minimised by adequate warm-up and cool down procedures supervised by qualified strength and conditioning personnel. In addition, qualified personnel with first aid and CPR certification will be monitoring testing.

Because some of this testing involves exercise at your maximum ability, it is our duty of care to inform participants of the possible risks associated with such activity. Although very unusual in young or well trained individuals, there exists the possibility of certain physical changes during the test, which include: abnormal blood pressure, fainting, fast or slow heart rhythm, and in extremely rare instances, heart attack, stroke or death. Every effort to will be made to minimise these risks by

a) have the participant complete a medical questionnaire, and if deemed necessary, cleared by the participants local medical practitioner prior to reporting to testing, and

b) through careful observations of the participant during the exercise test.

Personnel trained in cardiopulmonary resuscitation will be present during the testing. It should be pointed out that although it is extremely unlikely that any of these 'rare instances' will occur during training, it is our duty of care to each participant to inform of all possible eventualities.

DXA scans are routine clinical tests but carry a small risk to the patient. DXA involves an exceedingly small dose of radiation (10-30μSv). A person on a return airline flight from Perth to

Sydney (of 8 hours duration) would be exposed to approximately 80 µSv. A typical chest –ray is 30 to 40 µSv. The number of scheduled scans in this study is well within the guidelines provided by the DXA manufacturer.

Benefits

Involvement in this investigation will provide you with multiple detailed body composition, speed, change of direction and lower body power assessment. This is highly valuable process that will allow for future training interventions specific to your needs. All study activities are free of charge to the participant.

Confidentiality

It is a critical aspect of this research that your results are kept confidential. A report will be provided to your employer regarding the outcomes of the study. You will be anonymous in this report, unless you indicate otherwise. If the results are published in a scientific journal, your identity will not be revealed. All records will be help in a locked filing cabinet in a private office, or on password protected computer hard drives for a period of 10 years. Video recording of the sessions will be conducted for exercise technique verification.

Contacting the Investigators

We are happy to answer any questions you may have at this time. If you have queries late, you can contact:

Brendyn Appleby: ( ), Brendyn.appleby@rugbywa.com.au

Professor Rob Newton: (6304 5106), r.newton@ecu.edu.au

Dr Prue Cormie: (6304 3418), p.cormie@ecu.edu.au

If you have concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer
Human Research Ethics Officer
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA, 6027
Phone: (08) 6304 2170
research.ethics@ecu.edu.au

Feedback

All participants will be provided with the test results as soon as they are available. A summary of the study results will be made available to all interested participants as soon as possible upon completion of the trial.

Voluntary Participation

Whether you decide to participate in this study or not is your decision and will not prejudice you in any way. If you do not decide to participate, you are free to withdraw your consent and discontinue your involvement at any time.

Privacy Statement

The conduct of this research involves the collection, access and or use of your identified personal information. The information collected is confidential and will not be disclosed to a third party without your consent, except to meet government, legal or other regulatory authority requirements. A de-identified copy of this data may be used for other research purposes. However, your anonymity will be safeguarded at all times.

INFORMED CONSENT FORM

This study has been approved by the Edith Cowan University Human Research Ethics Committee

Project Title: The relationship between bilateral and unilateral resistance training exercises to measures of functional athletic performance.

Researchers: Brendyn Appleby (Chief investigator):
/ brendy.appleby@rugbywa.com.au
Prof. Rob Newton (Supervisor)
6304 5106 / r.newton@ecu.edu.au
Dr Prue Cormie (Co-supervisor)
6304 3418 / p.cormie@ecu.edu.au

I confirm that (please tick):

- ☐ I have been provided with a copy of the INFORMATION LETTER explaining the research study,
- ☐ I have read and understood the information provided,
- ☐ I have been given the opportunity to ask questions and have had my questions answered satisfactorily,
- ☐ I am aware that if I have any additional questions, I can contact the research team,
- ☐ I understand that participation in the project will involve:
  - The measurement of height and weight,
  - An assessment of body composition by a DEXA scan,
  - The performance of maximal effort in familiar field tests (vertical and drop jumps, 10m sprint accelerations and change of direction testing),
  - The performance of maximal effort back squats and step-ups at 70-90% of 1RM.
- ☐ I understand that the information from all testing will be kept confidential and that my identity will not be disclosed without my consent,
- ☐ I understand that the information provided by me will only be used for the purposes of this research project and I understand how the information is to be used,
- ☐ I understand that I am free to withdraw from further participation at any time, without explanation or penalty,
- ☐ I am aware that the session will be video recorded for exercise technique verification,
- ☐ I freely agree to participate in the project.

Participant:

Name ___________Signature ________________________Date ______________

Researcher

Name ___________Signature ________________________Date ______________

INFORMATION LETTER TO PARTICIPANTS

Project Title

An examination of the efficacy of bilateral and unilateral resistance training on maximum strength and power development and improvements in functional athletic performance..

Purpose

Resistance training is a fundamental component of rugby union player development. Strength and conditioning coaches need to implement programs based on sound scientific practice. The relationship of lower body resistance training to performance has long been established, yet the little research regarding transfer effect of double or single leg training to jumping, sprinting and change of direction performance. The purpose of this research is to determine the effect of a short-term concurrent resistance and speed/change of direction training program on the performance of jumping, sprinting and changing direction capability.

Testing Procedures

As a participant in this investigation, you will be required to perform the following assessments at Edith Cowan University. It is important to note that all of these tests are no more strenuous that a typical training session. You will be thoroughly instructed on the correct technique and procedure prior to testing, complete adequate warm-up and cool down procedures, be provided adequate hydration and nutrition and be supervised by certified professionals during all testing sessions.

- Body Composition
    - Height will be determined with a wall-mounted stadiometer to the nearest millimetre.
    - Body mass will be measures on electronic scales to the nearest 100 grams.
    - Body composition will be assessed by a dual energy x-ray absorptiometry (DEXA), a test that involves lying still on a platform for approximately seven minutes.
- Power
    - Jumping Exercises: You will be required to perform double and single leg countermovement jumps (CMJ) and drop jumps (DJ). A CMJ requires an athlete to perform a rapid lower movement to a self-selected depth (usually 70-120 degrees of knee angle) and then jump, explosively, upwards as fast as possible with the feet leaving the floor. The DJ requires an athlete to step off a 40 cm box (double leg trials) or a 20cm box (single leg version), perform a rapid countermovement on contact with the ground and then jump, explosively, upwards as fast as possible with the feet leaving the floor. During these jump assessments, subjects will be required to hold a light (400g) fibreglass pole across their upper back, similar to a squat bar position.
- Strength:

  - One Repetition Maximum (1RM): this is a dynamic measure of maximal force production that determines the maximum amount of weight an individual can move in one effort. The exercises to be used here include the back squat and step-up.
- Speed:
  - Maximal speed: involves accelerating in a straight line as fast as possible over 10 metres or 30 metres.
- Change of Direction:
  - 50 Degree cut: subjects will accelerate as fast as possible over 2.5 metres and then change direction (50 degrees) to continue running an additional 2.5 metres. Tests need to be performed to the right and left and are pre-planned.

Training Procedures

As a participant in this investigation, you will be involved in a 16-week, fully supervised strength and conditioning program at RugbyWA, Mt Claremont. The purpose of this training program will be to improve your strength, power and speed through specific resistance and field training interventions. It is important to note that this training period will involve the periods of intense exercise, but no more strenuous that a typical training session. You will be thoroughly instructed on the correct technique of all exercises and procedures throughout each session. You will be provided adequate warm-up and cool down procedures, adequate hydration and be supervised by certified professionals during all sessions.

Risks

There are no inherent risks involved with this investigation. However, as with all physical training, there is the risk of muscle pulls or strains. As with lower body resistance exercises, there is a risk to the lower back. Typically, an injury occurs as a result of poor movement technique. As such, all participants will be thoroughly instructed and familiarised with the correct technique by trained professionals. Furthermore, with any exercise intervention, there is the risk of delayed onset muscle soreness. This will be minimised by adequate warm-up and cool down procedures supervised by qualified strength and conditioning personnel. In addition, qualified personnel with first aid and CPR certification will be monitoring testing. Standardised procedures for physical activity testing will be followed as previously performed in the RugbyWA training facility.

Because some of this training involves exercise at your maximum ability, it is our duty of care to inform participants of the possible risks associated with such activity. Although very unusual in young of well trained individuals, there exists the possibility of certain physical changes during the test, which include: abnormal blood pressure, fainting, fast or slow heart rhythm, and in extremely rare instances, heart attack, stroke or death. Every effort to will be made to minimise these risks by

a) have the participant complete a medical questionnaire, and if deemed necessary, cleared by the participants local medical practioner prior to reporting to testing, and

b) through careful observations of the participant during the exercise test.

Personnel trained in cardiopulmonary resuscitation will be present during the testing. It should be pointed out that although it is extremely unlikely that any of these 'rare instances' will occur during training, it is our duty of care to each participant to inform of all possible eventualities.

DXA scans are routine clinical tests but carry a small risk to the patient. DXA involves an exceedingly small dose of radiation (10-30µSv). A person on a return airline flight from Perth to Sydney (of 8 hours duration) would be exposed to approximately 80 µSv. A typical chest –ray is 30 to 40 µSv. The number of scheduled scans in this study is well within the guidelines provided by the DXA manufacturer.

Benefits

Involvement in this investigation will provide you with multiple detailed body composition, speed, change of direction and lower body power assessment. Additionally, your involvement in a structure training program in an elite training facility will improve your physical condition for the following season. This is highly valuable process that will allow for future training interventions specific to your needs. All study activities are free of charge to the participant.

Confidentiality

It is a critical aspect of this research that your results are kept confidential. A report will be provided to your employer regarding the outcomes of the study. You will be anonymous in this report, unless you indicate otherwise. If the results are published in a scientific journal, your identity will not be revealed. All records will be help in a locked filing cabinet in a private office, or on password protected computer hard drives for a period of 10 years.

Contacting the Investigators

We are happy to answer any questions you may have at this time. If you have queries late, you can contact:

Brendyn Appleby: (   ), Brendyn.appleby@rugbywa.com.au

Professor Rob Newton: (6304 5106), r.newton@ecu.edu.au

Dr Prue Cormie: (6304 3418), p.cormie@ecu.edu.au

If you have concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer
Human Research Ethics Officer
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA, 6027
Phone: (08) 6304 2170
research.ethics@ecu.edu.au

Feedback

All participants will be provided with the test results as soon as they are available. A summary of the study results will be made available to all interested participants as soon as possible upon completion of the trial.

Voluntary Participation

Whether you decide to participate in this study or not is your decision and will not prejudice you in any way. If you do not decide to participate, you are free to withdraw your consent and discontinue your involvement at any time.

Privacy Statement

The conduct of this research involves the collection, access and or use of your identified personal information. The information collected is confidential and will not be disclosed to a third party without your consent, except to meet government, legal or other regulatory authority requirements. A de-identified copy of this data may be used for other research purposes. However, your anonymity will be safeguarded at all times.

INFORMED CONSENT FORM

Project Title: An examination of the efficacy of bilateral and unilateral resistance training on maximum strength and power development and improvements in functional athletic performance.

Researchers: Brendyn Appleby (Chief investigator):
/ brendy.appleby@rugbywa.com.au
Prof. Rob Newton (Supervisor)
6304 5106 / r.newton@ecu.edu.au
Dr Prue Cormie (Co-supervisor)
6304 3418 / p.cormie@ecu.edu.au

I confirm that (please tick):

- ☐ I have been provided with a copy of the INFORMATION LETTER explaining the research study,
- ☐ I have read and understood the information provided,
- ☐ I have been given the opportunity to ask questions and have had my questions answered satisfactorily,
- ☐ I am aware that if I have any additional questions, I can contact the research team,
- ☐ I understand that participation in the project will involve:
  - The measurement of height and weight,
  - An assessment of body composition by a DEXA scan,
  - The performance of maximal effort in familiar field tests (vertical and drop jumps, 10m sprint accelerations and change of direction testing),
  - The performance of maximal effort back squats and step-ups at 70-90% of 1RM,
  - Involvement in a 16-week training resistance and sprint training study, supervised by the primary investigator, performed at RugbyWA. During this phase, I will be required to attend to training sessions each week where I will be asked to perform a variety of sub-maximal and maximal physical exertions, as would be performed in any resistance and fitness program.
- ☐ I understand that the information from all testing will be kept confidential and that my identity will not be disclosed without my consent,
- ☐ I understand that the information provided by me will only be used for the purposes of this research project and I understand how the information is to be used,
- ☐ I understand that I am free to withdraw from further participation at any time, without explanation or penalty,
- ☐ I freely agree to participate in the project.

Participant:

Name ___________Signature _______________________Date ______________

Researcher

Name ___________Signature _______________________Date ______________

APPENDIX C

TURNITIN ORIGINALITY REPORTS

Turnitin Originality Report

Ch1. Introduction by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 07-Dec-2018 5:30 PM AWST
ID: 993636604
Word Count: 4318

Similarity Index	Similarity by Source	
7%	Internet Sources:	6%
	Publications:	2%
	Student Papers:	0%

Turnitin Originality Report

Lit Review by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 26-Feb-2019 7:27 AM AWST
ID: 993636604
Word Count: 28325

Similarity Index	Similarity by Source	
14%	Internet Sources:	13%
	Publications:	0%
	Student Papers:	7%

Turnitin Originality Report

CH 3. 1RM Step-up by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 27-Aug-2018 1:58 PM AWST
ID: 993636604
Word Count: 3524

Similarity Index	Similarity by Source	
11%	Internet Sources:	10%
	Publications:	9%
	Student Papers:	3%

Turnitin Originality Report

Ch4. BB Displacement by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 04-Oct-2018 11:09 AM AWST

Similarity Index	Similarity by Source	
9%	Internet Sources:	6%
	Publications:	6%
	Student Papers:	2%

Ch5. Squat kinetics reliability by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 10-Oct-2018 6:33 AM AWST
ID: 993636604
Word Count: 4466

Similarity Index	Similarity by Source	
13%	Internet Sources:	11%
	Publications:	8%
	Student Papers:	4%

Turnitin Originality Report

Processed on: 21-Sep-2018 6:57 AM AWST
ID: 993636604
Word Count: 3071
Submitted: 5

CH 6 - Tech paper 1 Sq kinematics By Brendyn APPLEBY

Similarity Index	Similarity by Source	
11%	Internet Sources:	8%
	Publications:	8%
	Student Papers:	4%

Turnitin Originality Report

CH7. Sq kinematics by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 2018년 12월 11일 6:00 PM AWST
ID: 993636604
Word Count: 1994

Similarity Index	Similarity by Source	
6%	Internet Sources:	4%
	Publications:	4%
	Student Papers:	2%

Turnitin Originality Report

Ch8. Ste ; by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 10-Dec-2018 5:42 PM AWST
ID: 993636604
Word Count: 1994

Similarity Index	Similarity by Source	
6%	Internet Sources:	4%
	Publications:	4%
	Student Papers:	2%

Ch9. Sq v St by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 09-Dec-2018 5:32 PM AWST
ID: 993636604
Word Count: 5333

Similarity Index	Similarity by Source	
10%	Internet Sources:	7%
	Publications:	6%
	Student Papers:	5%

Turnitin Originality Report

Ch 10. Strength by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 28-Aug-2018 5:52 AM AWST
ID: 993636604
Word Count: 4294

Similarity Index	Similarity by Source	
10%	Internet Sources:	8%
	Publications:	5%
	Student Papers:	4%

Turnitin Originality Report

CH 11 Speed and COD by Brendyn APPLEBY

From Research Proposal/Thesis Chapter (GRS Turnitin _629443_1)

Processed on 28-Aug-2018 6:18 AM AWST
ID: 993636604
Word Count: 5002

Similarity Index	Similarity by Source	
9%	Internet Sources:	6%
	Publications:	5%
	Student Papers:	2%

END