



# **Does Lower-Extremity Symmetry Matter for Anterior Cruciate Ligament Injury Risk in Male Rugby Union Athletes?**

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## Abstract

Rugby injuries are frequent and often severe. Injury to the anterior cruciate ligament (ACL) is devastating and can cause serious hardship. Differences between an athlete's two legs, also known as an asymmetry, can increase injury risk. The question of interest in this thesis is does lower-extremity symmetry matter for ACL injury risk in male rugby union athletes. A review of the literature describing the aetiology and mechanisms of ACL injuries was performed in conjunction with a pilot investigation analysing rugby match footage to support the rationale of the thesis of investigating the sidestep manoeuvre in rugby. An in-depth systematic review and meta-analysis of knee mechanics during sidestepping concluded that weight acceptance is the most important phase to examine abduction moments of the knee when assessing ACL injury risk. A theoretical ACL injury model was conceived from our examination of the sidestep manoeuvre in rugby and contained elements of strength, balance and sprint kinetics. Laboratory-based practical assessment tools within our theoretical model were used to evaluate thirty male academy-level rugby athletes.

The preferred legs were stronger ( $ES = 0.21 - 0.37$ ), had better balance ( $ES = 0.63 - 1.0$ ), produced greater sprint kinetics ( $ES = 0.32 - 0.67$ ) and experienced a smaller knee abduction moment, a more flexed knee, less trunk lateral flexion and less distance between the centre-of-mass and the ankle-joint-centre while sidestepping ( $ES = -0.26 - -0.97$ ) compared to the non-preferred legs. Forwards were stronger ( $ES = 0.50 - 0.66$ ), had worse balance with larger asymmetries ( $ES = -0.66 - -1.8$ ) and produced greater sprint kinetics with larger asymmetries ( $ES = 0.74 - 0.81$ ) compared to backs. A hierarchical multiple regression was used to examine the contribution of each leg in determining increased knee abduction moments during sidestepping. While single-leg balance did not contribute to increased ACL injury risk ( $\bar{R}^2 = < 1 - 4\%$ ), lower-extremity strength and sprint kinetics did ( $\bar{R}^2 = < 1 - 31\%$ ). The preferred ( $\bar{R}^2 = 41\%$ ) and non-preferred ( $\bar{R}^2 = 8\%$ ) legs independently contribute to increased ACL injury risk with unique distributions of strength and sprint kinetics, however these contributions all appear linked with posterior-chain strength.

In summary, criterion and practical laboratory-based assessment tools to measure and assess ACL injury risk factors in rugby athletes were identified in this thesis. Assessment tools were used to quantify the differences in strength, balance, sprint kinetics and three-dimensional sidestepping mechanics between the preferred and non-preferred legs and between forwards and backs in amateur academy-level male rugby athletes. Normative values, symmetry angle scores and a discussion of assessment components and training recommendations were provided. A new model and framework for assessing ACL injury risk were outlined to guide the progression of ACL injury prevention strategies in rugby athletes.

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## Attestation of Authorship

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

Chapters 2 to 9 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. My contribution and the contributed by the various co-authors to each of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.



.....

Scott Randall Brown

15<sup>th</sup> June, 2016

## Co-Authored Works

**Table 1. Co-authored works.**

Chapter publication reference	Author %
Chapter 2. Brown SR, Brughelli M, Hume PA. Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. <i>Sports Med.</i> 2014;44(11):1573-88.	SRB: 90% MB: 5% PAH: 5%
Chapter 3. Brown SR, Brughelli M, Bridgeman LA. Profiling isokinetic strength by leg preference and position in rugby union athletes. <i>Int J Sports Physiol Perform.</i> 2016;11(4):500-7.	SRB: 90% MB: 5% LAB: 5%
Chapter 4. Brown SR, Brughelli M, Lenetsky S. Profiling single-leg balance by leg preference and position in rugby union athletes. <i>J Athl Train.</i> 2016:[in review].	SRB: 90% MB: 5% SL: 5%
Chapter 5. Brown SR, Brughelli M, Cross MR. Profiling sprint mechanics by leg preference and position in rugby union athletes. <i>Int J Sports Med.</i> 2016;37(11):890-7.	SRB: 90% MB: 5% MRC: 5%
Chapter 6. Brown SR, Cross MR, Morin J-B, Samozino P, Brughelli M. Mechanical sprinting asymmetries exist in un-injured academy rugby union athletes. <i>J Sports Sci.</i> 2016:[in review].	SRB: 80% MRC: 5% JBM: 5% PS: 5% MB: 5%
Chapter 7. Brown SR, Hume PA, Lorimer AV, Brughelli M, Besier TF. An individualised approach to assess the sidestep manoeuvre in rugby union athletes: Are we missing individual asymmetries by focusing on group means? <i>Am J Sports Med.</i> 2016:[in review].	SRB: 80% PAH: 5% AVL: 5% MB: 5% TFB: 5%
Chapter 8. Brown SR, Hume PA, Brughelli M. Clinical determinants of individual knee joint loads experienced while sidestepping: An exploratory study with male rugby athletes. <i>Am J Sports Med.</i> 2016:[in preparation].	SRB: 90% PAH: 5% MB: 5%
Chapter 9. Brown SR, Brughelli M, Hume PA. A lower-extremity multi-component assessment strategy for individualised ACL injury prevention and athletic performance in rugby union: A new framework. <i>J Athl Train.</i> 2016:[in preparation].	SRB: 90% MB: 5% PAH: 5%



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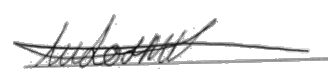
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**Tāwhaitia te ara o te tika, te pono me te aroha; kia piki kit e taumata tiketike.**

Follow the path of integrity, respect and compassion; scale the heights of achievement.

## **Ethics Approval**

Ethical approval for the thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC) on 17<sup>th</sup> June 2013 for a period of three years:

- AUTEC: 12/332 Sports Performance Research Institute New Zealand (SPRINZ) Clinics database.

and on 17<sup>th</sup> December 2013 for a period of three years:

- AUTEC: 13/378 Does leg symmetry matter in strength, balance and sidestepping measures for male rugby players?

## **Chapter 1: Introduction and Rationalisation**

### **The sport of rugby**

Rugby union (hereinafter referred to as rugby; unless otherwise specified) is the most played collision sport in the world with over 7.7 million participants spanning 120 countries and an annual increase of 9.3% over the past five years [1, 2]. As a result of this growth and world-wide popularity, in 2009 the decision was made to re-include rugby sevens (a faster variant of rugby) into the programme for the Rio 2016 Olympic Games. Additionally, the Rugby World Cup 2015 in England set all-time high attendance (2.4 million) and viewership (120 million) records and reached over 1.5 billion individuals through social media outlets [2]. For the second Rugby World Cup in a row (2011 and 2015), the New Zealand All Blacks have taken titles with dominating force.

To provide some background, the sport of rugby consists of two teams (sides) of no more than fifteen athletes each on the playing area with an additional eight athletes as replacements and / or substitutes (twenty-three in total). While many subdivisions of the playing position can be made, athletes are generally categorised into forwards and backs based on positional characteristics (Table 2) [3].

Table 2. Playing positions in rugby union.

Number	Position	
Forwards		
1	Loosehead prop (front row; tight five)	1
2	Hooker (front row; tight five)	2
3	Tighthead prop (front row; tight five)	3
4	Left lock (second row; tight five)	6
5	Right lock (second row; tight five)	4
6	Blindside flanker (back row; loose forward)	5
7	Openside flanker (back row; loose forward)	7
8	Number 8 (back row; loose forward)	8
Backs		
9	Scrumhalf (half-back <sup>b</sup> )	9
10	Flyhalf (outside-halves <sup>a</sup> ; first five-eighth <sup>b</sup> )	10
11	Left wing (three-quarters <sup>a</sup> )	11
12	Inside centre (three-quarters <sup>a</sup> ; second five-eighth <sup>b</sup> )	12
13	Outside centre (three-quarters <sup>a</sup> )	13
14	Right wing (three-quarters <sup>a</sup> )	14
15	Fullback	15

Footnote: Alternative colloquial names are included in brackets with specific uses in the <sup>a</sup>northern and <sup>b</sup>southern hemispheres.



The main objective in rugby is to score more points than the opposition within an 80 minute match (two continuous 40 minute periods) [4]. Points can be scored via grounding the ball in the opponents' in-goal, kicking the ball between the uprights or through various other penalty situations (Table 3). Essentially, rugby is a 'war of attrition' with no pads or time-outs, involving physically challenging aerobic and anaerobic activities like running, sprinting, kicking, passing, jumping, colliding and tackling [5].

**Table 3. Law 9: Method of scoring in rugby union.**

Term and definition	Value
Try. When an attacking player is first to ground the ball in the opponents' in-goal, a try is scored.	5 points
Penalty try. If a player would probably have scored a try but for foul play by an opponent, a penalty try is awarded between the goal posts.	5 points
Conversion goal. When a player scores a try it gives the player's team the right to attempt to score a goal by taking a kick at goal; this also applies to a penalty try. This kick is a conversion kick: a conversion kick can be a place kick or a drop kick.	2 points
Penalty goal. A player scores a penalty goal by kicking a goal from a penalty kick.	3 points
Dropped goal. A player scores a dropped goal by kicking a goal from a drop kick in general play. The team awarded a free kick cannot score a dropped goal until the ball next becomes dead, or until an opponent has played or touched it, or has tackled the ball carrier. This restriction applies also to a scrum taken instead of a free kick.	3 points

Footnote: 2016 World Rugby Law Book.

Forwards and backs tend to have different anthropometric and physiological characteristics from one another which relate well to their positional demands. The primary purpose of the forwards for example, is to contest for possession of the ball; holding specific roles in strength dominated situations such as scrums, rucks, mauls and line-outs [6]. The primary purpose of the backs, is to equally create an offensive attack and a defensive front; holding specific roles in technical and velocity dominated situations including long and accurate passing, targeted kicking, change-of-direction agility and proficiency in open-field tackling [7]. As a result of these positional demands, forwards tend to be larger in body-mass, body-height and body-mass index compared to backs [8]. Additionally, forwards possess greater relative strength in the upper- and lower-extremities compared to backs [9]. Unsurprisingly, backs are known for faster sprint velocities, change-of-direction agility, vertical jump and aerobic / anaerobic fitness compared to forwards [5]. Because of the substantial differences found between forwards and backs,

rugby research in recent years has moved towards a division of positions for statistical analyses and interpretation in an attempt to make more accurate recommendations for the athletes [10].

Determinants of success in rugby include percentage of tries scored and gaining possession (stolen line-outs, turnovers, etc.) to name a few [11]. As evidenced by the statistics from the winning team of the Rugby World Cup 2015, the All Blacks scored more tries than their opponents in every match, maintained a high scrum retention rate, produced the highest ruck retention rate, scored more tries than any other team from their own lineout and scored the most tries from within their own half [2]. The ability to hit harder, sprint faster, move more efficiently and outperform the opposition in skills are key elements that separate club-level from elite athletes and injured from healthy athletes. These attributes have been studied at great lengths to increase athletic performance and attempt to increase the longevity of the athlete. Rugby is not a sport for the timid; it is an aggressive collision sport accompanied with risk of injury.

### **Injuries in rugby**

The innate physicality of rugby continually places the athletes in ‘high risk’ situations that may result in an injury; defined as, “Any physical complaint, which was caused by a transfer of energy that exceeded the body’s ability to maintain its structural and / or functional integrity, that was sustained by a player during a rugby match or rugby training, irrespective of the need for medical attention or time-loss from rugby activities. An injury that results in a player receiving medical attention is referred to as a ‘medical-attention’ injury. An injury that results in a player being unable to take part in full in future rugby training or match play is known as a ‘time-loss’ injury” [12].

Several groups of authors [13-15] have constructed in-depth reviews over recent years to provide valuable information on incidence and severity of injuries as they specifically relate to rugby. The overall meta-analysed incidence of injuries in male rugby is shown as 81 injuries / 1,000 athlete hours during match play and decreases with level of play (123, 89 and 35 injuries / 1,000 athlete hours for international, level one club and level two club, respectively) [15]. Incidence of injuries during training remain relatively low at 3 injuries / 1,000 athlete hours across all levels of play [15]. The most frequent types of

injuries (and accompanying time-loss severity) include muscle / tendon strains (15 days), joint (non-bone) / ligament sprains (29 days), central / peripheral nervous system injuries (25 days) and fractures / bone stresses (42 days) [15]. The location of injuries is greater in the lower-extremities compared to any other body location (head, trunk and upper-extremities) [6, 13, 14, 16, 17]. To better understand the causality of an injury, the event is traditionally categorised as a contact or non-contact cause.

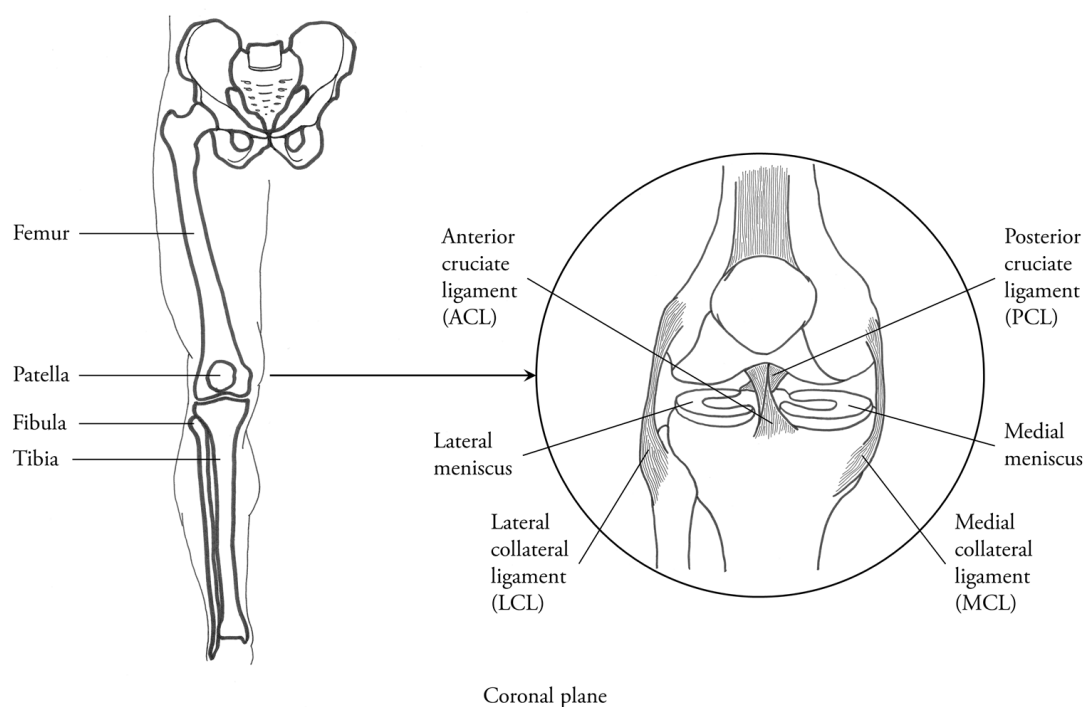
Contact injuries during match play occur most frequently while being tackled (29 injuries / 1,000 athlete hours), tackling (19 injuries / 1,000 athlete hours), rucks / mauls (17 injuries / 1,000 athlete hours), collisions (11 injuries / 1,000 athlete hours), scrums (7 injuries / 1,000 athlete hours) and lineouts (1 injury / 1,000 athlete hours) when the athletes of both sides are directly contesting for ball possession [15, 18]. Contact events account for a greatest injury incidence (~72%) as a result of the sport [13, 19]; caused by contact with another athlete, the ground or both. During match play, each team can perform an estimated ~300 tackles and ~85 collisions to further increase the potential for injury [20, 21]. Non-contact injuries, on the other hand, are far less understood in rugby and sport in general.

Non-contact injuries are classified by no apparent contact with another athlete, ground or ball [22]. The most commonly reported injury site for non-contact injuries are the lower-extremities with muscle strains (~27 days) and knee ligament sprains (~21 days) where the mechanisms consist of running (~12 injuries / 1,000 athlete hours) and 'twisting / turning' (sidestepping) (~4 injuries / 1,000 athlete hours), respectively [13, 20]. Damage to the anterior cruciate ligament (ACL) is known as one of the most detrimental injuries in rugby accounting for the most time missed in participation from practice and / or match time (~107 days / 1,000 athlete hours) [20, 23], the most financial cost associated with medical treatment and compensation (\$8.75 million New Zealand Dollars between 1999 and 2006) [24] and can lead to debilitating osteoarthritis later in life (increased pain / discomfort and anxiety / depression and decreased mobility) [25]. In New Zealand, the number of Accident Compensation Corporation (ACC) claims for sport-related ACL injuries are higher in rugby than in any other sport (952 [-24%] between 2000 and 2005) [26]. The rate of ACL injury in rugby has been reported as two

to three times that of rugby league [23]. Non-contact ACL injuries occur more frequently than in contact situations and are most commonly seen during change-of-directions where the external load placed on the ACL exceeds its mechanical properties [27-31]. To understand ACL injury, it is useful to consider a potential ACL injury model [32] where combined knee loading is the likely mechanism of injury [32, 33].

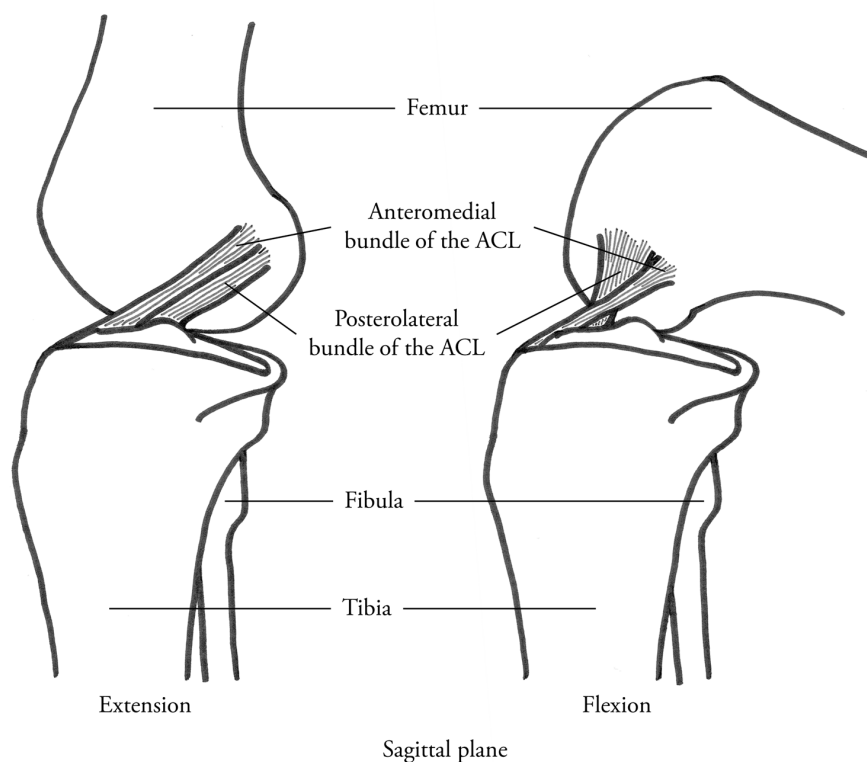
### **The anatomy of the knee and its relation to ACL injury**

The knee complex is the largest stabilising hinge joint in the body [34, 35] with primary motions consisting of flexion / extension in the sagittal plane and secondary motions consisting of adduction / abduction in the coronal plane and internal / external rotation in the transverse plane. Allowing these motions to occur are the soft tissue structures (i.e. muscles, tendons and ligaments) which are intricately positioned throughout the knee (Figure 1). While the muscles surrounding the knee function to actively protect the integrity of the structure through the different movements, the ligaments within the knee function to passively protect the structure. The intracapsular structures are the cruciate ligaments (posterior cruciate ligament [PCL] and ACL). The PCL functions in conjunction with the ACL to stabilise the knee during dynamic movements. However, since the ACL is notably smaller (50% less) and more fragile (half the tensile strength) than the PCL, it sustains more injuries and has therefore undergone more intense scrutiny [36]. The ACL sits in the intercondylar notch of the femur and consists of two distinct bundles that twist in a medial spiral as they travel from the tibia to the femur: the anteromedial bundle and the posterolateral bundle. As a unit, the ACL inserts proximally to the posterior medial surface of the lateral femoral condyle, travels anteriorly, and passes laterally next to the PCL where it distally inserts to the anteromedial portion of the intercondylar eminence of the tibia [37]. The ACL is known as one of the major static stabilising ligaments of the knee and serves several functions in the protection of the knee joint [34, 38-40]. The primary role of the ACL is to prevent excessive anterior subluxation of the tibia relative to the femur [35, 41]. The ACL also moderates internal and external rotation of the tibia on the femur and limits hyperextension of the tibiofemoral joint [39].



**Figure 1. The knee joint.**

Due to the juxtaposition of the attachment sites, both ACL bundles are placed in a continually taut position while the knee joint moves through its normal range of motion (ROM). When the knee is fully extended, the posterolateral bundle becomes taut and when the knee is fully flexed, the anteromedial bundle becomes taut (Figure 2) [35, 39, 42]. This in turn places the ACL in a stressed position throughout multiple knee positions during events such as walking or squatting. On their own, these positions are typically harmless; consisting of normal movement patterns and ROM. However, when more intense movements are performed, such as running, jumping or a change-of-direction (as commonly seen in sport), the ACL becomes more at risk for disruption.



**Figure 2. The double bundle of the ACL.**

The contributing factors for non-contact ACL injury are known to involve a step-stop action, cutting task, a sudden change-of-direction and landing from a jump with inadequate lower-extremity mechanics and / or a lapse in concentration [43-46]. Concurrent movements in the coronal plane (abduction / adduction) and transverse plane (internal / external rotation) are believed to increase stress and the possibility for injury to the ACL compared to sagittal plane motion alone [47-49]. The greatest forces occur during a deceleration manoeuvre combined with a change of direction, i.e. sidestepping [34, 50-54] where ACL disruption is speculated to occur at a threshold of  $\sim 2,200$  N in the sagittal plane [55]. For multi-planar movements the mechanism and critical loads are far less understood [56]. The foot is placed in a closed chain position and slightly pronated as the tibia internally rotates and the knee is at or near full extension. When the athlete attempts to change direction, excessive torsional force can injury the ACL [34].

### **The sidestep manoeuvre**

The term 'sidestep', as used throughout the thesis, is synonymous with the terms / phrases 'change of direction', 'side-step', 'side-step and a cut', 'cut' and 'cutting manoeuvre' and

was originally defined as “a directional change of only a few degrees to better than 90°” in 1977 [50]. In present day, the foundation of the definition remains the same with only slight technical modifications depending on the movements utilised by the sport being studied. For example, in this thesis investigating rugby, the term sidestep refers to a rapid deceleration of an athletes’ forward velocity on one leg to enter / initiate the manoeuvre, a reorientation of the centre-of-mass (COM) in a new direction (at any deviation from the initial straight-line [0°]), followed by a quick acceleration in the chosen direction to exit / complete the manoeuvre (Figure 3).



**Figure 3. The sidestep manoeuvre in rugby.**

Sidestep characteristics, from my unpublished pilot study analysing match video data of male academy-level rugby union athletes (6 matches; 12 teams; 15 positions), are presented in Table 4. Backs performed 2.6x (more than double) the frequency of sidestepping in matches compared to the forwards. Essentially, every back performs a

minimum of two sidestep manoeuvres each match and every forward performs a minimum of one sidestep manoeuvre each match; or in other words, a total of ~11 and ~28 sidestep manoeuvres are performed by forwards and backs, respectively, every match. The distribution of which leg the athletes sidestepped off was well balanced for the forwards (45 vs 55% for the right and left legs, respectively) and backs (50 vs 50% for the right and left legs, respectively). While sidestep velocity and angle are presented in Table 4, the accuracy at which these variables were recorded should be interpreted with caution as video quality, camera angle variability and parallax error can make analyses difficult [57-60]. To minimise the variation of velocity and angle variables, a single highly-skilled video-coder performed all analyses. Velocity analyses used criterion of 0 – 3 m·s<sup>-1</sup> equivalent to walking or jog, > 3 – 6 m·s<sup>-1</sup> equivalent to running and > 6 m·s<sup>-1</sup> equivalent to sprinting. Angle analyses used criterion of 0 – 30°, > 30 – 60° and > 60°. Under these criteria, forwards sidestepped the most at moderate – fast velocities (running and sprinting; > 3 m·s<sup>-1</sup>) whereas backs tended to sidestep more frequently at a fast velocity (sprinting; > 6 m·s<sup>-1</sup>). Both forwards and backs sidestepped most frequently at angles between 30 – 60°. The pilot video analysis of match sidestep velocity and angle, albeit limited due to methodological difficulties, has provided background information on sidestep characteristics of male academy-level rugby union athletes. Additional video analysis studies including examination of injuries would complement these findings.

**Table 4. Sidestep characteristics from match video footage.**

	Forwards	Backs	Combined
Frequency: (# / position / match)	0.88	2.30	1.54
Leg: Right / Left (%)	45 / 55	50 / 50	48 / 52
Velocity: 0 – 3 m·s <sup>-1</sup> / > 3 – 6 m·s <sup>-1</sup> / > 6 m·s <sup>-1</sup> (%)	31 / 36 / 34	30 / 30 / 40	30 / 32 / 38
Angle: 0 – 30° / > 30 – 60° / > 60° (%)	27 / 62 / 11	22 / 57 / 21	23 / 58 / 18

Footnote: Sidestep characteristics from match ( $n = 12$ ) video footage among male academy-level rugby union athletes (15 positions; 8 forwards and 7 backs). “Leg” refers to the leg at which the sidestep was performed off; meaning the direction the athlete will travel following the sidestep will be opposite to the leg mentioned. Abbreviation: #, number; %, percent; m, metre; s, second; °, degree.

The majority of all ACL injuries are classified as non-contact and are seen most commonly in a sidestepping manoeuvre [61]. Video data for documented ACL injuries has shown



that three out of four ACL injury situations analysed were non-contact sidestepping manoeuvres and seven of the ten ACL injury situations occurred during sidestepping [44]. In elite team sports, video analysis studies of game play have determined that sidestepping is a more common manoeuvre than straight-line running for non-contact ACL injuries as it involves elements of single-leg deceleration from a large horizontal velocity and a change-of-direction [33, 57, 62]. These video observations have been confirmed in laboratory-based experiments showing that coronal plane knee loading during sidestepping is six times greater than straight-line running and two and a half times greater than transverse plane knee loading [54]. Individual coronal and transverse loads have elevated ACL strain in cadaveric models [48] but when combined, associations between multi-plane loading can greatly increase ACL injury risk in males and females [32, 63].

Risk factors associated with non-contact ACL injury include: anatomical / structural, hormonal, environmental and biomechanical / neuromuscular. A number of studies [41, 43, 47, 53, 57, 61, 64-71] have investigated the biomechanical and neuromuscular characteristics of sidestepping as it involves an increased horizontal running velocity, compared to single-leg landings, and increased skill so that an individual might pursue or evade an opponent. Rugby research has shown maximal sprinting velocities are typically performed between 6.8 and 8.4 m·s<sup>-1</sup> during match play [72, 73]. While the velocity of a rugby athlete performing a sidestep are currently not available in the literature, my unpublished video data has shown that they are performed at very similar (if not slightly lower) velocities depending on position. In laboratory studies, increasing the velocity of sidestepping has increased knee loading and decreased task acquisition (sidestepping angle) [74]. Sidestepping at higher velocities, as commonly seen in rugby, may therefore be placing an athlete's ACL at a higher risk of injury compared to manoeuvres at lower velocities (2.3 – 4.6 m·s<sup>-1</sup>) [75].

Each body of work has examined specific factors within the sidestep manoeuvre by replicating and modifying the common elements involved (i.e. sex [76], style [77], speed [74], angle [78] and planning [79]). The reactive component associated with an unplanned movement has gained attention in recent years. Athletes can likely sustain an ACL injury due to excessive knee loading by an unplanned or late decision to initiate the

change-of-direction movement [79]. Unplanned movements occur as a sudden reaction to an external stimulus such as another athlete or movement of a ball [79] or as an instantaneous action to gain better position within the playing area [80]. Experimental research has found that unplanned sidestepping generates knee loads of up to two times greater than during planned sidestepping in the coronal and transverse planes [79]. Researchers are also particularly interested in the carryover of unplanned manoeuvres to game situations and the ability to modify reaction ability through training interventions [77, 81-83]. Given differences between planned and unplanned conditions in joint moments [79] and muscle activation [84] during sidestepping, greater understanding of the effects of unplanned movements are necessary to recognise possible implications towards injury risk during sidestepping. The sidestep manoeuvre has thus become our closest measure to determine ACL injury risk in sports that involve a change-of-direction with a high horizontal velocity component; like rugby.

The more variations an athlete can create when sidestepping, such as when evading an opponent or in reaction to one, the greater the skill level of that athlete and the more valuable an asset they become to a team. The fewer possibilities an athlete has (e.g. preferring to sidestep to one side over the other), the more predictable they become on offense and less efficient they become on defence. An athlete with low movement variability is at a disadvantage in performance measures and may also be placing themselves at a greater risk of injury [85]. While assessing ACL injury risk during the sidestep, an assortment of biomechanical characteristics is necessary to perform the task without injury including strength, balance and sprint kinetics. It is proposed that a lack of these biomechanical characteristics may be damaging, with athletes showing asymmetries in these measures at a greater risk of injury compared to symmetrical athletes.

### **Assessment strategies**

Athletic assessments and injury prevention strategies in rugby are of interest for both sporting clubs and athletes alike as ACL injuries can be devastating. Despite this importance and our efforts to understand the aetiology of ACL injury [86], several risk factors remain unknown. There is a lack of scientific data describing the relationship

between leg preference (the preferred stance or support leg during sidestepping) and knee mechanics and how these variables affect risk factors for ACL injury.

Only a few studies [87-89] have investigated the role of leg preference as a possible mechanism for non-contact ACL injuries; reporting little or no significant relationship between side of injury and leg preference. Although strong trends for ACL injuries were found in the non-preferred leg, it was concluded that the side most likely to sustain a non-contact ACL tear could not be predicted alone by the determination of leg preference [89]. Unfortunately, these retrospective studies were limited with combined sex, sport (ten different sports) and experience in the analyses and must therefore be interpreted with caution. Brophy and colleagues [66] took many of the aforementioned limitations into account when examining 93 (41 male and 52 female) footballers all with medically confirmed non-contact ACL injuries. Results showed that 74% of male subjects sustained an injury to the preferred kicking leg and 68% of female subjects sustained an injury to the non-preferred kicking leg (support leg) [66]. This observation of gender bias [66] was proposed as the result of anatomical and neuromuscular differences in the lower-extremities which are uniquely connected to the sidestep manoeuvre. Recently, musculoskeletal asymmetries between the lower-extremities have been discovered [90] in male footballers which aid the previous hypothesis that morphological adaptations are present in sport. As the majority of studies are retrospective in nature, any definitive answer of whether or not leg preference has an effect on mechanical knee joint loading in healthy athletes is still inconclusive. There remains however, a possibility of lower-extremity neuromuscular asymmetry, core and joint stabilisation deficits and proprioceptive insufficiencies within the athlete that may in turn increase risk of ACL injury. Authors [66] further recommend experimental and prospective studies to examine the relationship between leg preference and knee mechanics in healthy athletes to confirm or refute the findings of these studies. The advancement of sport- and athlete-specific neuromuscular training protocols to improve lower-extremity asymmetries have thus become a necessity.

Training interventions have been developed to maintain dynamic stability around the knee [91, 92]. Injury prevention programmes have been developed to alter an athlete's

biomechanical and / or neuromuscular control during specific events, i.e. non-contact ACL injury prevention in females. Researchers [93] have suggested that overall injury rates may be decreased more effectively if prevention programmes focus on lower-extremity injury prevention as a whole, rather than on a specific or lower-incident injury prevention programme. Such training programmes aim to alter strength, balance, proprioception and reactive components within common sporting manoeuvres such as sidestepping. A multi-component assessment strategy has yet to be developed to evaluate the contribution of leg symmetry in strength, balance and movement variability and whether this asymmetry can affect injury risk. The short- and long-term effectiveness of ACL injury prevention programmes, that include a focus on developing strength, balance and movement ability, are inconclusive and need to be further analysed [94].

The majority of research has shown decreased injury rates in programmes that focus on multifaceted ideals [95]. Despite the advances of injury prevention programmes over the past decade, and the continuing growth of knowledge towards injury prevention in athletes, few studies have attempted to illuminate the true mechanisms of the body that are being modified in these programmes.

### **Measuring the difference between legs**

Assessing the difference between the legs is common in making clinically relevant decisions in sport regarding injury risk and performance. However, substantial variations in terms and definitions currently exist in the literature that need further clarification. A percent difference (e.g. Equation 1 and Equation 2) describes the difference between two points (i.e. high vs low, non-injured vs injured, etc.) with respect to an appointed reference. While these “difference equations” have been used extensively throughout the literature, inconsistencies in reference selection make uniform comparisons difficult [96].

Equation 1. High vs low percent difference (Imbalance [%]) [97] =

$$\frac{\text{high value} - \text{low value}}{\text{low value}} \times 100$$

Equation 2. Injured vs non-injured percent difference (Asymmetry [%]) [98] =

$$\frac{\text{non-injured} - \text{injured}}{\text{non-injured}} \times 100$$

Further work to describe the differences between the legs has used the term symmetry; defined as the correspondence of body parts in size, shape, and relative position, on opposite sides of a dividing line or distributed around a central point or axis [99]. In its opposition, asymmetry is defined as the absence of symmetry. Over the years, authors have attempted to alter the “difference equations” to describe the levels of symmetry of an athlete. Similar to percent difference equations, the symmetry index (Equation 3) has its own unique pros and cons within sports science. The primary difficulties with the symmetry index are with the over-inflation of reported values as a result of the mean reference selection, and artificial inflation by near-zero numbers [96, 100-103].

Equation 3. Symmetry index (SI) [104] =

originally described as

$$\frac{2 (non-injured - injured)}{(non-injured + injured)} \times 100$$

also described as

$$\frac{(left - right)}{0.5 (left + right)} \times 100$$

In an attempt to resolve the fundamental issues in the symmetry index, Zifchock and colleagues [103] described a symmetry angle equation (Equation 4). The symmetry angle is an arctan ( $\tan^{-1}$ ) function of the ratio between two values (bilateral legs in this case) and describes any deviation away from the line of perfect symmetry [103, 105]. Unlike its predecessors, the symmetry angle does not suffer from reference selection, over-inflation or artificial inflation but rather reports a true value between -100% and 100%. In this instance, a score of 0% indicates perfect symmetry, -100% indicates perfect asymmetry in one direction and 100% indicates perfect asymmetry in the other direction. To simplify even further, Exell and colleagues [101, 102, 105] included a modified symmetry angle equation (Equation 5) to limit the interpretations between 0 and 100%. The modified symmetry angle therefore describes an absolute deviation of the observed relationship between the two values from a theoretically perfect relationship. The simplicity of this final symmetry angle equation aids researchers in determining clinically

relevant information in sports science to then relay comprehensible material to the athlete and / or coaching staff [101, 102].

Equation 4. Symmetry angle (SA) [103] =

$$\frac{45^\circ - \left( \tan^{-1} \left[ \frac{left}{right} \right] \right)}{90^\circ} \times 100$$

but if

$$\left( 45^\circ - \tan^{-1} \left[ \frac{left}{right} \right] \right) > 90^\circ$$

then

$$\frac{45^\circ - \left( \tan^{-1} \left[ \frac{left}{right} \right] - 180^\circ \right)}{90^\circ} \times 100$$

Equation 5. Modified symmetry angle ( $ABS\theta_{SYM}$ ) [105] =

$$\frac{\left| 45^\circ - \left( \tan^{-1} \left[ \frac{left}{right} \right] \right) \right|}{90^\circ} \times 100$$

but if

$$\left( 45^\circ - \tan^{-1} \left[ \frac{left}{right} \right] \right) > 90^\circ$$

then

$$\frac{\left| 45^\circ - \left( \tan^{-1} \left[ \frac{left}{right} \right] - 180^\circ \right) \right|}{90^\circ} \times 100$$

The majority of studies investigating symmetry have focused on walking [106-108], submaximal running [103] and sprinting [101, 102]. As gait is a very cyclic activity, regardless of the velocity, it has been suggested that an athlete who displays more symmetrical attributes (kinematic and kinetic) would maintain more stability and thus a more efficient system [109]. However, in rugby, sprinting is just one of many technical skills required in the sport. Like many other team sports, rugby falls more in line with a dynamical systems theory, wherein variability is inherently functional [110].

Symmetry may present more information related to an athlete's ability to perform. Additionally, asymmetry has been identified as a clinical indicator of injury risk [102, 111]. Therefore, examining asymmetry during common laboratory assessments of strength, balance, sprint kinetics and sidestepping mechanics in rugby athletes may give researchers a unique perspective as to how a rugby athlete's performance could be hindered and what effects those hindrances may have on anterior cruciate injury risk.

Normal strength profiles (including between-limb asymmetries) are acknowledged [112] to be present in athletes and can exist throughout an entire career without producing any injury. It could be argued that an asymmetrical strategy would inevitably be developed in order to progress task-acquisition in high-level athletes. A deficit is an asymmetry that has surpassed any normal or natural range, even when accounting for sport or positional demands, which can potentially place an athlete at risk for injury. The question becomes: When does a normal asymmetry become a deficit? Researchers [112-114] have shown through isokinetic strength assessments that normal between-leg asymmetries can be 10-15% and that a deficiency would exist beyond these values. While similar standards in hamstring to quadriceps (H:Q) ratio deficits have detected up to 70% of injuries in professional footballers [112, 115], it was not reported if the injury occurred to a previously injured or healthy leg. Unfortunately there remains only sparse clinical documentation [113] examining the relationship between lower-extremity asymmetries (in muscular strength or any other measure) and injury risk.

Given the lack of understanding into the biomechanical differences between the legs and then how these differences may ultimately affect ACL injury risk in rugby, this thesis examines the potential effects of lower-extremity asymmetry on non-contact ACL injury risk. At the start of this thesis, assessments to detect and measure asymmetries in strength, balance, sprinting and sidestepping had never been used together as a multi-component assessment strategy to identify potential risk factors for ACL injury in rugby athletes. The development of these areas enables a better understanding of tools that might best assess ACL risk factors.

## Structure of the thesis

Quantitative research methodology was conducted in this PhD following the Sports Injury Prevention model originally described by van Mechelen et al. in 1987 [116, 117] and further detailed by Finch [118] as the Translating Research into Injury Prevention Practice (TRIPP) framework (Table 5) for research leading to real-world sports injury prevention. Under Auckland University of Technology's pathway 2, this thesis contains three sections and eight chapters suitable for journal publication (Figure 4) and progressively works through answering the key question, "Does lower-extremity symmetry matter for anterior cruciate ligament injury risk in male rugby union athletes?" The concluding discussion chapter ties together the findings of each chapter within Section 2 (body) and portrays how the information may impact the field moving forward. The key points and links between each chapter are outlined in Table 6. Appendices contain conference presentations that helped provide feedback to improve chapter content.

**Table 5. Progression of sports injury prevention models.**

Step / stage	Sequence of prevention [116]	Translating Research into Injury Prevention Practice (TRIPP) [118]
1	Establishing the extent of the sports injury problem: incidence and severity	Injury surveillance
2	Establishing aetiology and mechanism of injuries	Establish aetiology and mechanisms of injury
3	Introducing preventative measures	Develop preventative measures
4	Assessing their effectiveness by repeating step 1	"Ideal conditions" / scientific evaluation
5		Describe intervention context to inform implementation strategies
6		Evaluate effectiveness of preventative measures in implementation context



The thematic sections to address the thesis question include:

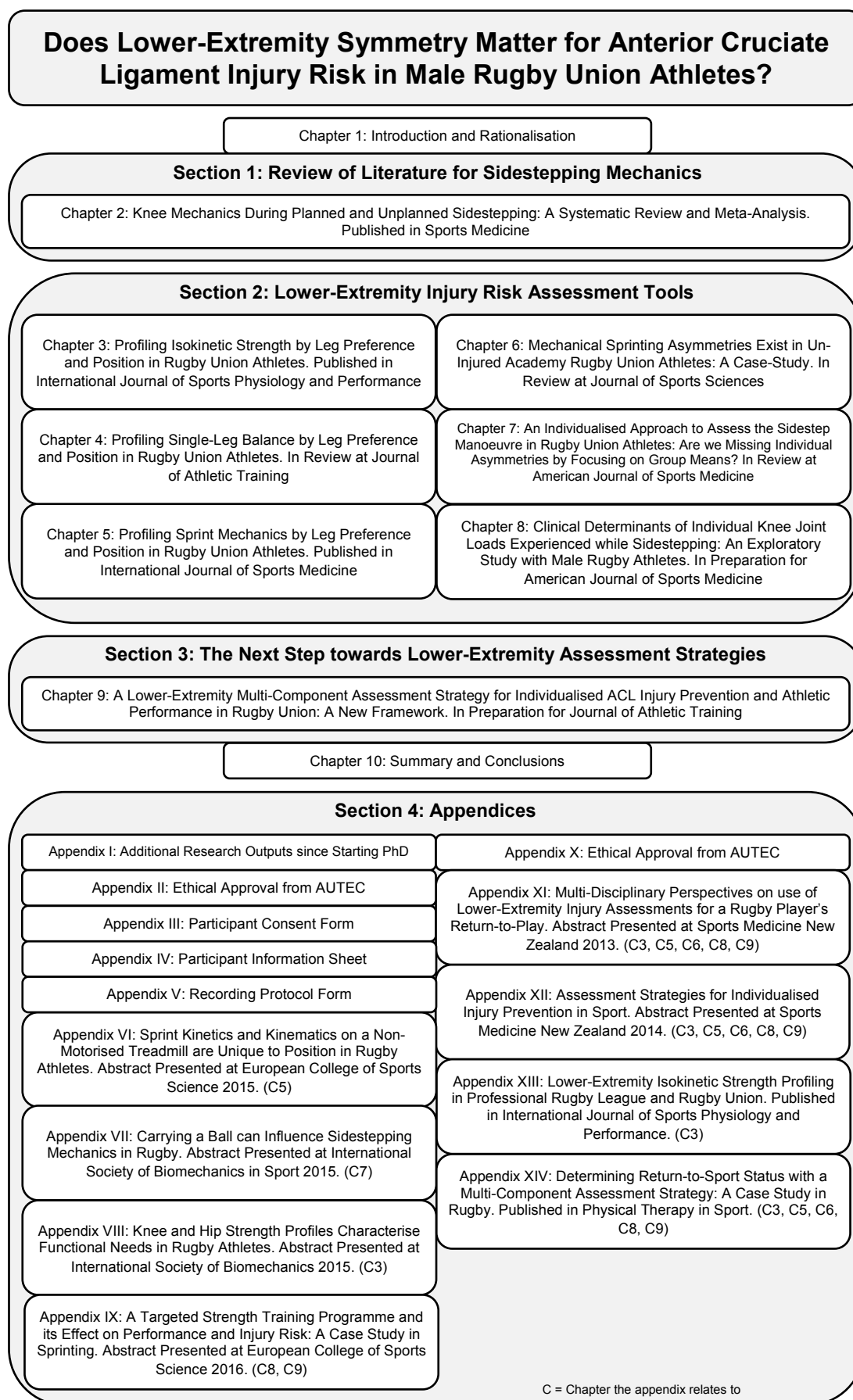
Section 1: Review published literature for sidestepping mechanics;

Section 2: Examine laboratory-based practical assessment tools used to evaluate injury risk;

Determine normative values of the laboratory-based practical assessments and normative values of symmetry within these assessments;

Determine the most worthwhile variables as they relate to injury risk; and

Section 3: Create a comprehensive assessment strategy and framework to guide us forward.



**Figure 4. Overview of doctoral thesis chapter flow.**

The first thematic section of the thesis (Chapter 2) is focused on a review of literature for sidestepping mechanics; our surrogate measure of ACL injury risk. Chapter 2 (published in *Sports Medicine*, 2014) comprises a review of the literature and a meta-analysis on knee mechanics during planned and unplanned sidestepping. This chapter also discusses the most important variable (external knee abduction moment at weight acceptance phase) to examine within the sidestep. The publication resulting from Chapter 2 was:

**Brown SR**, Brughelli M, Hume PA. Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. *Sports Med.* 2014;44(11):1573-88.

The second thematic section of the thesis (Chapters 3 – 8) examine the laboratory-based practical (isokinetic dynamometry, single-leg balance and non-motorised treadmill sprinting) and laboratory-based criterion (three-dimensional sidestepping) assessment tools used to evaluate lower-extremity injury risk and symmetry. Chapter 3 (published in *International Journal of Sport Physiology and Performance*, 2016) reports that forwards were stronger compared to backs. Chapter 4 (in review at *Journal of Athletic Training*) reports that forwards produced worse single-leg balance scores and larger asymmetries compared to backs. Chapter 5 (published in *International Journal of Sport Medicine*, 2016) reports that forwards produced larger sprint kinetics and subsequent asymmetries compared to backs. Chapter 6 (in review at *Journal of Sports Sciences*) reports that forwards and backs produced larger asymmetries in horizontal force compared to vertical force while sprinting. Chapter 7 (in review at *American Journal of Sports Medicine*) reports that the non-preferred leg experienced greater knee loads during sidestepping compared to the preferred leg but that sidestepping assessments need to be analysed on an individual basis due to the variation among rugby athletes. Chapter 8 (in preparation for *American Journal of Sports Medicine*) reports that the preferred and non-preferred leg contributed to increased injury risk via unique distributions of lower-extremity strength and sprint kinetics. Publications at the time of thesis submission for examination, resulting from Chapters 3 and 5 were:

**Brown SR**, Brughelli M, Bridgeman LA. Profiling isokinetic strength by leg preference and position in rugby union athletes. *Int J Sports Physiol Perform.* 2016;11(4):500-7.

**Brown SR**, Brughelli M, Cross MR. Profiling sprint mechanics by leg preference and position in rugby union athletes. *Int J Sports Med.* 2016;37(11):890-7.

The third thematic section of the thesis (Chapter 9) consists of a general discussion of findings from Chapters 3 – 8, reports the normative values and normative symmetry scores, provides pros and cons of assessments strategies and subsequent training programme strategies and provides a model and framework to use when evaluating rugby athletes for ACL injury risk. This section also provides limitations of the research, suggestions for future research and concluding statements on the key findings from the thesis. Chapter 9 (prepared for *Journal of Athletic Training*) reports that multiple components need to be used in conjunction with symmetry values in a holistic fashion when assessing injury risk status. Individual programming may provide the greatest benefit towards reducing deficits, asymmetries and injury risk in rugby athletes.

The appendices contain supportive or technical material for the chapters and / or thesis as a whole. Information detailing additional research outputs while working on the Doctor of Philosophy (Appendix I). Documentation regarding ethical approval from the Auckland University of Technology Ethics Committee (AUTEC) covering all of the experimental studies (Appendix II), participant consent form (Appendix III), participant information sheet (Appendix IV) and recording protocol form (Appendix V) are provided. Conference abstracts providing rationale for this thesis that have been presented at, or accepted to, national / international conferences are included in Appendices VI – IX. Documentation regarding ethical approval from the Auckland University of Technology Ethics Committee (Appendix X), conference presentations (Appendix XI and XII) and publications (Appendix XIII and XIV) with colleagues conducted during the thesis, that provided further rationale for thesis chapter work are provided:

**Brown SR**, Brughelli M, Griffiths PC, Cronin JB. Lower-extremity isokinetic strength profiling in professional rugby league and rugby union. *Int J Sports Physiol Perform*. 2014;9(2):358-61.

**Brown SR**, Brughelli M. Determining return-to-sport status with a multi-component assessment strategy: A case study in rugby. *Phys Ther Sport*. 2014;15(3):211-5.

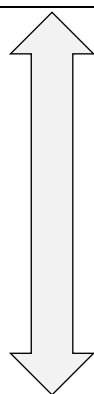
The research key points and the links between each chapter in the three thematic sections of the research are outlined in Table 6.

Table 6. Research key points and links between chapters.

<b>Does Lower-Extremity Symmetry Matter for Anterior Cruciate Ligament Injury Risk in Male Rugby Union Athletes?</b>		
<b>Outcome:</b> The thesis identified criterion and practical laboratory-based assessment tools to measure and assess ACL injury risk factors in rugby. Assessments tools were used to quantify the differences in strength, balance, sprint kinetics and three-dimensional sidestepping mechanics between the preferred and non-preferred legs and between forwards and backs in amateur academy-level male rugby athletes. Normative values and symmetry scores in these measures were provided for the reader in addition to a discussion of pros and cons regarding assessments components and training recommendations. A new model and framework for assessing ACL injury risk was developed to guide the progression of injury prevention strategies in rugby.		
<b>Chapter</b>	<b>Chapter Title</b>	<b>Chapter Content - Question / Rationale / Findings</b>
1	Introduction and Rationalisation.	<p><b>Main Questions of the Thesis:</b></p> <ol style="list-style-type: none"> <li>1. What is our current criterion and associated factors for determining an increased risk of ACL injury?</li> <li>2. What tools are currently used to assess anterior cruciate ligament injury risk?</li> <li>3. Do lower-extremity asymmetries exist in male rugby athletes?</li> <li>4. Is injury risk influenced by leg preference during our criterion?</li> <li>5. Are asymmetries related to injury risk?</li> <li>6. What is the best strategy for assessing ACL injury risk?</li> </ol> <p><b>Rationale for the Questions:</b></p> <p>The key outcomes of the thesis were to:</p> <ol style="list-style-type: none"> <li>A. Identify the when the ACL is most at risk;</li> <li>B. Identify how to best measure lower-extremity asymmetries;</li> <li>C. Provide an overview of what lower-extremities are; and</li> <li>D. Provide a new framework and injury prevention model to guide us forward.</li> </ol>

## Section 1: Review of Literature for Sidestepping Mechanics

Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
2	Knee Mechanics during Planned and Unplanned Sidestepping: A Systematic Review and Meta-Analysis.	<p><b>Question:</b></p> <p>What does the literature say about the differences between planned and unplanned sidestepping and how might this effect knee mechanics and ACL injury risk?</p> <p><b>Rationale for the Question:</b></p> <p>Knee joint mechanics during sidestepping are associated with ACL injury. Unplanned sidestepping more closely emulates match scenarios when compared with planned sidestepping but little is known about the true effects. It is important to quantify the loads that may challenge the integrity of the knee.</p> <p><b>Approach:</b></p> <p>Systematic literature review and meta-analysis.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• Unplanned sidestepping effects on knee mechanics are larger than planned sidestepping.</li> <li>• The most substantial effects occurred during the weight acceptance phase of sidestepping.</li> <li>• Knee abduction and internal rotation moments are most commonly associated with ACL injury risk.</li> </ul> <p><b>Novel Contribution:</b></p> <p>A comprehensive summary of the current knowledge regarding planned and unplanned sidestepping and a synthesis of the effects of sidestepping on knee mechanics. A new rationale was proposed to incorporate unplanned sport tasks in the development of future ACL screening and training.</p>

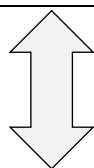


*Link between  
Sections 1 and 2:*

Having first identified gaps in the literature regarding the variable and phase of interest pertaining to ACL injury risk while sidestepping, the next step was to assess the mechanical characteristics associated with sidestepping in a laboratory-based setting using practical measures. In addition, we also needed to independently assess the sidestep manoeuvre using three-dimensional motion capture as a criterion measure. Finally, an examination of any links between our practical and criterion measure was needed to help answer the thesis question.

## Section 2: Lower-Extremity Injury Risk Assessments Tools

Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
3	Profiling Isokinetic Strength by Leg Preference and Position in Rugby Union Athletes.	<p><b>Question:</b></p> <p>Do lower-extremity strength differences exist between the preferred and non-preferred legs and between forwards and backs?</p> <p><b>Rationale for the Question:</b></p> <p>Muscle imbalances aid in the identification of athletes at risk for lower-extremity injury. Little is known regarding the influence that leg preference or playing position may have on lower-extremity muscle strength and asymmetry.</p> <p><b>Approach:</b></p> <p>Cross-sectional analysis with comparisons between legs and positions.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• The non-preferred leg was weaker than the preferred leg for forwards during extension and flexion and for backs during extension actions.</li> <li>• Backs were weaker at the knee than forwards in the preferred leg during extension and flexion.</li> <li>• No differences in strength ratios between legs or position.</li> <li>• Backs produced peak torque at longer muscle lengths in both legs at the knee and hip compared to the forwards.</li> </ul> <p><b>Novel Contribution:</b></p> <p>Our findings highlighted a need for individual isokinetic athlete assessment. We recommended that strength and conditioning programs for forwards and backs include targeted single-leg exercises and that forwards might benefit the most from eccentric exercises to increase lower-extremity strength at longer muscle lengths.</p>

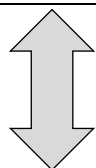


*Link between  
Chapters 3 and 4:*

The first mechanical characteristic (strength) of sidestepping has been described in detail, however, the full picture remains incomplete. It is unknown whether single-leg balance has an effect on ACL injury risk.



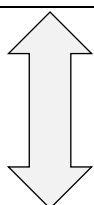
Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
4	<b>Profiling Single-Leg Balance by Leg Preference and Position in Rugby Union Athletes.</b>	<p><b>Question:</b></p> <p>Do single-leg balance differences exist between the preferred and non-preferred legs and between forwards and backs?</p> <p><b>Rationale for the Question:</b></p> <p>Poor balance has been linked with an increased risk of injury in athletic populations, including rugby athletes. No research has profiled single-leg balance in healthy rugby athletes as a means to better understand the influence of balance in rugby.</p> <p><b>Approach:</b></p> <p>Cross-sectional analysis with comparisons between legs and positions.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• The non-preferred leg had worse balance than the preferred leg for backs.</li> <li>• Forwards had worse balance than the backs in both legs and both difficulties.</li> <li>• Position is more important than leg preference when using balance as an assessment tool to monitor injury risk.</li> <li>• Forwards may be at the greatest risk of injury.</li> </ul> <p><b>Novel Contribution:</b></p> <p>Single-leg balance is an important screening tool to use with rugby athletes to detect individual asymmetries in balance. Positional separations are needed when analysing balance as forwards possess worse balance ability compared to backs.</p>



*Link between  
Chapters 4 and 5:*

The second mechanical characteristic (balance) of sidestepping has been described in detail, however, the full picture still remains incomplete. It is currently unknown whether sprint kinetics has an effect on ACL injury risk.

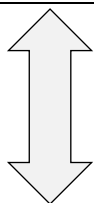
Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
5	Profiling Sprint Mechanics by Leg Preference and Position in Rugby Union Athletes.	<p><b>Question:</b></p> <p>Do sprint kinetic differences exist between the preferred and non-preferred legs and between forwards and backs?</p> <p><b>Rationale for the Question:</b></p> <p>Lower-extremity power characteristics are central to performance in rugby. Little is known regarding the effects of leg preference and playing position on sprint mechanics.</p> <p><b>Approach:</b></p> <p>Cross-sectional analysis with comparisons between legs and positions.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• Non-preferred leg of the forwards produced less <math>F_V</math>, <math>F_H</math> and <math>P_{\max}</math> than the preferred leg during acceleration and maximal velocity.</li> <li>• Backs produced more <math>F_V</math>, <math>F_H</math> and <math>P_{\max}</math> than the forwards during initial acceleration but less at maximal velocity.</li> <li>• Backs had faster split times at 2, 5, 10 and 15m but slower times at 35 and 40m compared to the forwards.</li> <li>• Forwards presented greater magnitudes of kinetic variables and peak velocity, but larger imbalances than backs.</li> </ul> <p><b>Novel Contribution:</b></p> <p>We highlighted the need for positional and leg separations when analysing sprint efforts to detect imbalance that global measures of sprinting can miss. Recommendations to monitor athletes intra-session were made to determine if these asymmetries can influence ACL injury risk and / or athletic performance.</p>



*Link between  
Chapters 5 and 6:*

The third mechanical characteristic (sprint kinetics) of sidestepping has been presented. However, the full scope of sprint kinetics has yet been described in detail. More insight into asymmetries in sprint kinetics is needed to add to the picture.

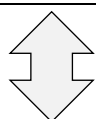
Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
6	<b>Mechanical Sprinting Asymmetries Exist in Un-Injured Academy Rugby Union Athletes.</b>	<p><b>Question:</b></p> <p>Do sprint mechanical asymmetries exist in un-injured rugby athletes?</p> <p><b>Rationale for the Question:</b></p> <p><math>F_H</math> production is imperative during sprint acceleration. Lower-extremity asymmetries are commonly assessed in injury prevention programming as they are thought to precede injury. Little is known regarding normative symmetry values in <math>F_V</math> and <math>F_H</math> production during sprinting in un-injured male rugby athletes.</p> <p><b>Approach:</b></p> <p>Cross-sectional analysis with observations of asymmetries in <math>F_V</math> and <math>F_H</math> while sprinting.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• There were no differences found between the legs in <math>F_V</math>.</li> <li>• The non-preferred kicking leg produced less <math>F_H</math> than the preferred leg.</li> <li>• Mean symmetry angle scores were substantially lower in <math>F_V</math> compared to <math>F_H</math>.</li> </ul> <p><b>Novel Contribution:</b></p> <p>Although all athletes were cleared to play by their team's medical staff, large asymmetries in <math>F_H</math> remained present, showing potential for athletes to "slip under the radar" of traditional injury prevention assessments. Additionally, symmetry angle scores were extremely variable in <math>F_H</math> whereas they remained low in <math>F_V</math>.</p>



*Link between  
Chapters 6 and 7:*

The third mechanical characteristic (sprint kinetics) of sidestepping has now fully been described in detail. The practical laboratory-based measures are complete, our criterion measure must be performed for further insight in ACL injury risk.

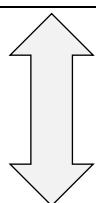
Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
7	<b>An Individualised Approach to Assess the Sidestep Manoeuvre in Rugby Union Athletes: Are we Missing Individual Asymmetries by Focusing on Group Means?</b>	<p><b>Question:</b></p> <p>Do knee abduction moment differences exist between the preferred and non-preferred legs during sidestepping?</p> <p><b>Rationale for the Question:</b></p> <p>Examining the sidestep manoeuvre provides a better understanding of ACL injury mechanisms; however, in sports like rugby where athletes must sidestep off both legs, research on leg preference as a possible contributor to ACL injury is lacking. The appropriateness of how we then interpret ACL injury risk from the group / team data is currently in question compared to the importance of individual differences and its impact on injury risk.</p> <p><b>Approach:</b></p> <p>Cross-sectional analysis with mean and individual comparisons between legs.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• The non-preferred leg produced 25% greater knee abduction moments during sidestepping.</li> <li>• The non-preferred leg produced a more extended knee, more trunk lateral flexion and a greater distance between the COM and the AJC when sidestepping.</li> <li>• Only 9 out of 16 athletes presented a higher abduction moment in their non-preferred leg.</li> <li>• Individual asymmetries ranged 2.2 and 47%.</li> </ul> <p><b>Novel Contribution:</b></p> <p>The non-preferred leg demonstrated increased knee abduction moments compared to the preferred leg which are commonly associated with ACL injury risk. Nearly half of our athletes showed the potential to “slip under the radar” of traditional group mean assessments. When assessing athletes “at risk” for ACL injury, individual data must be examined in conjunction with group means for a holistic view of the problem.</p>



*Link between  
Chapters 7 and 8:*

Now that our criterion measure of sidestepping has been performed, a final step is needed to detect any links between the practical and criterion measures.

Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
8	<b>Clinical Determinants of Individual Knee Joint Loads Experienced While Sidestepping: An Exploratory Study with Male Rugby Athletes.</b>	<p><b>Question:</b></p> <p>What are the relationships between strength, balance, sprint kinetics and external knee abduction moments during sidestepping?</p> <p><b>Rationale for the Question:</b></p> <p>The relationship between biomechanical factors during sidestepping and ACL injury risk has pointed our attention to hip strength and trunk orientation. While several clinical factors have independently been linked to ACL injury risk factors, how they might affect knee abduction moments during sidestepping is unknown.</p> <p><b>Approach:</b></p> <p>A hierarchical multiple regression analysis.</p> <p><b>Findings:</b></p> <ul style="list-style-type: none"> <li>• Larger abduction moments in the preferred leg were linked to concentric hip extension strength and <math>F_V</math> during maximal sprinting.</li> <li>• Larger abduction moments in the preferred leg were linked to concentric hip flexion strength and <math>F_V</math> during maximal sprinting.</li> <li>• Larger symmetry scores between the legs (representing abduction moments) were largely related to <math>F_H</math> during maximal sprinting and eccentric knee flexion strength</li> </ul> <p><b>Novel Contribution:</b></p> <p>A multicomponent assessment strategy of concentric hip extension strength and <math>F_V</math> and <math>F_H</math> during maximal sprinting may be useful in evaluating ACL injury risk factors in rugby athletes. The use of such a strategy would allow individualised or “targeted” strength training programmes to be created for the athlete to work on increasing lower-extremity strength and / or decreasing asymmetries where needed.</p>



*Link between  
Sections 2 and 3:*

Having identified strength, balance, sprint kinetic and sidestepping profiles and the links between our practical and criterion ACL injury risk measures, the final step of answer the thesis question is to report the normative data and outline future work to progress ACL research.

### Section 3: The Next Step towards Lower-Extremity Assessment Strategies

Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
9	A Lower-Extremity Multi-Component Assessment Strategy for Individualised ACL Injury Prevention and Athletic Performance in Rugby Union: A New Framework.	<p><b>Question:</b></p> <p>What are normative values in strength and sprint kinetics and what are the normative symmetry angle scores for male rugby athletes?</p> <p><b>Rationale for the Question:</b></p> <p>Differences between the preferred and non-preferred legs of rugby athletes exist in clinical assessments of strength, balance, sprint kinetics and three-dimensional sidestepping. As important as these differences are, there is currently no normative data at which practitioners can compare to when working with their own rugby athletes. Additionally, there is currently no framework to structure clinical injury prevention assessments specific to rugby athletes.</p> <p><b>Approach:</b></p> <p>Commentary.</p> <p><b>Novel Contribution:</b></p> <p>Isokinetic strength at the knee and the hip combined with sprint kinetic assessments during maximal velocity should be combined in a multi-component strategy to assess injury risk and performance in rugby athletes. A framework has been created to conduct such a theoretical model wherein athletes enter an assessment loop, have their data compared with normative data of their peers, are assessed on their symmetry values and are deemed “clear to continue team training” or “require individualised programming”. Athletes can continue within the loop until their data are within acceptable ranges to aid in decreasing injury risk.</p>

Chapter	Chapter Title	Chapter Content - Question / Rationale / Findings
10	Summary and Conclusions.	<p><b>Summary:</b></p> <p>Rugby is the most played contact sport in the world where a lot of injuries occur, specifically to the ACL. ACL injury occurs during the weight acceptance phase of sidestepping, which is a very common manoeuvre in rugby. Sidestepping requires elements of strength, balance and sprint kinetics and asymmetries in these elements have been independently linked with increased ACL injury risk. The non-preferred leg was generally weaker in strength, had worse single-leg balance, produced less force during sprinting, and displayed a greater theoretical risk of ACL injury during sidestepping compared to the preferred leg. Backs tended to be weaker in strength, have better single-leg balance, produce more force during sprinting and sprint faster and possess less asymmetries across all measures compared to the forwards. The non-preferred leg of forwards may potentially be at a greater risk of ACL injury.</p> <p>The preferred leg was linked with gluteal strength and <math>F_V</math> during sprinting, and the non-preferred leg was linked with hip flexors and <math>F_V</math> during sprinting. Additionally, the larger the asymmetries in <math>F_H</math> during sprinting and eccentric quadriceps strength, the larger the asymmetries were in injury risk. These findings indicate there should be focus on weak posterior muscular strength as a primary factor needing attention for ACL injury risk reduction.</p> <p><b>Conclusion:</b></p> <ul style="list-style-type: none"> <li>• Levels of symmetry vary substantially from athlete to athlete and from measure to measure.</li> <li>• Symmetry does matter for anterior cruciate ligament injury risk in male rugby union athletes</li> <li>• Asymmetries in strength and sprint kinetics have an effect on increasing the risk of ACL injury in rugby athletes; asymmetries in balance does not.</li> <li>• This thesis provides valuable information that asymmetries in strength and sprint kinetics may negatively affect athletic performance in force and / or velocity dominated situations.</li> </ul>

Footnote: Research key points from each chapter and the links between each chapter and the three thematic sections of the research conducted.

## **Key contributions to literature from the thesis**

This thesis, via the literature review and experimental studies, helps to provide answers to the following questions:

1. What is the current laboratory-based criterion measure for assessing ACL injury risk in athletes; and what variables within that measure are vital to the understanding of the injury aetiology?

**Sidestepping; knee abduction moment at weight-acceptance**

2. What additional laboratory-based practical measures are currently in place to aid in the detection of ACL injury risk; and what variable is vital to all assessments?

**Isokinetic strength, single-leg balance and sprint kinetics; asymmetry**

3. Are there lower-extremity asymmetries present within the laboratory-based criterion and practical measures (sidestepping, isokinetic strength, single-leg balance and sprint kinetics); and where might these asymmetries originate?

**Yes; sport / positional demands**

4. Is the laboratory-based criterion measure (sidestepping) for assessing ACL injury risk influenced by leg preference; and if so, are the effects best seen through group means or individualised methods?

**Yes; individualised methods**



5. What are the main determinates *within* the laboratory-based criterion measure (sidestepping) of increasing injury risk (knee abduction moment at weight acceptance) among male rugby athletes?

**Hip adduction, lateral trunk flexion angle and distance from centre-of-mass to ankle-joint-centre**

6. What are the main determinates *among* the laboratory-based practical measures (isokinetic strength, single-leg balance and sprint kinetics) of increasing injury risk (knee abduction moment at weight acceptance) among male rugby athletes?

**Eccentric hamstring strength, concentric hip extension strength and horizontal force production**

7. What is the best strategy for assessing ACL injury risk; and what information is needed to guide us forward when using laboratory-based practical measures?

**Individualised / multicomponent; model / framework**

If we understand risk factors for ACL injury in male rugby athletes we can improve our design of injury prevention assessments and programmes to keep our athletes healthy.

**Section 1:**  
**Review of Literature for**  
**Sidestepping Mechanics**

## Chapter 2: Knee Mechanics during Planned and Unplanned Sidestepping: A Systematic Review and Meta-Analysis

This chapter comprises the following paper published in *Sports Medicine*.

### Reference:

Brown SR, Brughelli M, Hume PA. Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. *Sports Med*. 2014;44(11):1573-88.

### Author contribution:

Brown SR, 90%; Brughelli M, 5%; Hume PA, 5%.

### Overview

Knee joint mechanics during sidestepping are associated with anterior cruciate ligament injury. Unplanned sidestepping more closely emulates game scenarios when compared with planned sidestepping by limiting decision time, increasing knee loading and challenging the integrity of soft-tissue structures in the knee. It is important to quantify the loads that may challenge the integrity of the knee during planned and unplanned sidestepping. Our objective was to review literature on knee mechanics during planned and unplanned phases of sidestepping. PubMed, CINAHL, MEDLINE (EBSCO), SPORTDiscus and Web of Science were searched using the terms knee mechanics OR knee kine\*, AND plan\*, unplan\*, anticipat\*, unanticipat\*, side\*, cut\* or chang\*. A systematic approach was used to evaluate 4,629 records. Records were excluded when not available in English, only available in abstract of conference proceedings, not involving a change-of-direction sidestep, not comparing planned and unplanned or maintaining a running velocity greater than 2 m·s<sup>-1</sup>. Included studies were evaluated independently by two authors using a custom-designed methodological quality assessment derived from the Physiotherapy Evidence Database (PEDro) scale and then confirmed by a third author. Only six studies met the inclusion criteria and were retained for meta-analysis. Magnitude-based inferences were used to assess the standardised effect of the differences between planned and unplanned sidestepping. Knee angles and knee moments were extracted and reported for flexion / extension, abduction / adduction and internal / external rotation for initial contact, weight acceptance, peak push-off and final push-off phases of sidestepping. For kinematic variables, unplanned sidestepping

produced a wide range of small to large increases in knee extension angles, small and moderate increases in knee abduction angles and a small increase in internal rotation angle relative to planned sidestepping during the sidestepping manoeuvre. For kinetic variables, unplanned sidestepping produced mostly small (small to large) increases in knee flexor moments, small to moderate increases in knee abductor moments and mostly moderate (small to large) increases in internal rotator moments relative to planned sidestepping. Approach velocity constraints during the sidestepping manoeuvre were lifted due to the low number of eligible studies. The varying approach velocities included (ranging from 3.0 to 5.5 m·s<sup>-1</sup>) may impact the kinematic and kinetic variables examined in this review. Differences in knee mechanics between planned and unplanned sidestepping exist. The most substantial effects occurred during the weight acceptance phase of sidestepping. It seems that biomechanical factors commonly associated with anterior cruciate ligament injury risk are affected the most during the loading phase compared with peak push-off; made evident in the coronal (abductor) and transverse (internal rotator) knee kinetic data presented in this review. The authors of this review propose a rationale for the incorporation of unplanned sport tasks in the development of anterior cruciate ligament injury screening and in prophylactic training programmes.

## Introduction

Injury rates of 3.7 per 1,000 match hours have been reported [93] for the anterior cruciate ligament (ACL) in competitive team sports such as rugby, football (soccer) and basketball. Additionally, an increase in lower-extremity injury rates are seen in younger athletes (i.e. aged 14-16 vs. 16-18 y) and in less experienced (i.e. low-level vs. high-level) youth team sport athletes [119]. ACL injuries can physically and financially cripple an athlete. Repercussions following ACL injury account for the most time missed in participation from practice and / or match time [20], long bouts of missed education or employment [17], the most financial cost to the supporting healthcare system associated with medical treatment and compensation [24] and can lead to debilitating osteoarthritis later in life [25]. In order to further understand the causality of these injuries, we must first understand the loads placed on the ACL during manoeuvres where the integrity of the knee joint is challenged.

To understand ACL injury, it is useful to consider a potential ACL injury model where combined knee loading is the likely mechanism of injury [32, 33]. The primary role of the ACL is to passively resist translation and rotation of the tibia on the femur while the quadriceps and hamstrings actively support the integrity of the knee during flexion [47, 120]. Throughout a normal range of motion, the two ACL bundles (anteromedial and posterolateral) are in a continually taut position as a result of the juxtaposed attachment sites. When the knee is fully extended, the posterolateral bundle becomes taut and when the knee is fully flexed, the anteromedial bundle becomes taut [35, 121]; stressing the ACL through multiple positions. Individual coronal and transverse loads have elevated ACL strain in cadaveric models [48] but when combined, associations between multi-plane loading can greatly increase ACL injury risk in males and females [32, 63]. Concurrent movements in the coronal plane (abduction / adduction) and transverse plane (internal / external rotation) are believed to increase stress and the possibility for injury to the ACL compared with sagittal plane motion alone [47-49, 122]. Tissue tolerance failure of the ACL is speculated to occur at a threshold of ~2,200 N of resultant force in young healthy knees [55]. However, the mechanisms and critical loads during more dynamic, multi-planar movements are far less understood [56]. In sports that require a dynamic and aggressive manoeuvre like sidestepping, where an athlete must decelerate and accelerate, increased knee loading is expected. While decelerating into the sidestep, high knee flexion velocities and the

lengthening of the anteromedial bundle of the ACL may result in high tension of the viscoelastic tissues [123]. Similarly, while accelerating out of the sidestep, high knee extension velocities and the lengthening of the posterolateral bundle of the ACL may also result in high tension of the viscoelastic tissues [123]. Both scenarios may increase the tensile loading of the ACL where a subsequent injury is possible. It is therefore important in laboratory studies to assess all phases of sidestepping.

Non-contact ACL injuries occur more frequently than in contact situations and are most commonly seen during change of direction, where the load placed on the ACL exceeds its mechanical properties [27-31]. Video data documenting ACL injuries show that three out of four injury onsets resulted from non-contact sidestepping [44]. Further video analysis studies of elite team sports have determined that sidestepping can increase the risk of non-contact ACL injuries compared with straight-line running, as sidestepping involves elements of single-leg deceleration and change of direction [33, 57, 124]. These video observations have been supported in laboratory experiments showing that coronal plane knee loading during sidestepping is six times greater than during straight-line running and two and a half times greater than transverse plane knee loading [54]. Sidestepping therefore involves neuromotor control of movements in all three planes of motion, whilst straight-line running occurs primarily in the sagittal plan. Since sidestepping is a substantially different movement from straight-line running, with different objectives and unique loads, the authors of this review deliberately decided not to include straight-line running as a reference to sidestepping. Our question of interest is the nature of sidestepping and how the biomechanics may differ when performed under anticipated or unanticipated conditions. We have therefore focused on the effect sizes for comparisons of unanticipated and anticipated sidestepping only.

A number of studies have investigated the biomechanical and neuromuscular characteristics of sidestepping as it involves an increased running velocity compared with single-leg landings, and increased skill, so that an individual might pursue or evade an opponent [41, 43, 47, 53, 57, 61, 64-71]. The examination of running velocity during sidestepping has shown increased knee loading and decreased task acquisition (sidestepping angle), with increased sidestepping velocity [74]. Each body of work has examined specific factors within the sidestep manoeuvre by replicating and modifying the common elements involved (i.e. sex [76], style [77], speed [74], angle [78] and planning [79]). The reactive component associated

with an unplanned movement has gained attention in recent years. While athletes are likely to sustain an ACL injury due to excessive knee loading by an unplanned or late decision to initiate the change-of-direction movement [79], there are currently no injury surveillance data to support or refute this idea. However, anecdotally, an unplanned movement occurs as a sudden reaction to an external stimulus such as another athlete or movement of a ball [79] or as an instantaneous action to gain better position within the playing area [80]. Experimental research has found that unplanned sidestepping generates knee loads of up to two times greater than during planned sidestepping in the coronal and transverse planes [79]. Researchers are therefore particularly interested in the carry-over of unplanned manoeuvres to game situations and the capacity to modify reaction ability through training interventions [77, 81-83]. Given differences between planned and unplanned conditions in joint moments [79] and muscle activation [84] during sidestepping, greater understanding of the effects of unplanned movements are necessary to recognise possible implications towards injury risk during sidestepping.

The aim of this review was to quantify the magnitude differences for knee mechanics during planned and unplanned phases of sidestepping.

## **Methods**

### ***Definition of terms***

Many authors examining anticipatory effects of sidestepping use different terminology when describing the study's experimental procedures. Therefore, definitions of these terms are vital to the clarity of this review. Where authors did not use the same definitions for variables, their raw data were used to derive the variables as defined in our review. A 'planned' task is synonymous with preplanned and anticipated, while an 'unplanned' task is synonymous with reactive and unanticipated. 'Sidestepping' is synonymous with a change of direction, side-step, side-step and a cut, or cutting manoeuvre.

Each article was individually assessed to determine if three-dimensional data were calculated using standard inverse dynamics [125] for the knee joint and normalised to body-height, body-mass and 100 % of the stance phase (identified as the period from initial contact to final contact of the foot, as determined by the force plate reading) to account for between-athlete variation. Knee joint moments are expressed in this review as those externally applied to the joint at the segments' distal end (Figure 5) for clarity, given that ACL injuries most

likely occur when these moments applied to the knee exceed the limits of the joints' integrity [81]. A knee flexor moment acts to flex the knee, whereas a knee extensor moment acts to extend the knee. An abductor moment abducts the knee into a knock-kneed or valgus position (defined as the movement of the distal tibia away from the midline of the body; knees in) whereas an adductor moment adducts the knee into a bow-legged or varus position (defined as the movement of the distal tibia toward the midline of the body; knees out). An internal rotator moment internally rotates the knee, whereas an external rotator moment externally rotates the knee [54, 126]. Following the movement descriptions above, knee extensor, abductor and external rotator moments are expressed as positive values in  $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  and knee flexion, adduction and internal rotation angles are expressed as positive values in degrees [126]. 'Initial contact' is defined as the time where vertical ground reaction force is higher than 10 N [127]. 'Weight acceptance' is defined as the average between initial contact and the first trough in the vertical ground reaction force trace or the first 20-30 % of stance [54, 77, 79, 81-84, 126]. 'Peak push-off' is defined as either the maximum / minimum value in the dependent variable [77, 127] or the average of 10 % either side of the peak vertical ground reaction force [54, 79, 81, 84]. 'Final push-off' is defined as the average of the last 15 % of stance in the vertical ground reaction force [79].



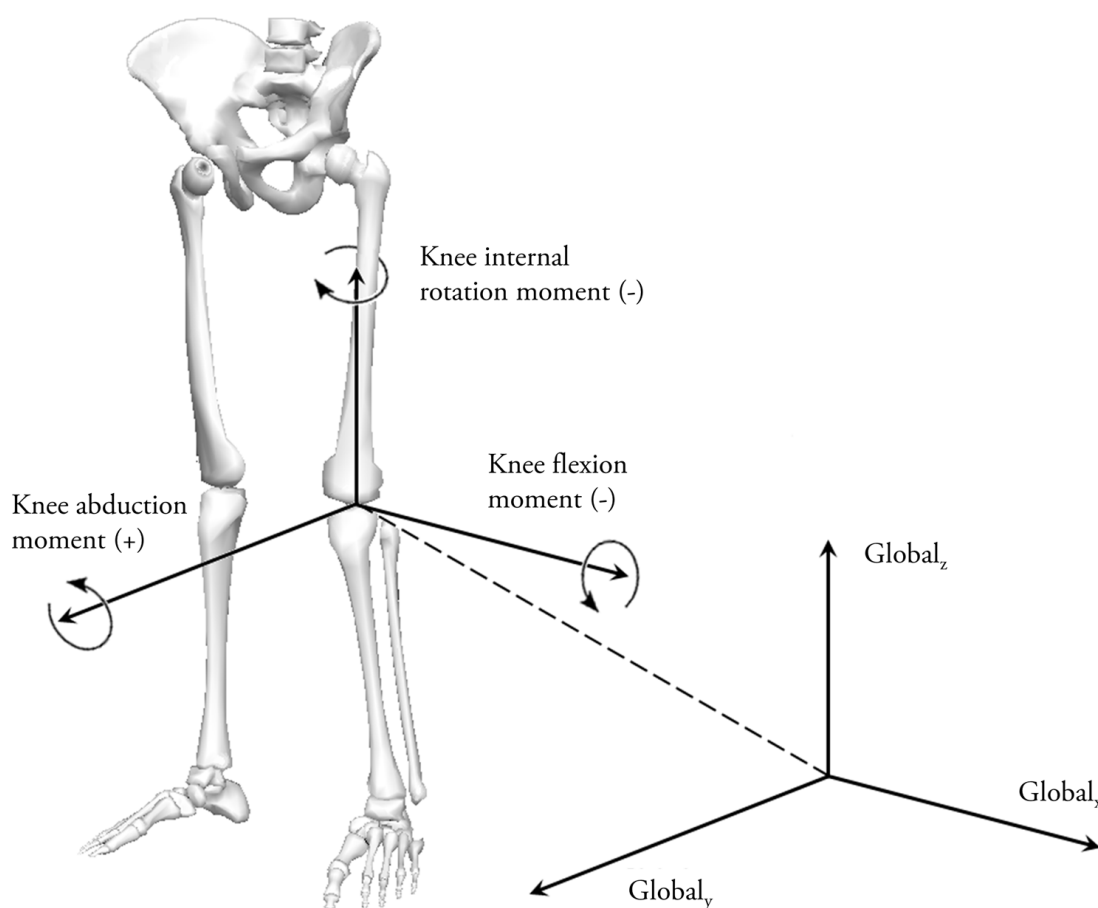


Figure 5. External knee moments.

External knee moments assigned three rotational degrees of freedom (flexion / extension, abduction / adduction and internal / external rotation) described locally and referenced with respect to a global coordinate system [75].

#### *Search parameters and criteria*

PubMed, CINAHL, MEDLINE (EBSCO), SPORTDiscus and Web of Science electronic databases were searched online up to May 2014. The employed search strategy limited database results to academic journals, reviews, dissertations and human subjects when applicable. Keywords were arranged to include either knee mechanics OR knee kine\*, AND plan\*, unplan\*, anticipat\*, unanticpat\*, side\*, cut\* or chang\*. Inclusion criteria for this review included articles providing one of the following variables: knee joint angles, ground reaction forces (GRFs), knee moments, knee power and / or lower extremity electromyography (EMG) during sidestepping. Exclusion criteria included articles that (1) were unavailable in English and not previously referred to by other sources; (2) were only available in abstract or conference proceeding form; (3) used protocols involving a jump-

landing or a landing from a raised surface; (4) did not analyse the effects of planned versus unplanned; (5) did not maintain a running velocity greater than  $2 \text{ m}\cdot\text{s}^{-1}$ ; (6) did not separate the participants into males and females; or (7) comprised a case study, a poorly designed cohort / case-control study, anecdotal evidence, animal research, bench research or unpublished clinical observations (i.e. levels of clinical evidence and study design of 4 or 5 as adapted from the Oxford Centre for Evidence-Based Medicine) [128]. Only full text sources were included so that methodology detail could be assessed. A comprehensive hand search of article reference lists and citation tracking on Google Scholar were used to identify any additional relevant articles. After performing the search, two of the authors from the current study independently screened each article for inclusion. The screening process was performed by (1) screening for duplicates; (2) screening the title; (3) screening the abstract; and (4) screening the full paper using the exclusion criteria. If the two authors were not in agreement with the inclusion / exclusion criterion of the study, a third author independently reviewed the study and a discussion occurred until consensus was reached.

When the issue of the effects of sex on knee mechanics arose, the literature was scrutinised to determine the appropriate action of inclusion. While some studies [129, 130] have reported similarities between kinematic and kinetic variables between males and females during sidestepping and single-limb landing, a majority of literature [51, 63, 131-138] has demonstrated that sex substantially affects knee mechanics during athletic manoeuvres. Females exhibit decreases in knee flexion angle ( $15^\circ$  less) [136] and increases in knee abduction angle (up to  $11^\circ$  more) [51, 136] when compared with males with similar athletic backgrounds during sidestepping. Additionally, female football and basketball athletes were reported to experience decreased peak flexor moments ( $0.70 \text{ Nm}\cdot\text{kg}^{-1}$  less) [76] and increased abductor moments (up to  $0.42 \text{ Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  greater) [63, 76] when compared with males of the same athletic background during sidestepping. There is also a stronger association between increased peak abductor moments and increased knee abduction angles for these females [63]. It was therefore decided by the authors to include only articles that separated male and female data during sidestepping.

### *Assessment of study quality*

Following the article search and examination, full text articles were retrieved, and a methodological quality assessment was performed. Although this type of evaluation is usually

quantified using the Delphi, Physiotherapy Evidence Database (PEDro) or Cochrane scales, many of the criteria were not relevant for the current review. For example, none of the included studies of this review would meet six of the 11 criteria of the PEDro scale: random allocation; concealed allocation; subject blinding; therapist blinding; assessor blinding; and intervention-to-treat analysis. Given that studies included would receive poor methodological scores as a reflection of a poor choice in quality scale rather than in the study design, two authors from the current study independently assessed each article using a ten-item custom-designed methodological quality assessment scale (see Table 7) comprising a 20-point scoring system (ranging from 0 to 20) where 0 = clearly no; 1 = maybe or inadequate information; and 2 = clearly yes. The scale in this review was adopted from similar quality assessments created by our group [139, 140] and was designed to assess the methodological quality of studies examining sidestepping. Subsequent to the quality rating, a third author from the current study assessed the articles and their rating to confirm or resolve all results. Several of the studies included in this review were likely to have referenced the biomechanical modelling procedures in previous research [54, 141]. However, the test–retest reliability of measurement devices (question eight) needed to be stated in text to fully satisfy this criterion.

### ***Data extraction and analysis***

Data were first extracted and categorised as kinematic (knee joint angles) or kinetic (knee joint moments) variables. The data were separated by planes or action (flexion / extension, abduction / adduction and internal / external rotation) and then further separated by the phase of stance (initial contact, weight acceptance, peak push-off and final push-off).

When standard deviations were not reported and could not be obtained from the authors, data were imputed using the following methods [140]: (1) similar variable and phase standard deviations reported were grouped together and independently squared; (2) the squared values were averaged together; (3) the square root of this average was used as the imputed standard deviation in that group. This method was repeated for the different phases of sidestepping. Similarly, when p-values were not accessible, imputation was performed as follows: (1) the standard deviation change of the mean was imputed based on similar studies' methods and athlete characteristics; (2) the standard deviation change of the mean was divided by the square root of the sample size to obtain the standard error of the mean change; (3) absolute value of the mean change was divided by the standard error of the mean change to obtain the

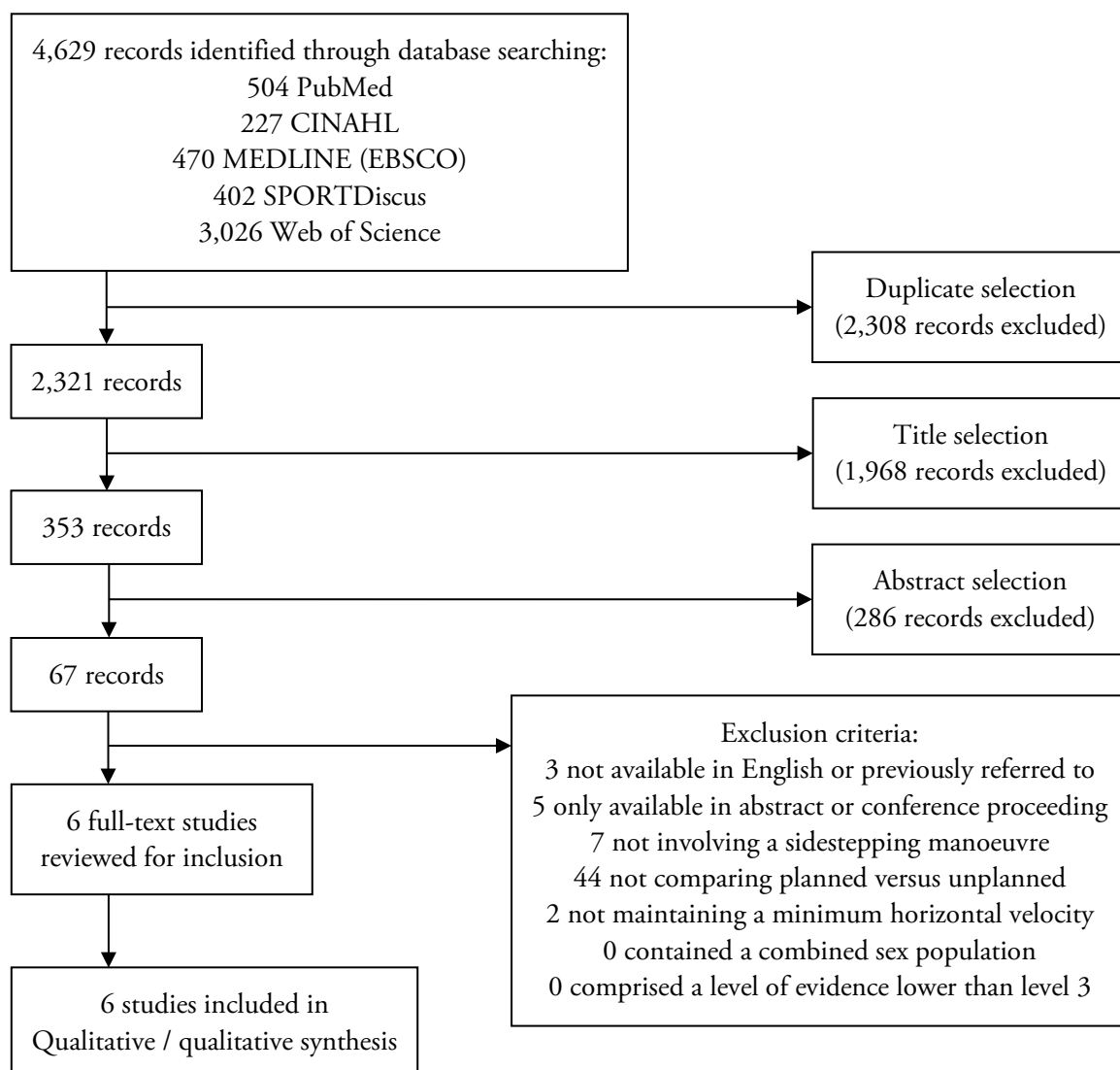
$t$  statistic; (4) a two-tailed Student's  $t$  distribution was used to obtain the imputed  $p$  value [142]. Imputed data are distinguished in the tables being surrounded by curved parentheses whereas back-calculated  $p$ -values from inequalities are surrounded by squared brackets. Once all data in the tables were complete, the standard error of measurement, the difference between the means, and the 90% confidence limits were computed. The magnitude of the difference was then assessed by standardisation by dividing the difference between the means (unplanned sidestepping mean [UNPm] minus the planned sidestepping mean [Pm]) by the planned sidestepping standard deviation (Psd) ( $\frac{UNPm-Pm}{PSSsd}$ ). Planned sidestepping was used as a baseline in this review as it is commonly chosen for analysis purposes. Threshold values of 0.2, 0.6, 1.2, 2.0 and 4.0 representing small, moderate, large, very large and extremely large differences, respectively, were used to assess the magnitude of standardised effects [142]. Uncertainty in the estimates was expressed as 90 % confidence limits, and qualitative probabilistic inferences were made regarding the true effect of the difference. If the true effect being substantially positive or negative were both >5 %, the effect was expressed as unclear; otherwise the effect was clear and expressed as the magnitude of its observed value using the following scale: 25-74 %, possible; 75-94 %, likely; 95-99.5 %, very likely; and >99.5 %, most likely [142]. Similarly, differences between the means with 90 % confidence limits and standardised inferences (ES,  $\pm 90$  % CL; qualitative inference on the likelihood the meta-analysed effect is clear) were calculated using a spreadsheet for combining independent groups with a custom weighting factor based on the standard error of the study estimate and the pooled standard deviation of planned sidestepping, effectively equivalent to weighting by sample size, for effects [142].

## Results

### *Search results*

The initial search procedure yielded 4,629 total records through five electronic databases. After removing duplicates, 2,321 publications were retained for the article selection process. Title selection excluded 1,968 records, and abstract selection excluded 286 records. The remaining 67 records were further examined using the specified inclusion / exclusion criterion, and 61 records were rejected, leaving six studies [77, 79, 81, 83, 126, 127] to directly compare planned versus unplanned conditions (see Figure 6). Three of these studies

[77, 81, 83] involved a training intervention with Australian football, rugby union or football athletes, therefore only pre-intervention or control data were used.



**Figure 6. Systematic flow-chart.**

Flow of information through the different phases of the systematic review.

### *Methodological quality assessment*

The methodological quality assessment (Table 7) used in this review was adopted from similar quality assessments [139, 140] and developed specifically for biomechanical testing of sidestepping. As such, it was expected that the mean and standard deviation of the scale would be very similar and reflect a true assessment of the included studies. Of the six studies assessed, there was a mean score of 16 / 20 (range 14–18). Only two studies used power analysis for sample size calculation. All studies presented athlete demographics, characteristics and inclusion / exclusion criterion clearly or at least partially and provided detailed and

repeatable descriptions of methods, clearly defined outcome variables and used appropriate statistical analyses. Test–retest reliability of measurement devices was only partially presented or referred to in all of the six studies included. The two highest scoring studies performed a power analysis and provided some test–retest reliability data, whereas the bottom three scoring studies did not include a power analysis.

**Table 7. Methodological quality assessment.**

Question	Criteria	Lee et al. [126]	Dempsey et al. [77]	Cortes et al. [127]	Donnelly et al. [83]	Besier et al. [79]	Cochrane et al. [81]
1	Power analysis was performed and justification of study sample size given.	2	2	0	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height and body-mass at the time of the test.	2	1	2	2	2	2
3	Athlete characteristics were clearly defined: Sport, experience or activity level and level of play at the time of test.	2	2	2	2	1	1
4	Inclusion and exclusion criteria were clearly stated for athletes.	1	1	2	2	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	2	2	2	2
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarisation.	2	2	1	1	2	1
7	Methods were described in great detail to allow replication of the test. Testing devices, number of trials, number and duration of rest, speed, angle, height and test limb were included when applicable.	2	2	2	2	2	2
8	Test-retest reliability of measurement device reported.	1	1	1	1	1	1
9	Outcome variables were clearly defined.	2	2	2	2	2	2
10	Statistical analyses were appropriate.	2	2	2	2	2	2
Total score (maximum 20 points)		18	17	16	16	15	14

Footnote: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes.

### *Study characteristics*

Athletic team sport populations (e.g. rugby and football), with abilities varying from university club sport to professional sport, were used in all studies (Table 8). Pooled means  $\pm$  standard deviation for age, body-height and body-mass were  $21 \pm 4$  y,  $1.8 \pm 0.1$  m and  $74 \pm 10$  kg, respectively. The most common sidestepping angle was  $45^\circ$  (range  $30\text{--}60^\circ$ ) at attempted speeds between  $3.0$  and  $5.7 \text{ m}\cdot\text{s}^{-1}$ . Only two studies standardised the footwear of the footballers tested; reporting no shoes (barefooted) [79] or running shoes [127]. Only the preferred sidestepping leg was used to define the direction of the sidestep manoeuvre. All but one study [127] included in this review reported the joint moments as externally applied. Similarly, all studies reported knee moments as normalised to body-mass and body-height ( $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) except for one [79] which reported knee moments normalised only to body-mass ( $\text{Nm}\cdot\text{kg}^{-1}$ ). Non-uniform data were adjusted for consistency where possible or noted as different in the footnote section.



Table 8. Athlete characteristics used in Chapter 2.

Reference	Methodological score	Study design	Athletes ( <i>n</i> ) and gender	Age (y)	Body-height (m)	Body-mass (kg)	Sport	Level (playing experience)	Attempted angle (°)	Actual angle (°)	Attempted speed (m·s <sup>-1</sup> )	Actual speed (m·s <sup>-1</sup> )
Lee et al. <sup>a</sup> [126]	18	Cross-sectional	15 M	23 ± 4	1.8 ± 0.1	71 ± 7	Football	Amateur league (7.5 ± 1.3 y)	45 ± 10	N / A	4.5 ± 0.5	N / A
Lee et al. <sup>b</sup> [126]	18	Cross-sectional	15 M	23 ± 4	1.8 ± 0.0	74 ± 10	Football	Semi-professional (14 ± 4 y)	45 ± 10	N / A	4.5 ± 0.5	N / A
Dempsey et al. <sup>c</sup> [77]	17	Training intervention	9 M	20 ± 1	1.8 ± 0.1	80 ± 13	Australian football, rugby union and football	University sporting club	45 ± 5	P: 32.1 ± 4.7 UNP: 29.8 ± 5.1	5.2 ± 0.5	P: 5.7 ± 0.4 UNP: 5.1 ± 0.3
Cortes et al. [127]	16	Cross-sectional	13 F	19 ± 1	1.7 ± 0.1	61 ± 6	Football	NCAA D1	45 ± 10	N / A	Min 3.5	P: 4.4 ± 0.5 UNP: 3.7 ± 0.2
Donnelly et al. <sup>c</sup> [83]	16	Training intervention	58 M	21 ± 3	1.9 ± 0.0	81 ± 10	Australian football	Amateur	45	P: 16.0 ± 3.2 UNP: 16.0 ± 3.2 30° P: 31 ± 3.4 UNP: 33 ± 2.2 60° P: 56 ± 4.4 NP: 53 ± 4.1	4.5 - 5.5	P: 4.6 ± 0.5 UNP: 4.4 ± 0.6 30° P: 2.7 ± 0.1 UNP: 2.6 ± 0.1 60° P: 2.3 ± 0.1 UNP: 2.3 ± 0.1
Besier et al. [79]	15	Cross-sectional	11 M	21 ± 3	1.8 ± 0.1	74 ± 7	Football	Amateur	30 and 60		3.0	
Cochrane et al. <sup>c</sup> [81]	14	Training intervention	50 M	23 ± 6	1.8 ± 0.1	78 ± 10	Australian football	Limited previous exposure to endurance, strength, or balance training	30 and 60	N / A	4.0 - 4.5	N / A

Footnote: Study and athlete characteristics. <sup>a</sup> low-level athletes, <sup>b</sup> high-level athletes, <sup>c</sup> only pre-intervention or control data used. M, male; F, female; NCAA D1, National Collegiate Athletic Association Division I; N / A, not applicable; P, planned; UNP, unplanned; Min, minimum. Values are means ± standard deviation where applicable.

### *Kinematic / Kinetic study variables*

Possibly trivial to most likely small effects ( $ES = 0.037\text{--}0.59$ ) were seen in knee flexion angles during the weight acceptance phase, while much larger effects were seen during peak push-off; ranging from likely small to likely large ( $ES = 0.30\text{--}1.6$ ). The meta-analysed effect of knee flexion angle during weight acceptance and peak push-off were unclear and possible moderate ( $ES = 0.95$ ) respectively. Likely and very likely small effects ( $ES = 0.30$  and  $0.41$ ) were seen during final push-off in knee flexion angles. A possibly trivial effect ( $ES = 0.18$ ) and a possibly moderate effect ( $ES = 0.60$ ) were seen in knee abduction angles during initial contact and peak push-off, respectively. A likely small effect ( $ES = 0.45$ ) was seen in internal rotation angles during initial contact. All other kinematic effects for unplanned sidestepping were unclear.

A possibly large effect ( $ES = 1.3$ ) was seen in knee flexor moments during initial contact, while most likely trivial to possibly small effects ( $ES = 0.051\text{--}0.20$ ) were seen during weight acceptance. The meta-analysed effect of knee flexor moment during weight acceptance was most likely trivial ( $ES = 0.090$ ). Possibly small to likely moderate effects ( $ES = 0.22\text{--}0.70$ ) were seen during peak push-off, and likely trivial to likely small effects ( $ES = 0.083$  and  $0.30$ ) were seen in knee flexor moments during final push-off. The meta-analysed effect of knee flexor moment during peak push-off was possibly trivial ( $ES = -0.19$ ). A possibly trivial effect ( $ES = 0.15$ ) was seen in knee adductor moment during initial contact, while a range of likely small to very likely moderate effects ( $ES = 0.37\text{--}1.1$ ) were seen at weight acceptance. The meta-analysed effect of knee abductor moment during weight acceptance was very likely moderate ( $ES = 0.65$ ). Likely trivial to very likely small effects ( $ES = 0.13\text{--}0.57$ ) were seen at peak push-off, and likely to very likely moderate effects ( $ES = 0.70$  and  $0.88$ ) were seen in knee abductor moments at final push-off. The meta-analysed effect of knee abductor moment during peak push-off was possibly trivial ( $ES = 0.19$ ). Likely small to very likely large effects ( $ES = 0.36\text{--}1.7$ ) were seen in knee internal rotator moments at weight acceptance, while possibly trivial and possibly moderate effects ( $ES = 0.18$  and  $0.64$ ) were seen at peak push-off, and likely moderate effects ( $ES = 0.71$  and  $0.75$ ) at final push-off. The meta-analysed effect of knee internal rotator moment during weight acceptance was possibly trivial ( $ES = 0.20$ ). Kinetic effects of unplanned sidestepping for all other variables were unclear.

## Discussion

### *Knee joint kinematics*

In sidestepping, the body experiences a deceleration and acceleration phase similar to straight-line running. Sidestepping becomes unique when the body attempts to re-orientate the centre of mass to initiate the change of direction. Knee flexion angles of  $\sim 15^\circ$  were seen at initial contact during planned conditions in the two studies that reported this variable (Table 9). During the unplanned condition, knee flexion increased between  $1^\circ$  and  $5^\circ$ . The larger increase of  $5^\circ$  was seen in the only study involving female footballers. These results are similar to two studies [143, 144] that reported larger knee flexion angles in females during unplanned sidestepping than in males; specifically at initial contact of stance.

Table 9. Knee kinematics during planned and unplanned sidestepping.

Knee joint angles Sidestepping phase	Angle of sidestep (°)	Planned sidestep (°)	Unplanned sidestep (°)	<i>p</i> value	SEM	Unplanned – planned sidestepping	
						Mean change; ±90 % CL	Qualitative inference
Flexion (+) / Extension (–)							
Initial contact							
Cortes et al. [127]	45	15 ± 5	21 ± 5	[0.0010]	3.1	5.3; ±2.2	Trivial*
Dempsey et al. <sup>a</sup> [77]	45	14 ± 5	15 ± 5	(0.37)	(3.1)	1.4; ±2.7	Unclear
Weight acceptance							
Besier et al. <sup>b</sup> [79]	30	32 ± (6)	35 ± (6)	[8.2E–5]	1.2	3.3; ±0.9	Small +ive****
Besier et al. <sup>c</sup> [79]	60	32 ± (6)	34 ± (6)	0.0050	1.3	2.0; ±1.0	Small +ive**
Cochrane et al. <sup>a</sup> [81]	30	26 ± 6	26 ± 7	0.42	3.7	0.59; ±1.23	Trivial*
Cochrane et al. <sup>a</sup> [81]	60	25 ± 6	25 ± 7	0.38	4.1	0.73; ±1.37	Trivial*
Dempsey et al. <sup>a</sup> [77]	45	30 ± 5	32 ± 3	0.038	2.1	2.4; ±1.8	Small +ive**
Donnelly et al. <sup>a</sup> [83]	45	30 ± 5	30 ± 5	(0.602)	(2.1)	0.20; ±0.64	Trivial***
<i>Meta-analysed effect</i>		± 5.5				1.6; ±0.6	Unclear
Peak push-off							
Besier et al. <sup>b</sup> [79]	30	45 ± (6)	51 ± (6)	[2.3E–7]	1.0	5.4; ±0.8	Moderate +ive****
Besier et al. <sup>c</sup> [79]	60	47 ± (6)	51 ± (6)	[9.4E–6]	1.1	3.9; ±0.9	Moderate +ive**
Cochrane et al. <sup>a</sup> [81]	30	48 ± 6	54 ± 7	2.3E-11	3.2	5.5; ±1.1	Moderate +ive****
Cochrane et al. <sup>a</sup> [81]	60	53 ± 6	54 ± 6	0.019	3.9	1.9; ±1.3	Small +ive**
Cortes et al. [127]	45	45 ± 5	52 ± 6	[0.0010]	4.3	7.2; ±3.0	Large +ive**
<i>Meta-analysed effect</i>		± 5.6				5.3; ±1.3	Moderate +ive*
Final push-off							
Besier et al. <sup>b</sup> [79]	30	23 ± (5)	25 ± (5)	[9.2E–4]	1.0	2.0; ±0.8	Small +ive***
Besier et al. <sup>c</sup> [79]	60	23 ± (5)	24 ± (5)	0.012	1.1	1.5; ±0.9	Small +ive**
Abduction (–) / Adduction (+)							
Initial contact							
Cortes et al. [127]	45	-0.80 ± 3.90	-1.5 ± 3.9	0.039	0.77	-0.70; ±0.54	Trivial*
Peak push-off							
Cortes et al. [127]	45	-4.0 ± 5.3	-7.2 ± 5.3	[0.0010]	1.9	-3.2; ±1.3	Moderate +ive*
Internal (+) / External rotation (–)							
Initial contact							
Cortes et al. [127]	45	5.2 ± 6.5	8.2 ± 4.7	0.031	3.0	2.9; ±2.1	Small +ive**

Footnote: Values are mean  $\pm$  SD;  $\pm$  *pooled standard deviation*; standard error of measurement (SEM); mean change;  $\pm$  confidence limits (CL) (90 %); *meta-analysed effect*;  $\pm 90$  % confidence limits (CL). (+), a positive kinematic value is associated with the corresponding knee joint angle; (–), a negative kinematic value is associated with the corresponding knee joint angle curved parentheses, imputed values; squared brackets, back-calculated p values from inequalities; +ive, –ive, substantial positive and negative changes with unplanned relative to planned sidestepping. Trivial, small, moderate and large inference: \* possibly, 25–75 %; \*\* likely, 75–95 %; \*\*\* very likely, 95–99.5 %; \*\*\*\* most (or extremely) likely, >99.5 %. <sup>a</sup> Only pre-intervention or control data used, <sup>b</sup> 30° sidestepping task, <sup>c</sup> 60° sidestepping task.

Similarly, during weight acceptance, knee flexion angles increased from  $\sim 29^\circ$  for planned sidestepping to  $\sim 31^\circ$  for unplanned sidestepping, with only small effects. Peak push-off showed the largest increases between planned and unplanned conditions; with likely to most likely moderate and likely large increases in average knee angles of  $\sim 48^\circ$  in planned to  $\sim 52^\circ$  in unplanned sidestepping. Final push-off also showed slight differences ( $\sim 1\text{--}2^\circ$ ) between conditions and was characterised with likely and very likely small effects. Larger knee flexion angles were seen in all unplanned conditions, irrespective of the phase or degree at which sidestepping occurred. Unanticipated sidestepping may start off slow and then speed up as the trials continue and the athletes are advised to sidestep as quickly as possible when they receive the direction stimulus; resulting in the larger knee flexion angles. Unfortunately, this idea is purely speculative at this time, as many studies have only controlled for the velocity of the approach run but have not reported the velocity throughout the phases. Interestingly, a reduced knee flexion angle ( $< 30^\circ$ ) has been considered [145, 146] a possible risk factor for ACL injury, as the anatomical location of the anterior and posterior ACL bundles allow for a continually taut position while the knee moves through its range of motion. Biomechanical simulations [49] have also highlighted the presence of a ceiling effect on ACL loading during sidestepping. More specifically, an interaction between lower-extremity muscles and joint mechanics in the sagittal plane can act together and assist the integrity of the ACL during athletic manoeuvres.

Movements eliciting high abduction angles may be a risk factor for ACL injury [147]; however, it is unclear whether knee abduction angles alone are a mechanism for ACL injury or whether it is only influential in combination with a high proximal tibia anterior shear force [148]. Knee abduction has been shown as more than a collapse of the knee but rather a combination of hip adduction and internal rotation, tibial external rotation and anterior translation, and ankle eversion [91, 149]. Any number of combinations of these movements can potentially influence the knee into a more abducted position, bringing the knee closer to the midline of the body. In this review, coronal plane knee angles were only reported by one study [127] at initial contact and peak push-off. Effects between adduction angles during planned and unplanned sidestepping only had a possibly small effect at initial contact, whereas peak adduction angle revealed a possibly moderate effect. Similar studies to those included in this review have independently noted that females demonstrate greater coronal

knee angles than males during planned [137, 150] and unplanned [134, 143, 151] sidestepping. Sigward et al. [152] reported knee abduction angles of  $\sim 3^\circ$  for males and  $\sim 6^\circ$  for females during planned sidestepping when maturation groups were combined. Female basketball athletes also demonstrated similar angles of  $\sim 7^\circ$  during planned conditions [153]. During unplanned sidestepping in collegiate footballers,  $1.5^\circ$  knee abduction for males and  $2.4^\circ$  for females were reported [130]. However,  $11^\circ$  in females during planned conditions and up to  $\sim 15^\circ$  and  $\sim 19^\circ$  for males and females during unplanned conditions were reported [134, 154].

Similar to coronal plane knee angles, internal rotation angles were only reported by one study [127] during the initial contact phase of sidestepping in females. Internal rotation angles of  $5.2^\circ$  and  $8.1^\circ$  during planned and unplanned conditions at initial contact had a likely small effect between conditions. A similar study [155] not included in the meta-analysis noted planned internal rotation of  $5.1^\circ$  occurring during the first 10-30% of stance in a healthy male and female control group. While the results from this review seem to follow the supporting literature, it remains very difficult to make meaningful inferences on coronal and transverse knee angles due to the lack of data.

As ACL injuries often occur during initial contact and weight acceptance [57, 58], the sagittal plane results of the current review do not seem to support this notion alone. Instead, the results suggest that a combination of knee angles in multiple planes may have a negative influence on knee loading. A greater risk of ACL injury will then occur when force passes through the knee joint or is applied to the ACL. Unfortunately, coronal and transverse kinematics are believed to produce large measurement errors with cross-talk and artefacts; leaving room for misinterpretation of data [156]. Many authors therefore prefer not to present coronal and transverse kinematic data, explaining why sagittal plane angles are the most commonly presented kinematic variable in sidestepping studies. Definitive conclusions regarding the impact of knee angles on injury risk in multiple planes are unavailable at this time.

### ***Knee joint kinetics***

Sagittal plane knee moments during sidestepping are similar to those during straight-line running in all phases of stance [157, 158]. From Table 10 it can be seen that knee flexor / extensor moments were also similar between planned and unplanned conditions, which is in

agreement with previous research [159]. A likely large effect was seen at initial contact, with a 163% increase between planned and unplanned conditions. Possibly to most likely small and likely moderate effects were seen at weight acceptance, peak push-off and final push-off. Overall increases in knee flexion moments occurred through to peak push-off and then returned to a near neutral position at final push-off as expected. Interestingly, footballers generally experienced greater knee flexion moments while decelerating during planned sidestepping than during unplanned. This may be explained by the lack of data reported for knee flexor moment at weight acceptance compared with knee flexion angle. Additionally, the difference may be due to the knowledge of the task in advance. Without the element of decision making during sidestepping, the task becomes easier to perform and therefore might explain these findings.

Table 10. Knee kinetics during planned and unplanned sidestepping.

Knee joint moments Sidestepping phase	Angle of sidestep (°)	Planned sidestep (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )	Unplanned sidestep (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )	<i>p</i> value	SEM	Unplanned – planned sidestepping	
						Mean change; ±90 % CL	Qualitative inference
Flexor (–) / extensor (+)							
Initial contact							
Cortes et al. [127]	45	-0.16 ± 0.14	0.014 ± 0.110	0.0030	0.12	0.18; ±0.09	Large -ive*
Weight acceptance							
Besier et al. <sup>a, b</sup> [79]	30	-0.29 ± 0.37	-0.31 ± 0.45	0.73	0.12	-0.019; ±0.096	Unclear
Besier et al. <sup>b, c</sup> [79]	60	-0.24 ± 0.47	-0.15 ± 0.47	0.14	0.14	0.093; ±0.105	Small +ive*
Dempsey et al. <sup>d</sup> [77]	45	-1.0 ± 0.3	-0.91 ± 0.23	(0.337)	(0.13)	0.060; ±0.109	Trivial*
Donnelly et al. <sup>d</sup> [83]	45	-2.1 ± 0.6	-2.2 ± 0.4	0.39	0.12	-0.020; ±0.041	Trivial****
<i>Meta-analysed effect</i>		± 0.43				-0.039; ±0.050	Trivial****
Peak push-off							
Besier et al. <sup>a, b</sup> [79]	30	-2.2 ± 0.6	-2.4 ± 0.6	0.010	0.10	0.14; ±0.08	Small -ive*
Besier et al. <sup>b, c</sup> [79]	60	-2.0 ± 0.5	-1.6 ± 0.6	[1.2E-5]	0.11	-0.37; ±0.08	Moderate +ive**
Cortes et al. [127]	45	-1.9 ± 0.2	-1.9 ± 0.2	0.27	0.09	0.042; ±0.065	Small -ive*
<i>Meta-analysed effect</i>		± 0.43				-0.080; ±0.042	Trivial*
Final push-off							
Besier et al. <sup>a, b</sup> [79]	30	0.010 ± 0.125	-0.027 ± 0.150	0.016	0.031	0.038; ±0.024	Small -ive**
Besier et al. <sup>b, c</sup> [79]	60	0.041 ± 0.145	0.029 ± 0.200	0.41	0.033	0.012; ±0.026	Trivial**
Abductor (+) / adductor (–)							
Initial contact							
Cortes et al. [127]	45	-0.050 ± 0.080	-0.038 ± 0.070	0.25	0.025	0.012; ±0.018	Trivial*
Weight acceptance							
Besier et al. <sup>a, b</sup> [79]	30	0.024 ± 0.270	0.31 ± 0.29	[2.7E-5]	0.092	0.29; ±0.07	Moderate -ive***
Besier et al. <sup>b, c</sup> [79]	60	0.33 ± 0.34	0.51 ± 0.33	[0.0020]	0.10	0.18; ±0.08	Small -ive***
Dempsey et al. <sup>d</sup> [77]	45	0.38 ± 0.26	0.40 ± 0.23	(0.67)	(0.097)	0.020; ±0.085	Unclear
Donnelly et al. <sup>d</sup> [83]	45	0.37 ± 0.30	0.48 ± 0.27	0.13	0.38	0.11; ±0.12	Small -ive**
Lee et al. <sup>e</sup> [126]	45	0.31 ± 0.28	0.59 ± 0.25	(7.4E-4)	(0.18)	0.28; ±0.11	Moderate -ive**
Lee et al. <sup>f</sup> [126]	45	0.47 ± 0.26	0.72 ± 0.36	(1.8E-3)	(0.18)	0.25; ±0.11	Moderate -ive**
<i>Meta-analysed effect</i>		± 0.29				0.19; ±0.04	Moderate +ive***



Table 10 continued.

Knee joint moments Sidestepping phase	Angle of sidestep (°)	Planned sidestep (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )	Unplanned sidestep (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )	<i>p</i> value	SEM	Unplanned – planned sidestepping	
						Mean change; ±90 % CL	Qualitative inference
Peak push-off							
Besier et al. <sup>a, b</sup> [79]	30	-0.33 ± 0.90	-0.18 ± 0.97	0.0050	0.097	0.15; ±0.07	Small -ive***
Besier et al. <sup>b, c</sup> [79]	60	-0.20 ± 0.99	-0.070 ± 0.730	0.014	0.11	0.13; ±0.08	Trivial**
Cortes et al. [127]	45	-0.52 ± 0.40	-0.37 ± 0.36	0.035	0.16	0.15; ±0.11	Small -ive**
<i>Meta-analysed effect</i>		± 0.76				0.14; ±0.05	Trivial*
Final push-off							
Besier et al. <sup>a, b</sup> [79]	30	0.12 ± 0.11	0.22 ± 0.09	[1.8E-5]	0.030	0.098; ±0.023	Moderate -ive***
Besier et al. <sup>b, c</sup> [79]	60	0.21 ± 0.12	0.29 ± 0.12	[1.3E-4]	0.033	0.084; ±0.025	Moderate -ive**
Internal (-) / external rotator (+)							
Weight acceptance							
Besier et al. <sup>a, b</sup> [79]	30	-0.075 ± 0.055	-0.17 ± 0.10	[5.9E-6]	0.026	-0.096; ±0.020	Large -ive***
Besier et al. <sup>b, c</sup> [79]	60	-0.15 ± 0.08	-0.23 ± 0.09	[1.1E-4]	0.028	-0.074; ±0.022	Moderate -ive***
Dempsey et al. <sup>d</sup> [77]	45	-0.17 ± 0.07	-0.26 ± 0.18	(0.0010)	(0.039)	-0.090; ±0.035	Large -ive*
Donnelly et al. <sup>d</sup> [83]	45	-0.33 ± 0.36	-0.20 ± 0.15	0.0020	0.22	0.13; ±0.07	Small +ive**
Lee et al. <sup>e</sup> [126]	45	-0.20 ± 0.10	-0.15 ± 0.11	(0.012)	(0.048)	0.050; ±0.031	Small +ive**
Lee et al. <sup>f</sup> [126]	45	-0.21 ± 0.10	-0.15 ± 0.10	(0.0040)	(0.048)	0.060; ±0.031	Moderate +ive*
<i>Meta-analysed effect</i>		± 0.15				0.030; ±0.024	Trivial*
Peak push-off							
Besier et al. <sup>a, b</sup> [79]	30	-0.27 ± 0.12	-0.34 ± 0.10	[5.9E-4]	0.036	-0.076; ±0.028	Moderate -ive*
Besier et al. <sup>b, c</sup> [79]	60	-0.31 ± 0.12	-0.33 ± 0.10	[0.217]	0.039	-0.022; ±0.030	Trivial*
Final push-off							
Besier et al. <sup>a, b</sup> [79]	30	-0.035 ± 0.032	-0.059 ± 0.030	[8.7E-5]	0.0087	-0.023; ±0.007	Moderate -ive**
Besier et al. <sup>b, c</sup> [79]	60	-0.060 ± 0.042	-0.090 ± 0.040	[2.7E-5]	0.0095	-0.029; ±0.007	Moderate -ive**

Footnote: Values are mean ± standard deviation; ± *pooled standard deviation*; standard error of measurement (SEM); mean change; ±confidence limits (CL) (90 %); *meta-analysed effect*; ±90 % *confidence limits (CL)*. (+), a positive kinetic value is associated with the corresponding knee joint moment; (-), a negative kinetic value is associated with the corresponding knee joint moment; curved parentheses, imputed values; squared brackets, back-calculated *p* values from inequalities; +ive, -ive, substantial positive and negative changes with unplanned relative to planned sidestepping. Trivial, small, moderate and large inference: \* possibly, 25–75 %; \*\* likely, 75–95 %; \*\*\* very likely, 95–99.5 %; \*\*\*\* most (or extremely) likely, >99.5 %. <sup>a</sup> 30° sidestepping task, <sup>b</sup> Knee moment data reported as Nm·kg<sup>-1</sup>, <sup>c</sup> 60° sidestepping task, <sup>d</sup> Only pre-intervention or control data used, <sup>e</sup> Low-level athletes, <sup>f</sup> High-level athletes.

During the loading phases in the coronal plane, unplanned conditions showed greater overall knee abduction moments than did planned conditions; with increases of ~63% at weight acceptance and ~64% at final push-off. After weight acceptance, when the body has finished decelerating, the knee experiences an adductor moment during peak push-off before returning to abduction at final push-off. It is during the early and end phases of sidestepping (both abducted conditions) where the largest differences are seen between planned and unplanned conditions; whereas the change in peak adductor moment was likely small. While one study [127] noted that footballers landed in a abducted angle, with increased abduction moment during initial contact, this population was made up of females. This finding is common for females and is supported by previous work [76], which found that 80% of female university footballers demonstrated an abductor moment during the early deceleration phase of sidestepping compared with only 40% of male university footballers. These peak coronal plane moments for females were two times greater than for males. Additional work concluded that knee abductor moments may be influenced largely by the position of the hip during sidestepping and is more evident in females than in males [63]. An internally rotated or adducted hip position may be the result of weak posterior-chain musculature or neuromuscular control and will, in turn, influence the position of the knee. This research supports the findings in the present review where female footballers demonstrated peak adductor moments 1.4 – 2.6 times greater than male footballers for similar planned conditions. Additionally, the moderate effects of a planned movement on coronal plane knee moments noted during weight acceptance and final push-off may occur due to the lack of time for postural adjustments and muscular activation strategies during sidestepping [79]. When planning can be done early, appropriate postural adjustments during change of direction are seen in laboratory testing by utilising proper foot placement strategies to reorient the centre of mass in the new direction, whereas inadequate planning utilises a trunk lean strategy for initiation [160]. Planned tasks allow for adequate time to prepare and strategise for the movement as efficiently and safely as possible; a lack of planning will increase the tasks' demands and can alter landing and sidestepping mechanics. This lack of time can also contribute to poor frontal or transverse foot placement, inadequate trunk lean or rotation or an unwanted position of the centre of mass [82, 127, 161].

During planned sidestepping, the weight-acceptance phase is completed before the initiation of a change of direction to control and direct the centre of mass towards the stance foot during knee adduction [159]. The support foot is medially positioned to assist the final push-off in changing directions. This appropriate foot orientation creates a vector towards the new direction. Conversely, unplanned sidestepping alters this pattern by initiating the change of direction during or near initial contact, when the knee is typically in abduction, with redirecting of the centre of mass away from the stance foot. The decreased decision-making time of an unplanned sidestep may not allow for an appropriate foot placement strategy to occur. As a result, contralateral trunk flexion is required to reorient the centre of mass in the desired direction of travel.

Similar to coronal plane moments, transverse plane moments are equally important when examining ACL injury during sidestepping. Substantial effects of internal rotator moments were seen during all phases of sidestepping. Unlike coronal plane knee moments that swayed back and forth between moments during stance, transverse moments stayed in internal rotation throughout stance. At weight acceptance, internal rotator moments generally increased from planned to unplanned conditions, ranging from likely small to very likely large effects between conditions. Unplanned conditions also showed likely moderate effects on internal rotator moments at final push-off. Individual changes between conditions in internal rotation moments showed large variation, with decreases of up to 39% and increases of up to 127% during weight acceptance. The reason behind this discrepancy remains unknown, as the athlete characteristics and study methodologies [79, 83] were consistent with the other included studies.

An increase in internal rotation moment and / or abductor moment will likely increase the load placed on the medial collateral ligament (MCL) as it is the principal structure responsible for resisting internal rotation and abduction at full extension and 30° of flexion [162, 163]. A complete ACL rupture would necessitate a complete MCL rupture if caused solely by a abductor moment [45, 145], however, the loading on the ACL in sidestepping is usually a combination of flexion, internal rotation and abduction and not an abductor moment in isolation [54]. Conversely, forces exclusively in the sagittal plane do not lead to ACL injury during sidestepping [49]. MCL rupture does not always occur simultaneously with ACL rupture, due to a higher failure load, fibre lines better orientated to resist abduction

load, a higher collagen density, a longer time to peak elongation and a different mechanism for restraining knee abduction in the MCL compared with the ACL [164].

*In vitro* testing [48] has shown that knee extensor moments, produced by the quadriceps during the deceleration and acceleration phases of sidestepping, do not dangerously load the ACL. However, when these forces are combined with an internal rotation moment or abductor moment, the loads placed on the ACL become greatly amplified. Specifically, when an extensor moment is combined with an internal rotation moment, ligament force is the greatest at knee flexion angles less than 20°; these high forces then diminished at angles greater than 40° [48]. In addition, similar *in vitro* testing [165] has demonstrated that hyperextension (-5°) and hyperflexion (80 – 90°) angles create the greatest loading on the ACL. Given that the degree of knee flexion during initial contact and final push-off is near or below 20°, an added internal rotation moment may only be of consequence to ACL loading. *In vivo* ACL loading has also shown that ACL high stress situations occur near full extension at initial contact and continue through the landing phase of jumping tasks [166]. Unfortunately, the degree at which *in vivo* ACL injury occurs in the knee during sport is still unknown. Extensive work has yet to be performed on cadavers to examine the force through the ACL with loading in the three planes simultaneously.

### ***Limitations***

The effects of planned and unplanned sidestepping on knee mechanics have not been substantially researched. The varying approach velocities, for example, were taken into account when the initial study selection was created, as approach velocity affects joint mechanics during sidestepping. However, in order to include the limited number of studies, we needed to lift the approach velocity constraints.

### **Conclusions**

This is the first meta-analysis to critically assess the magnitude differences for knee mechanics during planned and unplanned phases of sidestepping. Clear effects were seen between planned and unplanned sidestepping. Knee angles in the sagittal, coronal and transverse planes showed increases during unplanned sidestepping throughout all phases of stance. Mixed results were seen during peak push-off throughout all knee moments, which may infer that peak knee loads are not as impactful on the ACL as the loading phases are (i.e. weight acceptance). Overall, athletes that performed unplanned sidestepping manoeuvres

experienced higher knee joint angles and moments than those that performed planned manoeuvres, specifically during weight acceptance. Additionally, the increased angles and moments seen in the knee during these laboratory trials were also very similar to positions seen on fields / courts during ACL injury; thus, an athlete may be at a higher risk of injury during an unplanned sidestep than during a planned sidestep. More work with other unplanned manoeuvres (e.g. 180° change of direction seen in football and jump-stops seen in basketball and netball) must be conducted during these loading phases to gain a better understanding of knee mechanics. Researchers should provide better-quality evaluation of whether an athlete sustained an ACL injury when they changed direction unexpectedly or if the change of direction was pre-planned. Awareness of the possible dangers of unplanned sidestepping is important to sports biomechanists, clinicians and coaching staff. These manoeuvres are most closely related to actual game scenarios where the athlete has limited time to react to a stimulus. A better understanding of the loads placed on the body during landing phases could lead to relevant injury-prevention training programmes aimed at decreasing ACL injuries in athletes.

**Section 2:**  
**Lower-Extremity Injury Risk**  
**Assessment Tools**

## Chapter 3: Profiling Isokinetic Strength by Leg Preference and Position in Rugby Union Athletes

This chapter comprises the following paper published in *International Journal of Sports Physiology and Performance*.

### Reference:

Brown SR, Brughelli M, Bridgeman LA. Profiling isokinetic strength by leg preference and position in rugby union athletes. *Int J Sports Physiol Perform*. 2016;11(4):500-7.

### Author contribution:

Brown SR, 90%; Brughelli M, 5%; Bridgeman LA, 5%.

### Overview

Muscular imbalances aid in the identification of athletes at risk of lower-extremity injury. Little is known regarding the influence that leg preference or playing position may have on lower-extremity muscular strength and asymmetry. The purpose of this study was to investigate lower-extremity strength profiles in rugby union athletes and compare isokinetic knee and hip strength variables between legs and positions. Thirty male academy rugby union athletes, separated into forwards ( $n = 15$ ) and backs ( $n = 15$ ), participated in this cross-sectional analysis. Isokinetic dynamometry was used to evaluate peak torque, angle of peak torque and strength ratios of the preferred and non-preferred legs during seated knee-extension / flexion and supine hip-extension / flexion at  $60^\circ \cdot s^{-1}$ . Backs were older (ES = 1.6) but smaller in stature (ES = -0.47) and body-mass (ES = -1.3) compared to the forwards. The non-preferred leg was weaker than the preferred leg for forwards during extension (ES = -0.37) and flexion (ES = -0.21) actions and for backs during extension (ES = -0.28) actions. Backs were weaker at the knee than forwards in the preferred leg during extension (ES = -0.50) and flexion (ES = -0.66) actions. No differences were observed in strength ratios between legs or position. Backs produced peak torque at longer muscle lengths in both legs at the knee (ES = -0.93 to -0.94) and hip (ES = -0.84 to -1.17) compared to the forwards. In this sample of male academy rugby union athletes, the preferred leg and forwards displayed superior strength compared to the non-preferred leg and backs. These findings highlight the importance of individualised athletic assessments to detect crucial strength differences in male rugby union athletes.

## Introduction

Rugby union is classified as an intermittent high-intensity sport requiring maximal strength and power performances, interspersed with low-intensity efforts and rest periods [75]. While forwards and backs can both be involved in passing, kicking, scoring and tackling throughout an 80-minute match, an equal distribution of these events is not always practiced. In order to be successful, forwards require great force capabilities during contact situations such as front-on tackling, rucks, mauls, scrums and wrestling activities [167]. In contrast, backs require great velocity capabilities during side-on tackling and contact evasion [168]. The differing demands placed on forwards and backs may influence position-specific lower-extremity strength and asymmetry.

Profiling muscular strength via isokinetic dynamometry is commonly used to illustrate an individual's strengths and weaknesses [98, 169-171]. This type of profiling is used across a number of sports to categorise athletic performance and injury risk in athletes [168]. The majority of peer-reviewed literature has focused on amateur or professional football and rugby league athletes and has found success in reducing the risk of new or recurrent injury in these populations [98, 112, 172]. Since rugby union athletes possess substantially different strength profiles compared to similar football codes, it seems pertinent to explore these differences within the code and to profile across several ability levels. As with previous research, the information gained from strength profiling rugby union athletes could guide practitioners in specific individualised programming in regards to injury prevention and athletic performance. Further, the optimum joint angle for producing peak torque has yet to be described in rugby union athletes.

Previously the relationship between the hamstrings and the quadriceps has been based on the concentric strength of these opposing muscle groups, commonly referred to as the Conventional Strength Ratio (CSR) [173]; with a normative value of 0.60 typically reported in footballers. Recently a more functional method (Dynamic Control Ratio [DCR]) for describing this relationship has been reported, suggesting [173] that the hamstring-quadriceps ratio should be described as the eccentric hamstrings / concentric quadriceps ratio. This method is thought [174] to better represent the dynamic function of lower-extremity strength as it relates to injury risk. While there seems to be no current consensus on normative



values for the DCR, a value of 0.60 or below has been found [175] in athletes with previous hamstring injuries at an angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$ .

In an attempt to illuminate the interaction of unilateral muscular strength in the posterior-chain, a knee flexion to hip extension ratio (Posterior-Chain Ratio [PCR]) at an angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$  has been presented in elite sprinters [176], and professional rugby union and rugby league athletes [177]. This added functional ratio aids in the understanding of where an athlete's strength exists in respect to the posterior muscles crossing the knee and hip. Additionally [177], unilateral isokinetic strength has been assessed in the literature since between and / or within leg imbalances can lead to improper control of body movement and may ultimately result in injury.

The purpose of the current study was to assess isokinetic muscular strength profiles of the knee and hip joints in male academy-level rugby union forwards and backs and to compare the preferred and non-preferred legs during these movements. In line with current research [177], it was expected that forwards would display superior strength in the posterior-chain compared to backs while the backs would produce peak torque at longer muscle lengths (i.e. smaller angles during knee flexion and larger angles during knee extension).

## Methods

### *Athletes*

Thirty male academy (development-level) rugby union athletes (mean  $\pm$  SD: age  $22 \pm 4$  y, body-height  $1.85 \pm 0.07$  m, body-mass  $97 \pm 11$  kg), separated into forwards ( $n = 15$ ) and backs ( $n = 15$ ), volunteered as participants for this research (Table 11). Prior to participation, all aspects of the research study were verbally explained to each athlete, written informed consent was obtained, and a coded number was assigned to each athlete to ensure that the data remained anonymous. This study was approved by the Auckland University of Technology Ethics Committee (13/378).

**Table 11. Athlete characteristics used in Chapter 3.**

	Forwards ( <i>n</i> = 15)	Backs ( <i>n</i> = 15)	Backs – forwards	
			<i>Mean change; ±90% CL</i>	<i>Qualitative inference</i>
Age (y)	20 ± 1	24 ± 4	4.5; ±1.7	Large** +ive
Body-height (m)	1.87 ± 0.09	1.84 ± 0.04	-0.034; ±0.044	Small** -ive
Body-mass (kg)	103 ± 11	90 ± 8	-13; ±6	Large* -ive
Body-mass index (kg·m <sup>-2</sup> )	30 ± 4	27 ± 2	-2.8; ±1.8	Moderate** -ive
Rugby experience (y)	10 ± 4	7.1 ± 4.4	-3.0; ±2.5	Moderate* -ive
Preferred leg	R = 14, L = 1	R = 10, L = 5		

Footnote: SD, standard deviation; *n*, sample size; CL, confidence limits; y, year; m, metre; kg, kilogram; R, right; L, left. Values are means ± standard deviation and mean change; ±90% confidence limits. Small, moderate and large inference: \*possibly, 25–74%; \*\*likely, 75–94%. +ive and -ive = substantial positive and negative change of backs relative to forwards.

### *Design*

This cross-sectional analysis comprised isokinetic testing at an angular velocity of 60°·s<sup>-1</sup> to determine 1) concentric and eccentric knee strength; 2) concentric hip strength; 3) angle of peak torque; and 4) strength ratios of the athletes. Testing took place during the athletes' respective off-season after a rest day (~24 h) and before training on the testing day.

### *Methodology*

All athletes performed a general self-selected lower-extremity dynamic warm-up similar to the team's weight training, practice and match warm-up procedures. The leg that the athlete preferred to kick the ball with or which they could kick the ball the furthest with was noted as the preferred kicking leg [178]. Following the warm-up, athletes were secured to a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA) to assess isokinetic concentric and eccentric knee and concentric hip extension and flexion strength on each leg at a sampling rate of 100 Hz. The dynamometer was set up in two separate positions (seated knee and supine hip) using a standardised protocol [98, 177]. In both positions, gravity adjustments were made by determining the combined effects of leg mass and the passive muscle tension using the HUMAC software to measure peak torque.

Testing leg and position were randomly determined for each athlete and followed an identical protocol previously described by our group in detail [177]. Knee and hip extensor and flexor muscles of each leg were tested with a limited range of motion (0–90°; 0° being full anatomical extension to 90° of flexion) at a fixed speed of 60°·s<sup>-1</sup> during five extension and five flexion movements. Once properly secured to the testing apparatus, athletes were first verbally

familiarised with the required movements followed by a physical familiarisation protocol wherein they performed the required movement three times at an individually perceived 50, 70 and 90% of maximum exertion at each position. Where athletes did not understand or did not perform the movement properly, further instruction was verbally given or additional familiarisation trials were given as needed. Once the first test was completed at 100% maximum effort, athletes were tested on the contralateral leg. After both legs were tested in one position (sitting or supine), athletes were re-positioned for the remaining test. Investigators provided strong verbal encouragement during each trial to maximise the athletes' effort across trials [177]. Athletes were given a 45 second rest between each familiarisation and test trial, a two-minute rest between side-to-side testing and a five minute rest between positions to ensure adequate rest between trials and within the session.

A custom-made LabView programme (Version 14.0, National Instruments Corp, Austin, TX, USA) was used to fit the torque-angle curves with a fourth-order polynomial to identify peak torque and the angle of peak torque, averaging the peak values within the last four repetitions for the final value [98, 177]. The CSR were calculated at the knee by dividing the peak concentric flexion torque by the peak concentric extension torque of the same leg. The DCR were calculated at the knee by dividing the peak eccentric extension torque by the peak concentric extension torque of the same leg. The PCR were calculated at the knee and hip by dividing the peak concentric knee flexion torque by the peak concentric hip extension torque of the same leg in Excel (2010, Microsoft, Redmond, WA, USA).

### ***Statistical analysis***

Instead of statistical significance testing, magnitude-based inferences were utilised in this study to describe the results in detail. The purpose for this analysis is that we expected differences between legs and position but the importance (or magnitude) of that difference is currently unknown and must be reported [179, 180]. Excel spreadsheets (*Post-only crossover* and *Pre-post parallel groups trial*) found at Sportsci.org were used to assess the effects between the preferred and non-preferred leg and between forwards and backs. The magnitude of the difference was then assessed by standardisation; that is, the difference between the means was divided by the standard deviation of the reference criteria. We decided to use the preferred leg and forwards as references in this study as they have commonly been chosen [177, 178].

For assessing the magnitude of standardised effects, threshold values of <0.2, 0.2, 0.6, 1.2 represent trivial, small, moderate, and large differences, respectively [142, 181]. Uncertainty in the estimates of effects on leg preference and position were expressed at 90% confidence limits and as probabilities that the true value of the effect was substantially positive (+ive) and negative (-ive). Qualitative probabilistic inferences regarding the true effect were then made, as described in detail elsewhere [142]. In summary, if the probabilities of the true effect being substantially positive and negative were both >5%, the effect was expressed as unclear; otherwise the effect was clear and expressed as the magnitude of its observed value. The scale for interpreting the probabilities was 25-74%, possibly (\*) and 75-94%, likely (\*\*).

## Results

Athletes' characteristics compared between forwards and backs are presented in Table 11. Although backs were older (ES = 1.6), they were smaller in stature (ES = -0.47), lighter in body-mass (ES = -1.3), had a smaller body-mass index (ES = -0.91) and had less rugby experience (ES = -0.72) compared to forwards. Fourteen (93%) of the forwards and ten (67%) of the backs noted their right leg as the preferred kicking leg.

During isokinetic concentric knee strength testing, the non-preferred leg of the forwards produced lower peak torque values during extension (ES = -0.37) and flexion (ES = -0.21) actions compared to the preferred leg. The non-preferred leg of the backs produced lower peak torque values during extension (ES = -0.28) compared to the preferred leg. The backs also produced lower peak torque values in the preferred leg during extension (ES = -0.50) and flexion (ES = -0.66) actions compared to the forwards. With regard to the angle at which peak torque was concentrically produced at the knee, the non-preferred leg of the forwards produced smaller angles during extension (ES = -0.31) and similar angles during flexion (ES = 0.073) actions compared to the preferred leg. The backs showed smaller flexion angles in the preferred (ES = -0.94) and non-preferred (ES = -0.93) legs compared to forwards. All other effects were unclear (Table 12).

Table 12. Knee peak torque and angle of peak torque.

				Non-preferred – preferred	
		Preferred	Non-preferred	<i>Mean change; ±90% CL</i>	<i>Qualitative inference</i>
Peak torque (N·m)					
Extension	Forwards	252 ± 62	228 ± 38	-24; ±25	Small** -ive
	Backs	225 ± 38	214 ± 53	-11; ±16	Small* -ive
	<i>Mean change; ±90% CL</i>	-26; ±32	-13; ±29		
	<i>Qualitative inference</i>	Small** -ive	Unclear		
Flexion	Forwards	129 ± 25	124 ± 19	-5.6; ±8.3	Small* -ive
	Backs	115 ± 14	118 ± 28	2.4; ±10.3	Unclear
	<i>Mean change; ±90% CL</i>	-14; ±13	-5.8; ±14.7		
	<i>Qualitative inference</i>	Moderate* -ive	Unclear		
Angle of peak torque (Deg)					
Extension	Forwards	61 ± 12	57 ± 14	-4.0; ±3.7	Small* -ive
	Backs	62 ± 7	61 ± 8	-0.39; ±3.81	Unclear
	<i>Mean change; ±90% CL</i>	0.74; ±6.20	4.3; ±7.1		
	<i>Qualitative inference</i>	Unclear	Unclear		
Flexion	Forwards	34 ± 14	35 ± 13	1.1; ±3.6	Trivial** -ive
	Backs	24 ± 2	26 ± 6	1.4; ±2.6	Unclear
	<i>Mean change; ±90% CL</i>	-9.9; ±6.4	-9.6; ±6.2		
	<i>Qualitative inference</i>	Moderate** -ive	Moderate** -ive		

Footnote: Knee peak torque and angle of peak torque between the preferred and non-preferred kicking leg during isokinetic concentric extension / flexion at 60°·s<sup>-1</sup> for forwards and backs; and inferences for change in the means. SD, standard deviation; CL, confidence limits; N·m, newton-metre; Deg, degree. Values are means ± standard deviation and mean change; ±90% confidence limits. Trivial, small and moderate inference: \*possibly, 25–74%; \*\*likely, 75–94%. -ive = substantial negative change of backs relative to forwards or the non-preferred leg relative to preferred leg.

During isokinetic eccentric knee strength testing, the non-preferred leg of the forwards produced lower peak torque values during flexion ( $ES = -0.37$ ) actions compared to the preferred leg. The non-preferred leg of the backs produced similar peak torque values during flexion ( $ES = -0.15$ ) and lower peak torque values during extension ( $ES = -0.26$ ) compared to the preferred leg. There were no clear effects of eccentric strength between positions for either leg. With regard to the angle at which peak torque was eccentrically produced at the knee, the non-preferred leg of the forwards produced similar angles during flexion ( $ES = -0.074$ ) compared to the preferred leg. The backs showed larger flexion angles in the preferred ( $ES = 0.67$ ) and non-preferred ( $ES = 0.49$ ) legs and smaller extension angles in the preferred ( $ES = -0.70$ ) and non-preferred ( $ES = -0.64$ ) legs compared to forwards. All other effects were unclear (Figure 8).

During isokinetic concentric hip strength testing, the non-preferred leg of the backs produced similar peak torque values during extension ( $ES = -0.099$ ) and flexion ( $ES = -0.12$ ) actions compared to the preferred leg. The backs produced lower peak torque values in the non-preferred leg during flexion ( $ES = -0.45$ ) compared to the forwards. With regard to the angle at which peak torque was concentrically produced at the hip, the non-preferred leg of the forwards produced larger angles during extension ( $ES = 0.31$ ) and flexion ( $ES = 0.40$ ) compared to the preferred leg. The non-preferred leg of the backs produced similar angles during extension ( $ES = 0.14$ ) and smaller angles during flexion ( $ES = -0.69$ ) compared to the preferred leg. The backs showed larger extension angles in the preferred ( $ES = 0.49$ ) and non-preferred ( $ES = 0.43$ ) legs and smaller flexion angles in the preferred ( $ES = -0.84$ ) and non-preferred ( $ES = -1.17$ ) legs compared to forwards. All other effects were unclear (Table 13).

Table 13. Hip peak torque and angle of peak torque.

		Non-preferred – preferred			
		Preferred	Non-preferred	Mean change; ±90% CL	Qualitative inference
Peak torque (N·m)					
Extension	Forwards	340 ± 98	335 ± 81	-5.6; ±30.0	Unclear
	Backs	330 ± 78	322 ± 70	-8.2; ±11.8	Trivial**
	Mean change; ±90% CL	-10; ±55	-13; ±47		
	Qualitative inference	Unclear	Unclear		
Flexion	Forwards	176 ± 33	177 ± 35	1.0; ±12.3	Unclear
	Backs	165 ± 34	161 ± 32	-4.3; ±8.3	Trivial* -ive
	Mean change; ±90% CL	-10; ±21	-15; ±21		
	Qualitative inference	Unclear	Small** -ive		
Angle of peak torque (Deg)					
Extension	Forwards	64 ± 6	66 ± 3	2.02; ±2.92	Small* +ive
	Backs	68 ± 7	69 ± 6	0.97; ±1.04	Trivial** +ive
	Mean change; ±90% CL	3.2; ±4.0	2.1; ±3.0		
	Qualitative inference	Small** +ive	Small* +ive		
Flexion	Forwards	23 ± 2	24 ± 4	0.82; ±1.23	Small* +ive
	Backs	21 ± 1	20 ± 1	-1.01; ±0.38	Moderate* -ive
	Mean change; ±90% CL	-1.5; ±1.1	-3.3; 1.7		
	Qualitative inference	Moderate** -ive	Moderate** -ive		

Footnote: Hip peak torque and angle of peak torque between the preferred and non-preferred kicking leg during isokinetic concentric extension / flexion at 60°·s<sup>-1</sup> for forwards and backs; and inferences for change in the means. SD, standard deviation; CL, confidence limits; N·m, newton-metre; Deg, degree. Values are means ± standard deviation and mean change; ±90% confidence limits. Trivial, small and moderate inference: \*possibly, 25–74%; \*\*likely, 75–94%. -ive = substantial negative change of backs relative to forwards or the non-preferred leg relative to preferred leg.

The CSR showed the non-preferred leg of the backs to have a higher ratio ( $ES = 0.502$ ) compared to the preferred leg. There were no other clear effects for any ratio between positions for either leg (Figure 7).

## Discussion

To our knowledge, this is the first study to assess lower-extremity strength between the preferred and non-preferred legs and between positions among high-performance academy level rugby union athletes. The findings that the preferred leg was stronger for the forwards compared to the non-preferred leg are in agreement to similar studies of professional rugby union athletes [177], professional adult and youth footballers [182-185] and university athletes [186]. This could be directly related to sport and playing position as the largest differences between forwards and backs were found in the preferred leg. If less dynamic and multi-directional activities are required in the preferred leg by the forwards compared to the backs, bilateral and / or unilateral strength asymmetries could be developed and further progressed as time continues [182, 186]. Continual utilisation of a stronger leg to lead in the driving forward of a scrum, maul or ruck could lead to a favouritism in sidestepping and other strength orientated activities.

Rugby union forwards require large amounts of strength and power in contact situations. Each task required by forwards rely on ample lower-extremity eccentric and concentric strength as a means to secure an advantageous position. The concentric strength differences between forwards and backs of the current study are not unlike those found by our group [177] when we examined professional rugby athletes; professional rugby union being the next level for academy athletes to progress into. As would be expected, the academy athletes possessed lower concentric knee strength values in every peak torque measure compared to their professional counterparts, most likely a result of the lower-level competition and having less strength training history.

Kim and Hong [187] reported that CSRs of less than 0.60 may increase the risk of suffering a hamstring injury. In this current study the average CSR was less than 0.60 (ranging from 0.52 to 0.56). Academy forwards and backs possess lower concentric and eccentric hamstrings strength relative to quadriceps strength, which may explain this finding. Previous research [173] has indicated that a DCR of less than 0.60 may also indicate an athlete is at risk of a recurrent injury. In the current study the average DCR was greater than 0.60



(ranging from 0.64 – 0.66). As hamstring strains commonly occur following eccentric lengthen of the hamstring during the late swing phase of sprinting or kicking, the DCR may provide a more accurate assessment of potential hamstring injury risk as it takes into account eccentric hamstring strength which CSRs do not [182, 188]. While Coombs and Garbutt [173] suggested that a DCR ratio of 1.0 may represent the point of equality, the values seen in the current study are far below this. This finding may suggest the following: (1) that the basis for this criteria may not be suitable in rugby union; (2) the criteria may need to be re-examined in multiple athletic populations with the same methodologies for comparison; or (3) the athletes from the current study would be suggested to increase eccentric hamstring strength by ~60%.

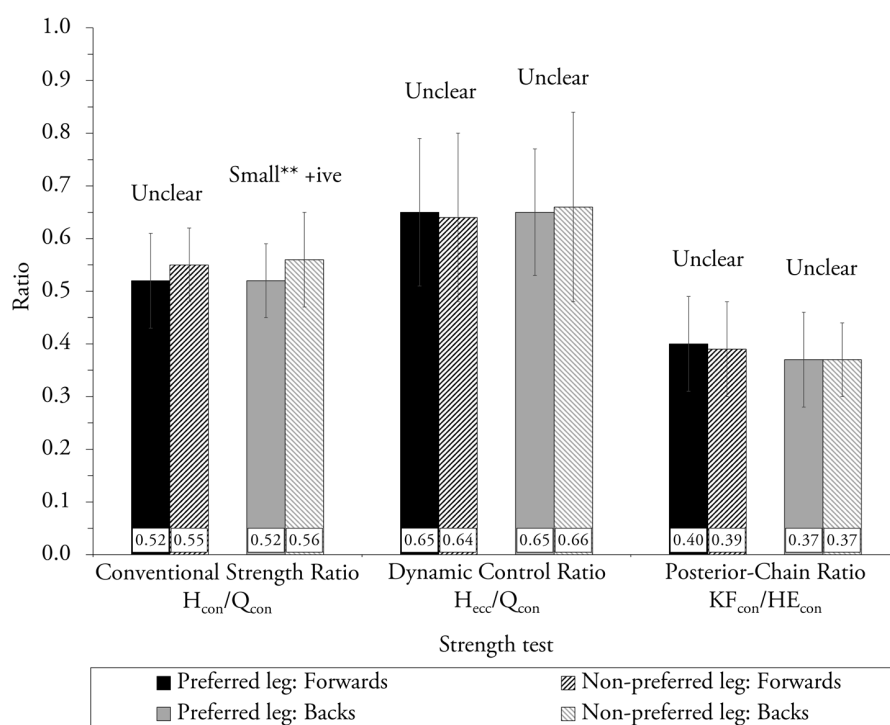


Figure 7. Strength ratios.

Strength ratios between the preferred and non-preferred kicking leg during isokinetic movements at  $60^{\circ}\cdot s^{-1}$  for forwards and backs and inferences for change in the means. Abbreviations: H, hamstrings; Q, quadriceps; KF, knee flexion; HE, hip extension; con, concentric; ecc, eccentric. Conventional strength ratio = concentric hamstrings:concentric quadriceps; dynamic-control ratio = eccentric hamstrings:concentric quadriceps; posterior-chain ratio = concentric knee flexion:concentric hip extension. Small inference: \*\*likely, 75% to 94%. +ive = substantial positive change of the non-preferred leg relative to preferred leg; -ive = substantial negative change of the non-preferred leg relative to preferred leg [9].

Eccentric strength about the knee is another important variable for assessment as athletes use their hamstrings to stabilise the knee in the stance phase during a change-of-direction [189] and decelerate the knee near the end of the swing phase when sprinting [176]. Eccentric strength may be of particular importance to rugby athletes when performing an evasive manoeuvre that may involve a change-of-direction. Forwards will need to possess the ability to perform similar movements to backs but with an increased body-mass. Additionally, forwards with larger concentric strength in the quadriceps will need to possess high levels of eccentric hamstring strength in order to decelerate the leg during sprinting and act as a synergist during landing for stabilisation. Surprisingly, there were no eccentric strength differences found between forwards and backs in the current study, potentially suggesting an equal need for eccentric strength from each position.

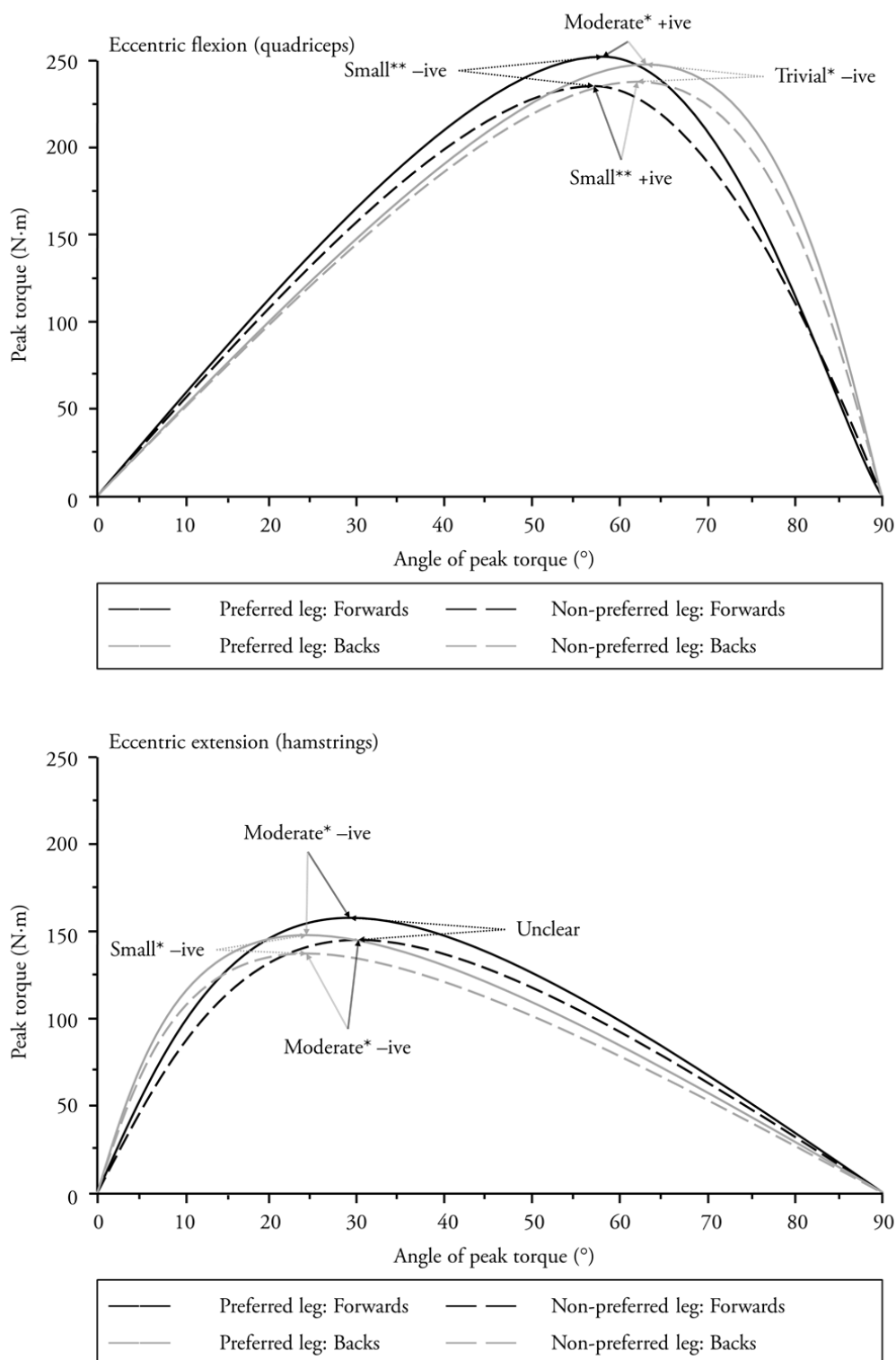


Figure 8. Knee torque and angle of torque.

Knee peak torque and angle of peak torque between the preferred and non-preferred kicking leg during isokinetic eccentric flexion / extension at  $60^{\circ}\cdot s^{-1}$  for forwards and backs and inferences for change in the means. Trivial, small, and moderate inference: \*possibly, 25% to 74%; \*\*likely, 75% to 94%. +ive and -ive = substantial positive and negative change, respectively, of backs relative to forwards or the non-preferred leg relative to preferred leg [9].

The hip joint has been identified [176] as having an important function in maintaining the neuromuscular control of the lumbopelvic region during sprinting. If the preferred and non-preferred leg muscles at the hip were equally utilised in force- or velocity-dominated activities, little to no differences would be expected. Backs were found to produce greater peak torque during hip flexion which may be a result of performing movements in a more upright position such as open field sprinting where forwards are involved in more static movements involving greater degrees of hip flexion such as scrummaging. In comparison to professional rugby union athletes [177], the forwards and backs in the current study produced substantially higher strength values in the hip during extension and flexion actions in the preferred and non-preferred leg.

There is an intricate interaction between the knee and hip in sports that involve the lower-extremities as a primary function of movement. A recent study [177] has shown the PCRs of the preferred and non-preferred legs in professional rugby union forwards are 0.59 and 0.57 and for backs are 0.59 and 0.63 (showing hip extension strength as  $\sim 1.8\times$  greater than knee flexion strength). Similarly, elite sprinters have showed PCRs of 0.56 in the uninjured leg compared to 0.51 in the leg that experienced a subsequent hamstring injury [176]. In the academy-level rugby athletes examined in this study, the PCRs of the preferred and non-preferred legs for forwards were 0.40 and 0.39 and for backs were 0.37 and 0.37 (showing hip extension strength as  $\sim 2.6\times$  greater than knee flexion strength). We suggest a more balanced PCR between 0.65 and 0.70 (or  $1.5\times$ ) would indicate proportionately stronger hamstring strength about the knee to protect it from injury during dynamic tasks. However, as this is only the second study to report PCR in rugby athletes, these suggested values must be further investigated before prescribed as normative and / or ideal.

A muscle producing peak torque at a shorter muscle length will spend more time in the region where it may be prone to microscopic damage from eccentric actions (i.e. descending leg of length-tension relation) [190]. Several studies [190-192] have found that previously injured legs produced substantially greater angles of peak torque (i.e. shorter muscle lengths) compared to uninjured legs during isokinetic knee flexion testing at  $30^\circ\cdot s^{-1}$  and  $60^\circ\cdot s^{-1}$ . Thus, the optimum angle of peak torque was of interest in the current study.

Different types of athletes have been shown to produce various optimum angles of peak torque. Cyclists, for example, have been shown to have greater optimum angles when

compared to long-distance runners [193, 194] and Australian rules footballers [169] possibly as a result of training and competing in a continually shortened hamstring muscle length. It could also be argued [169] that athletes may naturally gravitate towards sports that they are genetically predisposed to excel in (e.g. athletes with greater strength at longer muscle lengths may be attracted to sports that involve faster or longer sprinting bouts). Brughelli et al. [169] attributed their findings of smaller optimum angles in Australian rules footballers to the sport's mixture of training methods including relatively longer hamstring muscle lengths (e.g. maximum velocity sprinting, accelerating, change of direction, etc.) which are very similar to those seen in rugby union.

While the athletes in the current study were uninjured and were not compared to any other sport, the findings that forwards produced peak torque and shorter muscle lengths during knee and hip flexion and extension is of interest. This is the first study to our knowledge to examine the optimum angles of peak torque within a sport and between legs. The differences between forwards and backs can be attributed to sport and position specific training. As forwards will spend a large proportion of time in flexed positions, backs will spend an equally large proportion of time in long, extended positions.

We feel it is important to acknowledge several limitations of the current study as these restrictions may impact the interpretations of our findings. First, the validity of testing velocities used in isokinetic assessments are often questioned as they are much slower than the flexion / extension velocities seen in the actual movements [178]. If however, the isokinetic assessments are used only as a measure to assess muscular strength and optimum angle in an individual or team and are not attempting to make a direct comparison to on-field tasks, isokinetic assessment can provide invaluable information [170, 171]. Second, isokinetic assessments are unique in their examination of lower-extremity single-joint strength as a criterion when compared to surrogate 'field-measures' of strength such as one repetition maximum testing in a back-squat or an isometric mid-thigh pull which both use multiple-joints and muscles in the lower-extremities. Thus, the findings from an isokinetic assessment are not transferable to those found in other studies of lower-extremity strength. Finally, there is a great lack of normative data unique to sport, position and joint at which to make meaningful comparisons at this time.

### *Practical applications*

- The continuation of isokinetic assessments using relatively homologous populations, separated by position if applicable, is imperative to the growth of isokinetic knowledge.
- Peak torque profiling should include the knee and hip flexors / extensors so as programming can be individualised to better effect.
- Strength and conditioning programmes for forwards and backs should include targeted single-leg exercises (e.g. pistol-squats, single-leg hip-thrust, Bulgarian split-squats).
- It would appear that forwards might benefit the most from eccentric exercises (e.g. box drops, box lunge drops, towel pulls, resisted pushes, Nordic hamstring exercise) to increase lower-extremity strength at longer muscle lengths.
- Future research should investigate the angle at which peak torques occurs and how these numbers carry over into actual sprinting performance and risk of injury.

### **Conclusions**

This study investigated the differences in lower-extremity isokinetic strength, strength ratios and optimum angles between the preferred and non-preferred legs and between forwards and backs among male academy rugby union athletes. We detected several important observations which include: 1) the non-preferred leg was weaker than the preferred leg for forwards and backs; 2) backs were weaker at the knee than forwards in the preferred leg; 3) all strength ratios were substantially less than the professional counterparts; and 4) backs produced peak torque at longer muscle lengths in both legs at the knee and hip than the forwards. These findings support individual isokinetic assessments. It is apparent in this study's cohort that strength differences exist between legs and positions, however, it is unknown whether these differences are comparable to other male academy-level rugby union athletes or if they are unique to the athletes studied.

## Chapter 4: Profiling Single-Leg Balance by Leg Preference and Position in Rugby Union Athletes

This chapter comprises the following paper submitted to *Journal of Athletic Training*.

### Reference:

Brown SR, Brughelli M, Lenetsky S. Profiling single-leg balance by leg preference and position in rugby union athletes. *J Athl Train*. 2016:[in review].

### Author contributions:

Brown SR, 90%; Brughelli M, 5%; Lenetsky S, 5%.

### Overview

Poor balance has been linked with an increased risk of injury in athletic populations. Rugby union athletes are often plagued with lower-extremity injuries to the soft tissue structures as a result of the physical demands of the sport. However, no research has profiled single-leg balance in healthy rugby athletes as a means to better understand the influence of balance in rugby. Our aims were to assess male rugby athletes in single-leg dynamic balance during two levels of stability difficulties and compare the stability indices between the preferred and non-preferred kicking legs and between forwards and backs. Thirty male high-performance academy rugby union athletes, separated into forwards and backs ( $n = 15 / 15$ ). All athletes performed single-leg balance measured at two difficulty levels (Level 8 [more stable] and Level 2 [less stable]) using the Biodex Balance SD System. The backs' non-preferred leg had worse scores in medial-lateral and overall indices ( $ES = 1.0$  and  $0.63$ ) compared to the preferred leg on Level 8 stability. Backs had better scores in all indices in the preferred ( $ES = -1.2 - -1.8$ ) and non-preferred ( $ES = -0.66 - -1.4$ ) leg compared to the forwards at both stability difficulties. Differences in single-leg balance exist between the preferred and non-preferred legs and between forwards and backs. Asymmetry indices between the two legs are also present among forwards and backs when examined on an individual basis. This study illuminates the importance of single-leg balance screening among rugby athletes to detect individuals with asymmetries in balance that may increase the risk of lower-extremity injury.

## Introduction

To assess the balance of an athlete in a laboratory setting, the Biodex Balance SD system is employed as a reliable and practical assessment tool allowing clinicians to evaluate different modes across several levels of varying difficulty [62]. Over the past decade, a number of researchers have utilised the Biodex Balance SD system in athletic populations to assess the influence of balance on decreasing the incidence of lower-extremity injuries [195] and increasing athletic performance [196] via stability index scores; with encouraging results. It has been suggested [197, 198] that single-leg balance most accurately replicates sporting movements and may better encompass an athlete's potential to maintain balance as opposed to static or bilateral balance. Further, as athletes may inherently possess more skill in single-leg tasks compared to “non-athletes”, authors [197, 198] have reported the potential for athletes to be unchallenged when the difficulty was set to a more stable setting during single-leg balance assessments. Testerman and Vander Griend [199] verified this notion when using multiple difficulty settings and were able to clearly differentiate balance index scores among the injured and non-injured legs of athletes whilst using the more difficult stability setting. However despite the recommendation to incorporate multiple difficulty settings during single-leg balance assessments, to date there are only a handful of publications [200, 201] that have; with Levels 8 and 2 most commonly evaluated for “more stable” and “less stable” settings, respectively.

Rugby union is a multifaceted collision sport where lower-extremity injuries occur frequently [19]. Rugby athletes are repeatedly required to meet the physically demanding characteristics of the sport; which in turn may aid in the causation of injury [19, 177]. For example, sidestepping, jumping, kicking and sprinting are all extremely common movements seen in rugby that require a unique postural position (i.e. single-leg stance) that may predispose the athlete to injury [82]. During these positions the athlete is required to interpret complex coordination information via visual, vestibular and somatosensory pathways and then adjust their postural position accordingly. The failure to adjust the body to the correct position may result in the inability to perform the task proficiently, perform the task at all or introduce the potential for injury [82]. As such, rugby appears to be an ideal candidate sport to incorporate balance assessments to monitor injury risk and / or train to prevent it.



To our knowledge, only two studies [92, 202] have assessed balance in rugby, with one study reporting the usability and practicality of the Star Excursion Balance Test and the other attempting to correlate balance with injury incidence. Neither group used the Biodex Balance SD system at which to compare their results to similar balance research. In addition, only one of these studies [92] made a positional separation (recently identified [9] as paramount in detecting substantial effects in rugby research) but reported no significant differences between forwards and backs. Authors of current rugby research [9, 177] have identified the unique positional demands of rugby as contributing factors to substantial differences between forwards and backs. As such, there exists no consensus on whether or not the positions in rugby bring about a difference in balance ability found on the Biodex Balance SD; creating a large disconnect between single-leg balance ability and rugby athletes.

Finally, the influence of leg preference has gained popularity in recent years as substantial differences between the legs have been reported among male rugby athletes [9, 177]. As such, it seems intuitive to examine single-leg balance as another potential assessment tool in detecting lower-extremity asymmetries. While a number of authors [203-205] have examined leg preference during balance tasks, none have assessed rugby athletes and mixed results among the studies has made any consensus impossible at this time. Therefore the purpose of the current study was to assess single-leg balance among two stability difficulties in male academy-level rugby union athletes and to compare the balance index scores between the preferred and non-preferred legs and between forwards and backs. Due to the highly technical skill required by the position, it was initially thought that backs would display superior single-leg balance indices during the “less stable” Level 2 difficulty compared to forwards.

## Methods

### *Athletes*

Thirty male academy (development-level) rugby union athletes (mean  $\pm$  SD: age  $22 \pm 4$  y, body-height  $1.85 \pm 0.07$  m, body-mass  $97 \pm 11$  kg), separated into forwards ( $n = 15$ ) and backs ( $n = 15$ ), volunteered as participants for this research (Table 14). Prior to participation, all aspects of the study were verbally explained to each athlete, written informed consent was obtained, and a coded number was assigned to each athlete to ensure that the data remained

anonymous. This study was approved by the Auckland University of Technology Ethics Committee (13/378).

**Table 14. Athlete characteristics used in Chapter 4.**

	Forwards ( $n = 15$ )	Backs ( $n = 15$ )
Age (y)	$20 \pm 1$	$24 \pm 4$
Body-height (m)	$1.87 \pm 0.09$	$1.84 \pm 0.04$
Body-mass (kg)	$103 \pm 11$	$90 \pm 8$
Body-mass index ( $\text{kg}\cdot\text{m}^{-2}$ )	$30 \pm 4$	$27 \pm 2$
Rugby experience (y)	$10 \pm 4$	$7.1 \pm 4.4$
Preferred leg	R = 14, L = 1	R = 10, L = 5

Footnote: y, year; m, metre; kg, kilogram; R, right; L, left. Values are means  $\pm$  standard deviation.

### *Procedures*

This cross-sectional analysis comprised single-leg balance assessments at two stability difficulties. The assessment took place during the athletes' respective off-season after a rest day ( $\sim 24$  h) and before training that day.

All athletes performed a general self-selected lower-extremity dynamic warm-up similar to the team's weight training, practice and match warm-up procedures. The leg that the athlete preferred to kick the ball with or which they could kick the ball the furthest with was noted as the preferred leg [9, 178]. Following the warm-up, athletes were asked to position one leg in the center of the locked platform on the Biodex Balance SD System (Biodex Medical Systems, Inc., Shirley, NY, USA) in a self-assessed "comfortable" single-leg standing position. The positions of the athletes' most posterior aspect of the calcaneus and most medial aspect of the hallux were recorded into the Biodex software and maintained for every subsequent assessment on that foot. All athletes performed the assessments barefoot as the foot positions were used as the reference point by which all subsequent variables would be calculated from.

With eyes open, athletes were instructed to fold both arms across the chest, maintain slight knee flexion ( $\sim 15^\circ$ ) in the standing leg with  $0^\circ$  and  $90^\circ$  flexion for the contralateral hip and knee respectively and to not let the two legs touch whilst attempting to keep the platform as stable as possible. Due to the athletes' large stature (range of 1.8 – 2.0 m), the Biodex screen was lowered and faced away from the athlete and instructions were given to find a point on the wall in front of them at eye level and to focus on that point throughout the assessment (Figure 9).



**Figure 9. Body position for single-leg balance.**

Once properly positioned on the apparatus, all athletes were verbally familiarised with the assessment protocol. The single-leg balance assessment was performed randomly at either Level 8 (more stable) or Level 2 (less stable) and consisted of three trials lasting 20 seconds. Once the assessment on one leg was completed the contralateral leg was assessed using the aforementioned procedures. Once both legs were assessed, the procedure was repeated using the remaining stability level. The order of leg and stability level were randomised for all athletes. Visual and audio feedback / encouragement were not provided to any athlete during any of the assessments. Athletes were given a 45 second rest between the side-to-side assessment and a five minute rest between positions to ensure adequate rest between trials and within the session.

Described in detail elsewhere [206], anterior-posterior, medial-lateral and overall stability index scores resulting from the degrees of tilt about the balance platform were generated from the mean of the three trials (Equations 6-8). Smaller stability index scores represent better balance while larger scores represent worse balance. A global measure of asymmetry was

calculated (Equation 5) with a modified symmetry angle equation [103] to report an absolute relationship between the preferred and non-preferred legs, as used in previous research. Symmetry scores (ranging between 0 – 100%; where 0% = perfect symmetry and 100% = perfect asymmetry) for overall stability were calculated for forwards and backs during Level 8 and Level 2 difficulties. Additionally, individual athlete results of the time (presented as a percent of the total time of the trial) spent in specific balance quadrants and balance zones were provided as supplementary material only in Figure 16 and Figure 17 respectively.

Equation 6. Anterior-posterior stability index (*APSI*) =

$$APSI = \sqrt{\frac{\sum (0 - Y)^2}{\# \text{ samples}}}$$

Equation 7. Medial-lateral stability index (*MLSI*) =

$$MLSI = \sqrt{\frac{\sum (0 - X)^2}{\# \text{ samples}}}$$

Equation 8. Overall stability index (*OSI*) =

$$OSI = \sqrt{\frac{\sum (0 - Y)^2 + \sum (0 - X)^2}{\# \text{ samples}}}$$

### ***Statistical analysis***

Excel spreadsheets (*Post-only crossover* and *Pre-post parallel groups trial*) found at Sportsci.org were used to assess the differences between the preferred and non-preferred legs and between forwards and backs. The magnitude of the difference was then assessed by standardisation; that is, the difference between the means was divided by the standard deviation of the reference criteria. We decided to use the preferred leg and forwards as references in this study as they have commonly been chosen [9, 177, 178].

For assessing the magnitude of standardised effects, threshold values of <0.2, 0.2, 0.6, 1.2 represent trivial, small, moderate, and large differences, respectively [142]. Uncertainty in the estimates of effects on leg preference and position were expressed at 90% confidence limits and as probabilities that the true value of the effect was substantially positive (+ive) and negative (-ive). Qualitative probabilistic inferences regarding the true effect were then made, as described in detail elsewhere [142]. In summary, if the probabilities of the true

effect being substantially positive and negative were both >5%, the effect was expressed as unclear; otherwise the effect was clear and expressed as the magnitude of its observed value. The scale for interpreting the probabilities was 25-74%, possibly (\*); 75-94%, likely (\*\*); and 95-99.5%, very likely (\*\*\*)

## Results

Single-leg stability index scores for Level 8 (more stable) are presented in Table 15. During single-leg balance at Level 8, the non-preferred leg of the backs produced worse medial-lateral and overall stability index scores (ES = 1.0 and 0.63 respectively) compared to the preferred leg. All other effects between the preferred and non-preferred legs were unclear. The backs produced substantially better anterior-posterior, medial-lateral and overall stability index scores in the preferred (ES = -1.2, -1.5 and -1.4 respectively) and non-preferred leg (ES = -0.66, -0.97 and -0.95 respectively) compared to the forwards.

Table 15. Stability index scores during Level 8.

		Non-preferred – preferred			
		Preferred	Non-preferred	Mean change; $\pm 90\%$ CL	Qualitative inference
Level 8 (Deg)					
Overall stability index	Forwards	2.2 $\pm$ 0.7	2.2 $\pm$ 0.7	-0.022 $\pm$ 0.444	Unclear
	Backs	1.3 $\pm$ 0.3	1.5 $\pm$ 0.6	0.22 $\pm$ 0.32	Moderate* +ive
	Mean change; $\pm 90\%$ CL	-0.92 $\pm$ 0.36	-0.67 $\pm$ 0.43		
	Qualitative inference	Large** -ive	Moderate** -ive		
Anterior-posterior stability index	Forwards	1.4 $\pm$ 0.5	1.4 $\pm$ 0.4	-0.095 $\pm$ 0.237	Unclear
	Backs	0.90 $\pm$ 0.29	0.95 $\pm$ 0.40	0.050 $\pm$ 0.240	Unclear
	Mean change; $\pm 90\%$ CL	-0.54 $\pm$ 0.24	-0.40 $\pm$ 0.26		
	Qualitative inference	Large* -ive	Moderate** -ive		
Medial-lateral stability index	Forwards	1.4 $\pm$ 0.7	1.4 $\pm$ 0.8	0.051 $\pm$ 0.459	Unclear
	Backs	0.69 $\pm$ 0.19	0.90 $\pm$ 0.65	0.22 $\pm$ 0.28	Moderate* +ive
	Mean change; $\pm 90\%$ CL	-0.67 $\pm$ 0.34	-0.51 $\pm$ 0.47		
	Qualitative inference	Large* -ive	Moderate* -ive		

Footnote: Stability index scores (overall, anterior-posterior and medial-lateral) between the preferred and non-preferred kicking leg during Level 8 (more stable) for forwards and backs; and inferences for change in the means. CL, confidence limits; Deg, degree. Values are means  $\pm$  standard deviation and mean change;  $\pm 90\%$  confidence limits. Moderate and large inference: \*possibly, 25–74%; \*\*likely, 75–94%. +ive and -ive; substantial positive and negative change of backs relative to forwards or the non-preferred leg relative to preferred leg.

Single-leg stability index scores for Level 2 (less stable) are presented in Table 16. During single-leg balance at Level 2, there were no clear effects between the preferred and non-preferred legs. However the backs again produced substantially better anterior-posterior, medial-lateral and overall stability index scores in the preferred (ES = -1.5, -1.8 and -1.8 respectively) and non-preferred leg (ES = -0.80, -1.2 and -1.4 respectively) compared to the forwards.

Table 16. Stability index scores during Level 2.

		Preferred	Non-preferred	Non-preferred – preferred	
				Mean change; $\pm 90\%$ CL	Qualitative inference
Level 2 (Deg)					
Overall stability index	Forwards	6.6 $\pm$ 2.1	6.2 $\pm$ 2.1	-0.47; $\pm$ 1.24	Unclear
	Backs	3.0 $\pm$ 1.7	3.5 $\pm$ 2.2	0.50; $\pm$ 0.88	Unclear
	Mean change; $\pm 90\%$ CL	-3.6; $\pm$ 1.2	-2.6; $\pm$ 1.4		
	Qualitative inference	Large*** -ive	Large* -ive		
Anterior-posterior stability index	Forwards	4.1 $\pm$ 1.1	3.9 $\pm$ 1.4	-0.20; $\pm$ 0.61	Unclear
	Backs	2.0 $\pm$ 1.1	2.1 $\pm$ 1.1	-0.15; $\pm$ 0.41	Unclear
	Mean change; $\pm 90\%$ CL	-2.1; $\pm$ 0.7	-1.7; $\pm$ 0.8		
	Qualitative inference	Large*** -ive	Large* -ive		
Medial-lateral stability index	Forwards	4.3 $\pm$ 2.0	3.9 $\pm$ 1.9	-0.40; $\pm$ 1.31	Unclear
	Backs	1.8 $\pm$ 1.2	2.3 $\pm$ 2.1	0.43; $\pm$ 0.89	Unclear
	Mean change; $\pm 90\%$ CL	-2.5; $\pm$ 1.0	-1.7; $\pm$ 1.3		
	Qualitative inference	Large** -ive	Moderate* -ive		

Footnote: Stability index scores (overall, anterior-posterior and medial-lateral) between the preferred and non-preferred kicking leg during Level 2 (less stable) for forwards and backs; and inferences for change in the means. CL, confidence limits; Deg, degree. Values are means  $\pm$  standard deviation and mean change;  $\pm 90\%$  confidence limits.

Moderate and large inference: \*possibly, 25–74%; \*\*likely, 75–94%; \*\*\*very likely, 95–99.5%. -ive; substantial negative change of backs relative to forwards.



Mean symmetry angle scores for forwards and backs were  $8.0 \pm 7.9$  (range: 1.6 – 32) and  $7.5 \pm 9.2$  (range: 1.0 – 32) during Level 8 and  $8.8 \pm 9.1$  (range: 0.31 – 32) and  $9.2 \pm 7.8$  (range: 0.20 – 30) during Level 2 (Figure 10).

## Discussion

To our knowledge, this is the first study to assess single-leg balance between the preferred and non-preferred legs and between positions among high-performance academy-level rugby union athletes. Our findings indicate that the backs' non-preferred leg produced moderately worse medial-lateral and overall stability indices compared to the preferred leg and that backs produced substantially better anterior-posterior, medial-lateral and overall stability indices in both legs during both stability difficulties compared to the forwards. These results suggest that backs possess superior single-leg balance ability compared to forwards.

Rugby code athletes are often required to be positioned in single-leg stance during competitive play (i.e. kicking, sidestepping, jumping and sprinting). During these movements, single-leg balance is imperative in assisting task acquisition. As such requirements exist in rugby, it seems intuitive to assess single-leg balance on both legs independently in an attempt to detect any asymmetries that may exist. The results from the current study show that backs possess better single-leg balance on Level 8 on their preferred leg compared to their non-preferred leg in medial-lateral and overall orientations. These findings are in agreement with research [203] examining male adults during a more difficult setting of Level 4. However, during the more difficult Level 2 setting, between-leg differences for forwards and backs were unclear; the result of very large confidence limits. Gstöttner et al. [205] reported similar results (no differences between legs) when assessing single-leg balance at Level 3 in male amateur footballers with a tendency of better balance in the non-preferred leg. As footballers must kick the ball with a more even distribution of the legs, it could be assumed that each leg would possess similar balance attributes. As this equal distribution is not commonly found in rugby, it was assumed that clear differences between the legs would be present; however, this was not the case. Authors [92] using the Star Excursion Balance Test also showed no differences between left and right legs in male rugby athletes; however these results should be interpreted with care as leg preference was not accounted for. Additionally, the Star Excursion Balance Test is considerably different from the Biodex Balance SD system and results cannot be carried over for comparison. It has been

suggested [203] that asymmetrical single-leg balance results are largely the product of specific adaptations of the sport and that more research is greatly warranted in the area of leg preference in rugby athletes.

To better understand the differences found in single-leg balance between the preferred and non-preferred legs, an asymmetry index score was used to illuminate the number of individual athletes that may need further attention. Interestingly, both forwards and backs presented similar means and extremity wide ranges of asymmetry index scores during Level 8 and Level 2 difficulties. This individualised approach does however display several athletes whom are well outside of the majority grouping. We feel it is these athletes (whose index scores are between 24 and 32) that may be at the greatest risk of injury as their legs produce substantially different single-leg balance abilities. While it is unclear whether these differences are natural or a product of rugby training and match play, poor balance can be positively affected via specific training programs [207].

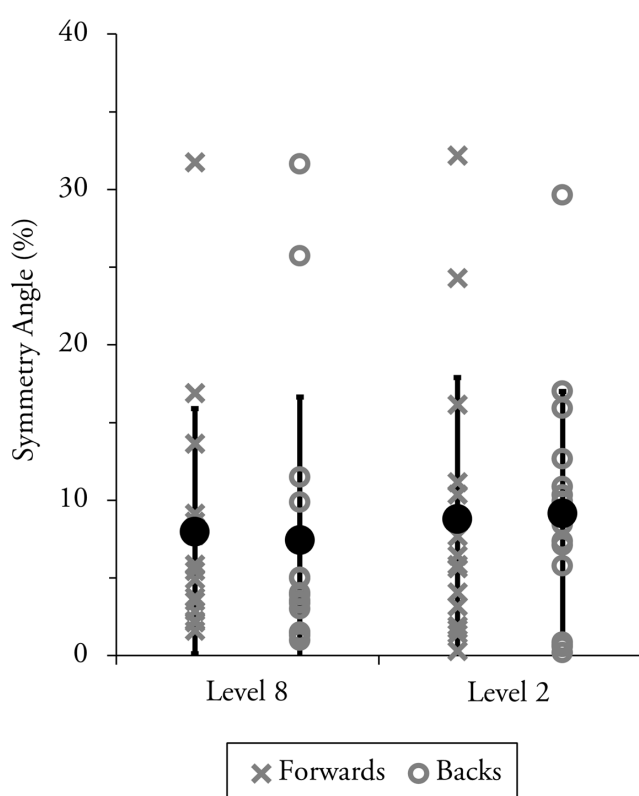


Figure 10. Single-leg balance symmetry angle scores.

Individual symmetry angle scores in overall stability for forwards (X) and backs (O) separated by Level 8 (more stable) and Level 2 (less stable). Means are shown in solid black circles and standard deviations as black error bars.

Another interesting finding of this study was the difference between the forwards and backs, regardless of the leg or difficulty. During the Level 8 assessment, the backs' stability indices ranged from 60 – 97% better in the preferred leg and 42 – 56% better in the non-preferred leg compared to the forwards. Even larger differences were noticed during the Level 2 assessment with the backs' stability indices ranging between 105 – 136% better in the preferred leg and 73 – 81% better in the non-preferred leg compared to the forwards. The overall stability index scores for the backs at Level 2 was  $\sim 3.0 - 3.5$  which is very consistent ( $\sim 2.0 - 5.4$ ) with similar balance research on male athletes at the same difficulty [208-210]. The forwards however, presented overall index scores between  $\sim 6.2 - 6.6$  which are more in line ( $\sim 5.6 - 7.5$ ) with “normal” (non-athletic) college-aged males and females [62] and even individuals diagnosed with rheumatoid arthritis [200]. While we are unaware of any research comparing single-leg balance among sporting positions (especially in rugby), the extreme differences found in the current study warrant further insight into the potential for lower-extremity injury.

Injury to the ankle and knee are among the most commonly injured body sites in rugby, accounting for 12 and 10% of all injuries respectively [211]. A number of authors [212, 213] have positively linked lower-extremity injuries with poor balance scores in male and female athletes comprising a wide variety of sports. As such, a large push for incorporating balance training into injury prevention protocols has been made; the effects of which have shown promising results of decreasing the incidence of lower-extremity injury [207, 214]. Other researchers have contributed to this movement with suggesting the importance of core [205] or hip [215] strength as a contributing factor. With such an abundance of literature suggesting a positive effect of balance training in preventing lower-extremity injury, the inclusion of such an assessment within a pre-season injury prevention assessment appears obvious; especially in a sporting code like rugby with such a large discrepancy between playing positions. The application of a single-leg balance training intervention using the Biodex Balance SD system among male rugby athletes would provide valuable information about influence of balance in reducing injury risk in rugby.

### ***Limitations***

We feel it is important to acknowledge limitations in the current study as these restrictions may impact the interpretations of our findings. First, the two stability difficulties used in the

current study (Level 8 and 2) encompass very specific degrees of tilt on the balance platform. As such, the different stability difficulties may induce unique body alterations that would then alter each stability index. Comparison among the varying levels of stability difficulty must be performed with caution. Second, the results from our single-leg balance assessment used in the current study do not differentiate between the influence of the peripheral somatosensory, visual and vestibular systems. Therefore interpretations must be inclusive of all three systems or when athletes are suspected of possessing deficiencies in individual systems, they should be assessed on more appropriate settings / machines (i.e. NeuroCom). Finally, there is a lack of normative data unique to sex, sport, position and leg at which to make meaningful comparisons at this time. Future research using the Biodex Balance SD system should take the above mentioned considerations into account when assessing athletes.

### **Conclusions**

This study investigated the differences in single-leg balance between the preferred and non-preferred legs and between forwards and backs among male academy rugby union athletes. Our findings suggest that leg preference may not be as impactful as position in single-leg stability indices. More importantly, our findings suggest that forwards possess substantially worse balance scores across both legs, both levels of stability difficulty and all stability indices compared to the backs; certainly deserving further investigations. These findings highlight a need for: 1) the inclusion of individual single-leg balance assessments; and 2) the addition of a high-quality training intervention to determine if balance training can decrease lower-extremity injury risk in a male rugby cohort.

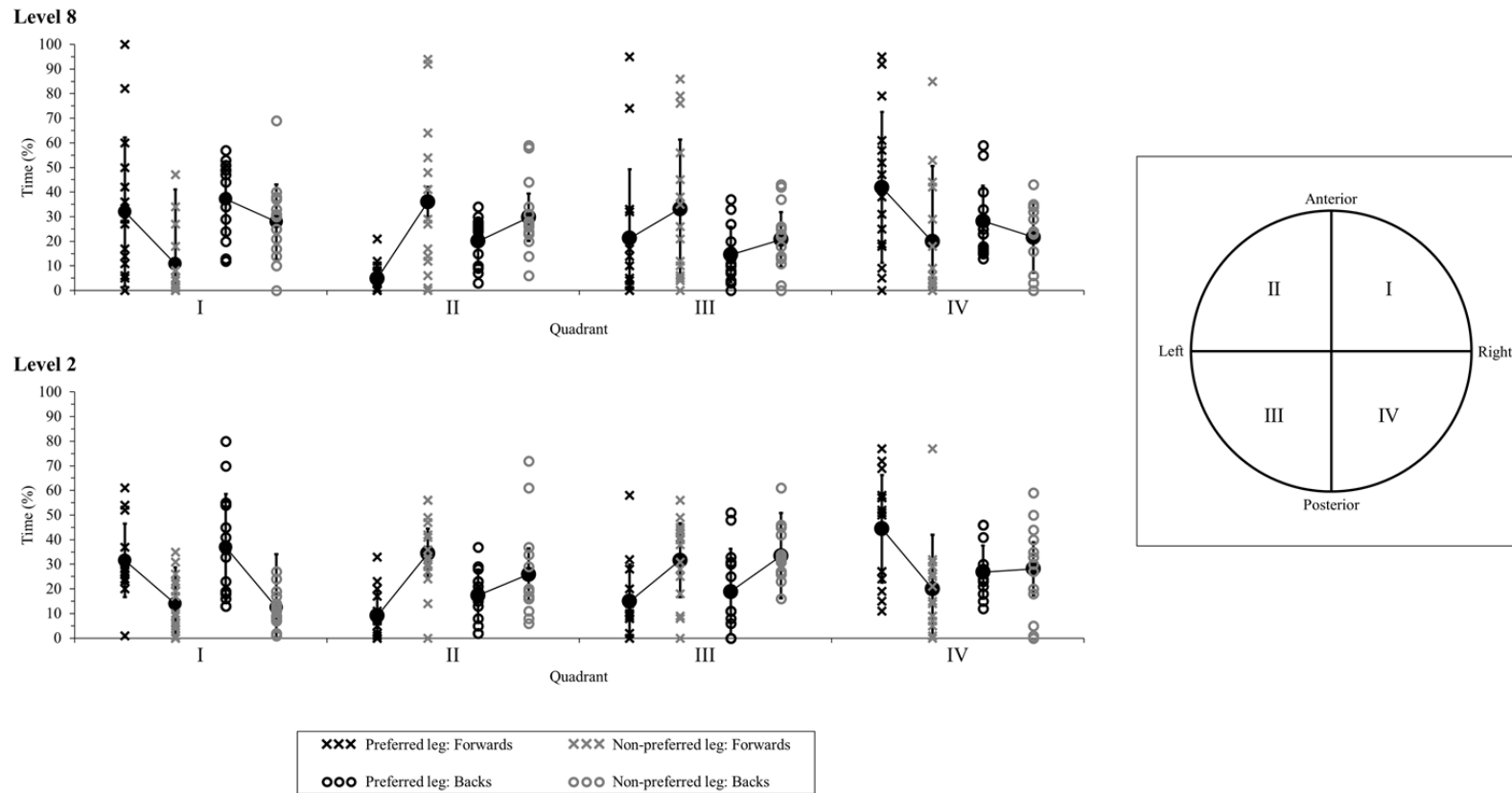


Figure 11. Percentage of time in quadrants during single-leg balance.

Individual athlete data for time spent as a percentage in each quadrant during Level 8 (more stable) and Level 2 (less stable) stability difficulties. Quadrants I, II, III and IV represent anterior-right, anterior-left, posterior-left and posterior-right respectively. Means are shown in solid black circles and standard deviations as black error bars.

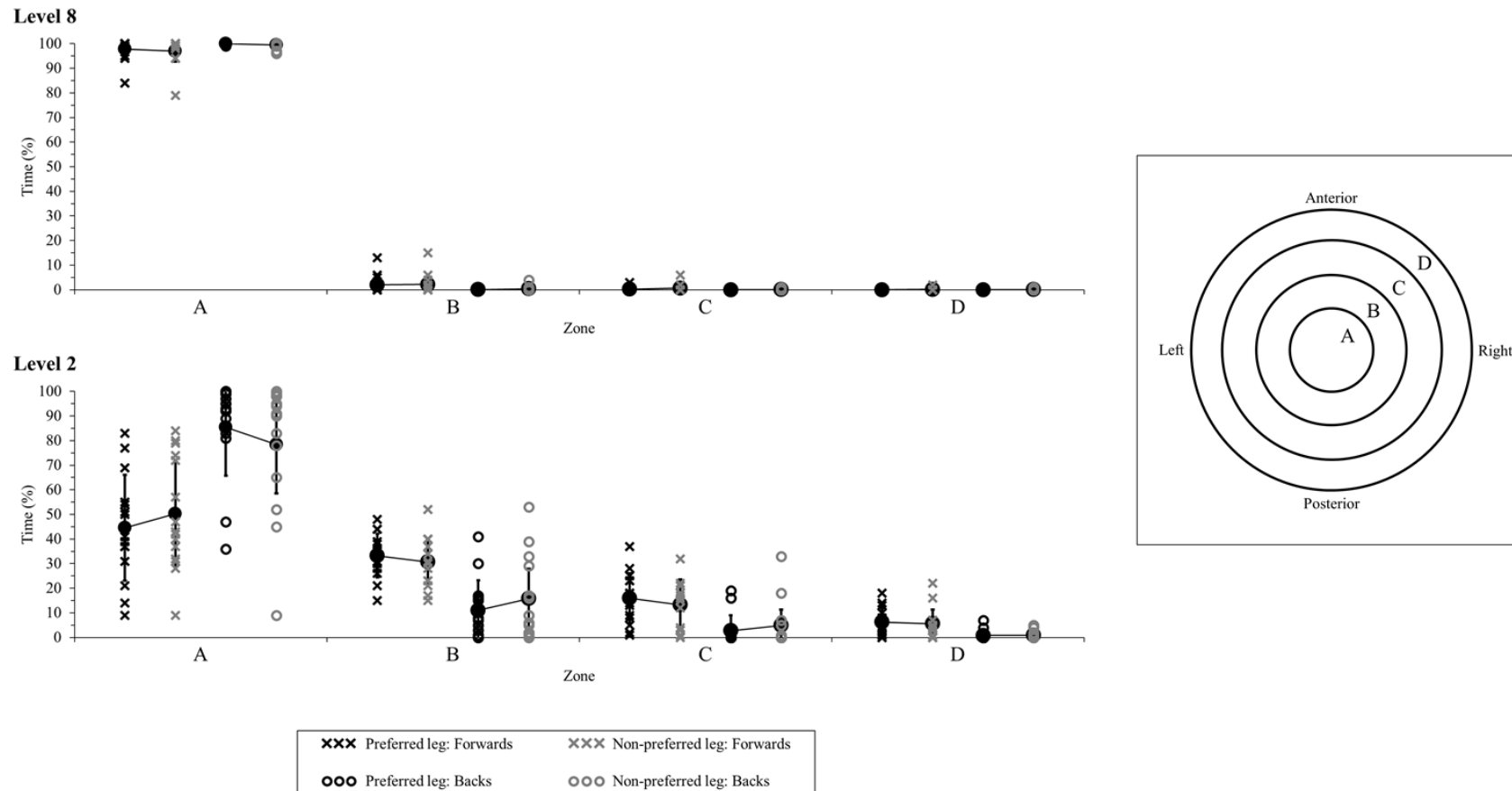


Figure 12. Percentage of time in s zones during single-leg balance.

Individual athlete data for time spent as a percentage in each zone during Level 8 (more stable) and Level 2 (less stable) stability difficulties. Zones A, B, C and D represent 0-5°, 6-10°, 11-15° and 16-20° respectively. Means are shown in solid black circles and standard deviations as black error bars.

## Chapter 5: Profiling Sprint Mechanics by Leg Preference and Position in Rugby Union Athletes

This chapter comprises the following paper accepted to *International Journal of Sports Medicine*.

### Reference:

Brown SR, Brughelli M, Cross MR. Profiling sprint mechanics by leg preference and position in rugby union athletes. *Int J Sports Med*. 2016.0;37(11):890-7.

### Author contribution:

Brown SR, 90%; Brughelli M, 5%; Cross MR, 5%.

### Overview

Lower-extremity power characteristics are central to performance in rugby. However little is known regarding the effects of leg preference and playing position on sprint mechanics. The purpose of this study was to profile sprint kinetics and kinematics in rugby union athletes and compare between legs and between positions. Thirty male academy-level rugby union athletes, separated into forwards ( $n = 15$ ) and backs ( $n = 15$ ), participated in this cross-sectional analysis. Non-motorised treadmill ergometry was used to evaluate peak relative vertical ( $F_V$ ) and horizontal ( $F_H$ ) force and peak relative power ( $P_{\max}$ ) of the preferred and non-preferred legs during maximal sprinting. The non-preferred leg of the forwards produced less  $F_V$ ,  $F_H$  and  $P_{\max}$  than the preferred leg during acceleration (ES = -0.32, -0.58 and -0.67) and maximal velocity (ES = -0.50, -0.65 and -0.60). Backs produced more  $F_V$ ,  $F_H$  and  $P_{\max}$  than the forwards during initial acceleration (ES = 0.51, 1.58 and 1.30) but less at maximal velocity (ES = -0.74, -0.79 and -0.81). Backs had faster split times at 2, 5, 10 and 15m (ES = -1.03, -0.82, -0.63 and -0.50) but slower times at 35 and 40m (ES = 0.78 and 1.10) compared with forwards. Forwards produced larger sprint kinetics compared with backs, but also larger lower-extremity imbalances; potentially reducing sprint efficiency and / or increasing injury risk.

## Introduction

Rugby union is a contact sport characterised by recurrent bouts of maximal sprinting and high-force events (i.e. tackling, scrums, rucks and mauls). Due to governing rules, forwards are more likely to be involved in high-force strength-dominated movements, whereas backs typically perform a greater frequency of high-velocity events with an emphasis on contact evasion [10]. Consequently, athletes may develop strength and speed characteristics unique to position [9, 177]. While research [216, 217] in rugby has illuminated many physiological and technical differences between playing position during such sprinting movements, the mechanical demands (such as the kinetic and kinematic output of sprinting) specific to position are relatively unknown. Such information may provide insight into injury prevention and athletic performance, and is therefore of interest to the rugby community.

Position-specific lower-extremity power characteristics have been scarcely investigated in research. Among the few studies [9, 177, 218-220] that have profiled positional differences in rugby codes, the majority have assessed strength, agility and aerobic capacity. Substantial differences have been shown in strength during knee flexion and hip extension in academy [9] and professional [177] rugby union athletes, with backs being weaker in both movements compared with forwards (up to 16% and 20% less, respectively). While isokinetic assessments provide a detailed understanding of lower-extremity strength ability and injury risk, they may lack specificity to practical performance when used in isolation (i.e. unilateral, single-joint, open-chain, constant velocity). As the injuries most commonly seen in rugby union (i.e. hamstring and anterior cruciate ligament) occur more frequently during closed-chain movements [20, 221], inclusion of assessments resembling such competition demands (i.e. sprinting) would provide a more detailed understanding of lower-extremity power ability and injury risk [170].

The potential for rugby athletes to develop unique positional differences highlights athletes may additionally develop individual, and perhaps position specific, bilateral differences (asymmetries). For example, several positions assumed by forwards (i.e. props, hookers and flankers) require unique body positions while exerting high levels of force in a scrum [222]. Across a season or career, the frequency and specificity of these body positions may create a lower-extremity asymmetry [9, 177]; wherein one leg may be stronger or more skilled than the other. Authors [223] have recently identified the importance of exploring asymmetries in



team-sport athletes and highlighted the practicality of the information gained. When specifically assessing male rugby athletes, lower-extremity asymmetries may have the potential to better inform an athlete's return-to-sport status following an injury, detect any adverse effects that may be lingering from a previous injury and potentially identify individuals at an increased risk of future injury [98, 172]. While assessing asymmetries in non-injured athletes, separation of the legs by the 'preferred' and 'non-preferred' kicking legs has been proposed as the most practical and applicable division since the answer is athlete-determined and applicable among most field-based sports [9]. However, while this division of legs has important utility when assessing strength, theoretically a more sport-specific assessment such as that of jumping or sprinting might provide more appropriate insight into injury risk and prevention.

Analysis of sprinting kinetics provides valuable injury prevention information to practitioners [98, 170, 171]. While direct assessment of lower-extremity ability is technically possible during over-ground sprinting, the requirements are in-ground force platforms of sufficient length to profile relevant sprinting phases [224, 225]. While recent methods [224] allow for estimation of external force measures from centre-of-mass movement, determining force production between legs is (at present) not possible. Sprint treadmill ergometry is currently the most practical means of directly assessing sprinting kinetics and kinematics [226]. Furthermore, instantaneous sampling allows the examination of individual footstrikes from ground reaction force, and division of sprint efforts into multiple phases (e.g. initial acceleration, acceleration and maximal velocity), permitting phase-specific comparison of variables between legs. Consequently, sprint treadmills enable profiling of unilateral sprint kinetics and kinematics, comparison against peers, determination of injury risk and preventative programming.

To the best of our knowledge, only two studies [97, 98] have investigated between-leg differences during maximal effort sprinting on an instrumented treadmill, with no research having compared unilateral sprint mechanics in rugby union athletes using direct treadmill ergometry. Therefore, the aims of this study were to profile sprint mechanics on a non-motorised treadmill (NMT) in male academy-level rugby union forwards and backs in reference to leg preference and position. As forwards are commonly known for possessing greater lower-extremity strength compared with backs [9, 177], it was postulated that the

superior strength of the forwards would translate to greater horizontal force whilst sprinting [227] and that backs would obtain higher maximal velocities as previously reported [228].

## Methods

### *Athletes*

Thirty male academy (development-level) rugby union athletes (mean  $\pm$  SD: age  $22 \pm 4$  y, body-height  $1.85 \pm 0.07$  m, body-mass  $97 \pm 11$  kg), volunteered to participate in this research (Table 17). Athletes were separated for analysis based on their most regular playing position as either 'forwards' ( $n = 15$ ) or 'backs' ( $n = 15$ ). All athletes were currently training and competing in a high-performance academy; the prelim to the highest level of New Zealand professional rugby. All athletes were currently healthy and trained under the supervision of their teams' strength and conditioning coaching staff. Athletes were excluded from the study if they reported any of the following: (1) any history of severe musculoskeletal or soft tissue injury to either leg; (2) any current injury or pain to either leg that would impair their ability to perform the required sprint testing; or, (3) any physical or neurological condition that would impair their ability to perform the required maximal sprint effort. Prior to participation, all aspects of the research study were verbally explained to each athlete, written informed consent was obtained and a coded number was assigned to each athlete to ensure the data remained anonymous. All procedures used in this study were approved by the Auckland University of Technology Ethics Committee (13/378), conducted ethically in accordance with the principles of the Declaration of Helsinki and meet the international standards in sport and exercise science research for the *International Journal of Sports Medicine* [229].

**Table 17. Athlete characteristics used in Chapter 5.**

	Forwards ( $n = 15$ )	Backs ( $n = 15$ )
Age (y)	$20 \pm 1$	$24 \pm 4$
Body-height (m)	$1.87 \pm 0.09$	$1.84 \pm 0.04$
Body-mass (kg)	$103 \pm 11$	$90 \pm 8$
Body-mass index ( $\text{kg}\cdot\text{m}^{-2}$ )	$30 \pm 4$	$27 \pm 2$
Rugby experience (y)	$10 \pm 4$	$7.1 \pm 4.4$
Preferred leg	R = 14, L = 1	R = 10, L = 5

Footnote: y, year; m, metre; kg, kilogram; R, right; L, left. Values are means  $\pm$  standard deviation.

## *Methodology*

Athlete characteristics were recorded, including leg preference determined as the preferential kicking leg. A general self-selected lower-extremity dynamic warm-up was performed by all athletes; similar to the team's standard warm-up procedures for weight training, practice and match play. Testing procedures were then fully explained to the athletes during a 3 min passive-recovery period before testing procedures commenced.

Maximal sprint performance was assessed on a Woodway Force 3.0 (Woodway USA, Inc., Waukesha, WI, USA) NMT ergometer. This system has been implemented in previous research [230] featuring sprinting performance in rugby codes and has been shown [231] to be reliable for kinetic and kinematic sprinting measurements. The NMT collected vertical ground reaction force data ( $F_V$ ) via four load cells underneath a user driven belt (0.55 m width x 1.73 m length) made up of 60 individualised slats of vulcanised rubber (38-43 Shore hardness) and horizontal propulsive force data ( $F_H$ ) via a load cell attached to a non-elastic tether at 200 Hz. External power output was calculated at each instant via the step averaged (within phase; see below) product of the  $F_H$  exerted on the load cell and the velocity of the treadmill belt; where the peak value was denoted as maximal power ( $P_{\max}$ ). All kinetic data were made relative to individual athlete body-mass and reported as  $\text{N}\cdot\text{kg}^{-1}$  ( $F_V$  and  $F_H$ ) or  $\text{W}\cdot\text{kg}^{-1}$  ( $P_{\max}$ ). Calibration occurred at the beginning of each collection in accordance with manufacturer recommendations and aligning with previously described methods [231].

Following the warm-up, athletes were tethered around the waist to a vertical strut at the rear of the ergometer. Horizontal alignment of the tether and load cell was ensured by adjusting a sliding gauge to athlete hip-height. The athletes then performed a standardised familiarisation, consisting of variable speed jogging ( $\sim 2 \text{ m}\cdot\text{s}^{-1}$  for  $\sim 2$  min), three submaximal sprints ( $\sim 8$  s at 50%, 70% and 90% of athlete's estimated maximum velocity), and a single short maximal trial ( $\sim 3$  s). Each sprint effort was followed by 3 min rest. For the submaximal and maximal sprints, the tester applied a brake to the stationary treadmill belt to allow the athlete to lean forward against the horizontal tether to better simulate a typical over-ground staggered sprint start [231]. Where athletes did not visually perform the sprint adequately (i.e. if they initiated the sprint start before the brake on the belt was released or stumbled at any time during the sprint effort; as visually assessed by the tester), additional verbal/visual cues were provided to the athlete and a subsequent familiarisation trial was performed.

Athlete trials consisted of  $\sim 8$  s maximal velocity sprints from a staggered start (as per the warm-up protocol detailed above). Athletes started the trial from a staggered stance with their preference of lead-leg forward, the likes of which were recorded to allow determination of left/right, and accordingly preferred/non-preferred leg comparisons. Athletes were instructed to accelerate maximally following countdown, and verbally cued to maintain at maximal velocity for  $\sim 5$  s to collect sufficient steps for analysis. Athletes performed two trials with a 5 min rest between trials. The trial with the highest peak velocity was selected for subsequent analysis.

Data were then analysed using a custom designed LabVIEW program (Version 14.0, National Instruments Corp., Austin, TX, USA) where the sprint effort was separated into initial acceleration (steps 1-2), acceleration (steps 3-12) and maximal velocity (steps 13-22) phases. The decision to divide the sprint effort into these three distinct phases was primarily based on previously collected “unpublished observations” from our laboratory wherein the majority of male athletes tested ( $n = 57$ ) did not display a flight phase within the first two steps of the sprint effort; an observation anecdotally similar to sprinting over-ground while towing a sled. However, this same majority of athletes did present a clearly identifiable flight phase between steps two and three (see first vertical dashed line in Figure 1). If an athlete did not reach a flight phase before the third step, the division between initial acceleration and acceleration was created in the same position between steps two and three at the smallest (closest to zero)  $F_V$  reading. Noting similar differences between the initial start of a sprint and the acceleration, authors [232] have suggested a potential benefit to examining the two phases separately in providing more accurate detail in acceleration mechanics. Additionally, all athletes ceased to accelerate within the subsequent 10 steps and reached maximal velocity within the next 10 steps. A secondary basis for the division of the sprint effort was to create a new standard for testing using an objective criteria as recently been suggested in the literature [223, 232]. These observations and subsequent sprint phases were manually identified by visually inspecting the ground reaction force data and selecting the corresponding steps for further examination (Figure 13) [223]. Sprint kinematics including contact time, flight time, step frequency and step length were determined using methods described elsewhere in detail [231]. In short, contact time was assessed as the duration of time in milliseconds that the  $F_V$  reading rose above 0 N and then returned to 0 N; flight time

was assessed as the duration of time in milliseconds immediately following the conclusion of contact time to the initiation of the next foot's contact time. Step frequency and step length were assessed using equations 9 and 10 respectively.

Equation 9. Step frequency (Hz) =

$$\frac{1000}{\text{contact time} + \text{flight time}}$$

Equation 10. Step length (m) =

$$\frac{\text{maximal velocity}}{\text{step frequency}}$$

Data obtained from each leg during the sprint effort were averaged during the initial acceleration phase (as the athletes were unable to obtain the flight-phase necessary to accurately detect a change in leg) and were separated into preferred and non-preferred leg during acceleration and maximal velocity phases for final statistical comparisons.

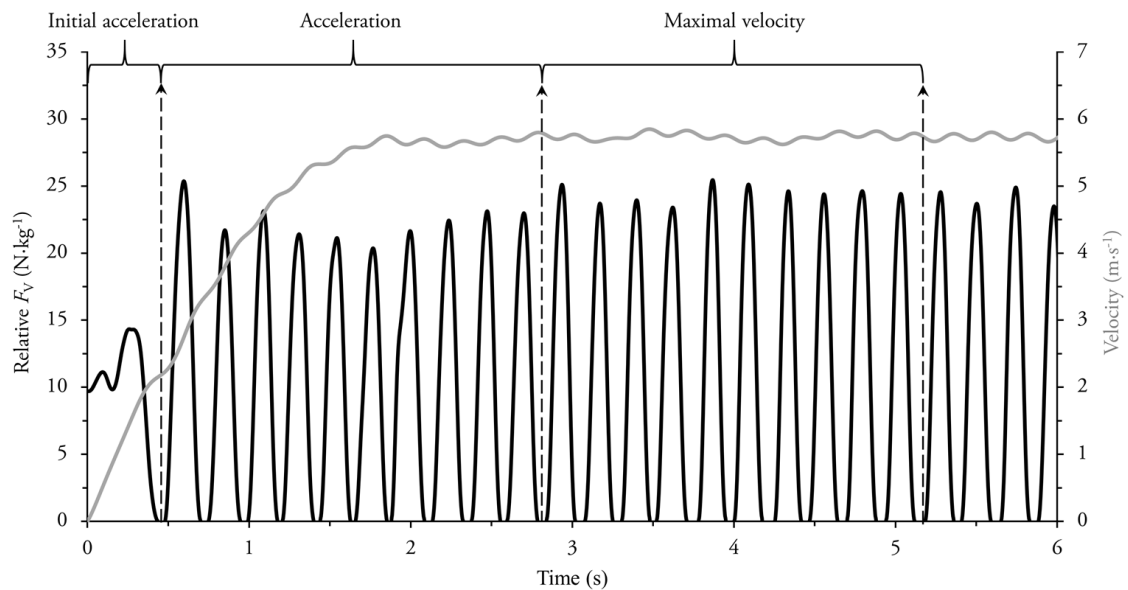


Figure 13. A maximal sprint effort and associated vertical force.

A visual representation of a typical maximal sprint effort on the Woodway non-motorised treadmill where data were separated into initial acceleration (steps 1-2), acceleration (steps 3-12) and maximal velocity (steps 13-22). Relative vertical force (relative  $F_v$ ; Newton per kilogram [ $\text{N} \cdot \text{kg}^{-1}$ ]) on the primary vertical axis (left) is shown in black and velocity (metres per second [ $\text{m} \cdot \text{s}^{-1}$ ]) on the secondary vertical axis (right) is shown in grey. Kinetic variables were normalised to time (seconds [s]) on the horizontal axis [233].

### ***Statistical analysis***

Magnitude-based inferences were utilised in this study in lieu of the traditional statistical significance approach as while differences between legs and position are expected, the magnitude of the difference is currently unknown [179, 180]. Excel spreadsheets (*Post-only crossover* and *Pre-post parallel groups trial*) found at Sportsci.org were used to assess the effects between the preferred and non-preferred leg and between forwards and backs. The magnitude of the difference was then assessed by standardisation; that is, the difference between the means was divided by the standard deviation of the reference criteria. Forwards and the preferred leg were chosen as references in this study due to their common selection in similar analyses [9, 177, 178].

Typical threshold values of <0.20, 0.20, 0.60, 1.20 (representing trivial, small, moderate, and large differences, respectively) were used for assessing the magnitude of the standardised effects reported in this study [142]. Uncertainty in the estimates of effects on position and leg preference were expressed at 90% confidence limits and as probabilities that the true value of the effect was substantially positive (+ive) and negative (-ive). Qualitative probabilistic inferences regarding the true effect were then made (described in detail in previous work [142]). In summary, if the probabilities of the true effect being substantially positive and negative were both >5%, the effect was expressed as unclear; otherwise the effect was clear and expressed as the magnitude of its observed value. The scale for interpreting the probabilities was 25-74%, possibly (\*) and 75-94%, likely (\*\*).

### **Results**

During the first two steps, backs produced higher  $F_V$ ,  $F_H$  and  $P_{\max}$  (ES = 0.51, 1.58 and 1.30, respectively) compared with forwards (Table 18).

**Table 18. Initial acceleration sprint kinetics.**

			Combined
Relative $F_V$ (N·kg <sup>-1</sup> )		Forwards	14 ± 2
		Backs	15 ± 2
	Backs – Forwards	<i>Mean change; ±90% CL</i>	1.01; ±1.20
		<i>Qualitative inference</i>	Small** +ive
Relative $F_H$ (N·kg <sup>-1</sup> )		Forwards	4.7 ± 1.2
		Backs	6.6 ± 1.3
	Backs – Forwards	<i>Mean change; ±90% CL</i>	2.0; ±0.8
		<i>Qualitative inference</i>	Large** +ive
Relative $P_{\max}$ (W·kg <sup>-1</sup> )		Forwards	8.9 ± 3.0
		Backs	14 ± 4
	Backs – Forwards	<i>Mean change; ±90% CL</i>	5.02; ±2.34
		<i>Qualitative inference</i>	Large* +ive

Footnote: Initial acceleration (steps 1-2). CL, confidence limits; relative  $F_V$ , peak vertical force production relative to body-mass; relative  $F_H$ , peak horizontal force production relative to body-mass; relative  $P_{\max}$ , peak power production relative to body-mass; N, newton; kg, kilogramme; W, Watt. Values are means ± standard deviation and mean change; ±90% confidence limits. Small and large inference: \*possibly, 25–74%; \*\*likely, 75–94%. +ive, substantial positive change of backs relative to forwards.

During acceleration, the forwards' non-preferred leg produced lower  $F_V$ ,  $F_H$  and  $P_{\max}$  (ES = -0.32, -0.58 and -0.67, respectively) compared with the preferred leg. The backs' non-preferred leg produced similar  $F_V$  (ES = 0.02) compared with the preferred leg and unclear differences in  $F_H$  and  $P_{\max}$ . During maximal velocity, the forwards' non-preferred leg produced lower  $F_V$ ,  $F_H$  and  $P_{\max}$  (ES = -0.50, -0.65 and -0.60, respectively) compared with the preferred leg. The backs' non-preferred leg produced similar  $F_V$  (ES = 0.10) and higher  $F_H$  (ES = 0.54) compared with the preferred leg and an unclear difference in  $P_{\max}$  (Table 19, left to right comparisons).

Also during acceleration, the non-preferred leg of the backs produced higher  $F_H$  and  $P_{\max}$  (ES = 0.66 and 0.55, respectively) compared with the non-preferred leg of the forwards. During maximal velocity, the preferred leg of the backs produced lower  $F_V$ ,  $F_H$  and  $P_{\max}$  (ES = -0.74, -0.79 and -0.81, respectively) while the non-preferred leg produced higher  $F_H$  (ES = 0.59) compared with the preferred and non-preferred legs of the forwards (Table 19, top to bottom comparisons). All other differences between positions were unclear.

Table 19. Acceleration and maximal velocity sprint kinetics.

				Non-preferred – preferred		
				Preferred	Non-preferred	Mean change; $\pm 90\%$ CL
Relative $F_V$ (N·kg <sup>-1</sup> )						
Acceleration	Backs – Forwards	Forwards	22 $\pm$ 1	21 $\pm$ 2	-0.41; $\pm 0.66$	Small* -ive
		Backs	21 $\pm$ 2	21 $\pm$ 2	0.045; $\pm 0.496$	Trivial**
		Mean change; $\pm 90\%$ CL	-0.25; $\pm 1.12$	0.21; $\pm 1.15$		
		Qualitative inference	Unclear	Unclear		
Maximal velocity	Backs – Forwards	Forwards	24 $\pm$ 1	24 $\pm$ 2	-0.68; $\pm 0.72$	Small** -ive
		Backs	23 $\pm$ 3	23 $\pm$ 3	0.31; $\pm 0.52$	Trivial**
		Mean change; $\pm 90\%$ CL	-1.7; $\pm 1.4$	-0.75; $\pm 1.39$		
		Qualitative inference	Moderate* -ive	Unclear		
Relative $F_H$ (N·kg <sup>-1</sup> )						
Acceleration	Backs – Forwards	Forwards	4.2 $\pm$ 1.1	3.5 $\pm$ 0.7	-0.65; $\pm 0.59$	Small** -ive
		Backs	3.9 $\pm$ 0.6	3.9 $\pm$ 0.4	-0.019; $\pm 0.357$	Unclear
		Mean change; $\pm 90\%$ CL	-0.23; $\pm 0.54$	0.404; $\pm 0.369$		
		Qualitative inference	Unclear	Moderate* +ive		
Maximal velocity	Backs – Forwards	Forwards	3.7 $\pm$ 1.1	2.9 $\pm$ 0.6	-0.79; $\pm 0.62$	Moderate* -ive
		Backs	3.0 $\pm$ 0.5	3.3 $\pm$ 0.5	0.30; $\pm 0.39$	Small** +ive
		Mean change; $\pm 90\%$ CL	-0.73; $\pm 0.56$	0.36; $\pm 0.37$		
		Qualitative inference	Moderate* -ive	Small** +ive		
Relative $P_{\max}$ (W·kg <sup>-1</sup> )						
Acceleration	Backs – Forwards	Forwards	22 $\pm$ 6	18 $\pm$ 5	-4.5; $\pm 3.1$	Moderate* -ive
		Backs	20 $\pm$ 3	20 $\pm$ 2	-0.34; $\pm 1.80$	Unclear
		Mean change; $\pm 90\%$ CL	-2.1; $\pm 3.1$	2.1; $\pm 2.4$		
		Qualitative inference	Unclear	Small** +ive		
Maximal velocity	Backs – Forwards	Forwards	23 $\pm$ 7	18 $\pm$ 4	-4.8; $\pm 3.7$	Moderate* -ive
		Backs	18 $\pm$ 3	19 $\pm$ 4	1.2; $\pm 2.4$	Unclear
		Mean change; $\pm 90\%$ CL	-4.9; $\pm 3.7$	1.03; $\pm 2.62$		
		Qualitative inference	Moderate* -ive	Unclear		

Footnote: Acceleration (steps 3-12) and maximal velocity (steps 13-22) relative sprint kinetics for preferred and the non-preferred legs and for forwards and backs; and inferences for change in the means. CL, confidence limits; relative  $F_V$ , peak vertical force production relative to body-mass; relative  $F_H$ , peak horizontal force production relative to body-mass; relative  $P_{\max}$ , peak power production relative to body-mass; N, newton; kg, kilogramme; W, Watt. Values are means  $\pm$  standard deviation and mean change;  $\pm 90\%$  confidence limits. Trivial, small and moderate inference: \*possibly, 25–74%; \*\*likely, 75–94%. +ive and -ive, substantial positive and negative change of the non-preferred leg relative to the preferred leg or backs relative to forwards.



Backs obtained faster split times at 2, 5, 10 and 15 m ( $ES = -1.03, -0.82, -0.63$  and  $-0.50$ , respectively) but slower split times at 35 and 40 m ( $ES = 0.78$  and  $1.10$ , respectively) compared with forwards (left vertical axis in Figure 14). Backs also produced higher combined  $F_H$  at initial acceleration ( $ES = 1.58$ ) but unclear differences at acceleration and maximal velocity (right vertical axis in Figure 14) compared with forwards. Overall, backs produced lower peak velocity ( $ES = -0.54$ ) and shorter time to maximal velocity ( $ES = -1.47$ ) compared with forwards (Table 20). All other differences between positions were unclear.

**Table 20. Maximal velocity sprint kinematics.**

	Forwards	Backs	Backs – Forwards	
			<i>Mean change; ±90% CL</i>	<i>Qualitative inference</i>
Maximal velocity ( $m \cdot s^{-1}$ )	$6.2 \pm 0.3$	$6.0 \pm 0.3$	$-0.17; \pm 0.19$	<i>Small** -ive</i>
Time of maximal velocity (s)	$4.4 \pm 0.9$	$3.3 \pm 0.5$	$-1.2; \pm 0.5$	<i>Large** -ive</i>
Contact time (ms)	$176 \pm 12$	$180 \pm 14$	$3.9; \pm 8.3$	<i>Unclear</i>
Flight time (ms)	$59 \pm 6$	$56 \pm 11$	$-2.6; \pm 5.7$	<i>Unclear</i>
Stride frequency (Hz)	$4.3 \pm 0.2$	$4.2 \pm 0.2$	$-0.031; \pm 0.127$	<i>Unclear</i>
Stride length (m)	$1.04 \pm 0.20$	$0.78 \pm 0.11$	$-0.27; \pm 0.10$	<i>Large** -ive</i>

Footnote: CL, confidence limits; m, metres; s, second; Hz, hertz. Values are means  $\pm$  standard deviation and mean change;  $\pm 90\%$  confidence limits. Small and large inference: \*\*likely, 75–94%. -ive, substantial negative change of backs relative to forwards.

## Discussion

To our knowledge this is the first study to examine between leg and positional differences in sprint kinetics and kinematics in rugby union athletes using NMT ergometry. We were able to detect the forwards' non-preferred leg produced smaller peak  $F_V$ ,  $F_H$  and  $P_{max}$  during acceleration and maximal velocity compared with the preferred leg. The backs' non-preferred leg, on the other hand, showed trivial differences in peak  $F_V$  and slightly larger peak  $F_H$  during maximal velocity compared with the preferred leg. Additionally, backs produced substantially greater peak  $F_H$  and  $P_{max}$  during initial acceleration and unclear differences during acceleration and maximal velocity, corresponding with small to moderately faster split times at 2, 5, 10 and 15 m but moderately slower split times at 35 and 40 m compared with forwards. Backs also produced inferior sprint kinematics compared with forwards (e.g. lower maximal velocity), which likely reflects the kinetic differences observed.

The primary purpose of this study was to profile leg preference on sprint mechanics. With this in mind, the division of legs was only applicable to acceleration and maximal velocity phases as during the first two steps of a sprint effort (initial acceleration) athletes did not

obtain the flight-phase necessary to accurately determine kinetics between legs. Despite this, profiling initial acceleration provides valuable insight into force production during the first few metres, and may influence subsequent performance during the sprint [231]. During initial acceleration backs produced substantially greater sprint kinetics ( $F_V$  [7%],  $F_H$  [30%] and  $P_{\max}$  [36%]) compared with forwards. While not clearly investigated in the literature, these findings may be reminiscent of the staggered starting position of the sprint assessment and its similarities to positioning commonly adopted by backs during match play. Positional requirements of rugby forwards to be more heavily involved in rucks, scrums and mauls [234] may observationally infer a better adaptation to a lower ‘crouched’ start position (even in some cases adopting a three- or four-point stance). The unfamiliar staggered sprint position used in the current study may have resulted in a new kinetic profile for the forwards; potentially causing unequal distribution of  $F_V$  and  $F_H$  and less overall efficiency in orientation force than that of the backs. Additionally, despite a lighter body-mass (-13 kg; -14%), the backs were technically better at orienting their force production (in the horizontal direction) during the first two steps compared with forwards. The relative sprint kinetics during the first two steps of the maximal sprint effort, found in the current study, are considerably different from the relative values found by other researchers (forwards:  $F_V$  [-5.4 N·kg<sup>-1</sup>; -39%],  $F_H$  [-1.2 N·kg<sup>-1</sup>; -25%] and  $P_{\max}$  [-6.4 N·kg<sup>-1</sup>; -72%]; backs:  $F_V$  [-4.4 N·kg<sup>-1</sup>; -29%],  $F_H$  [0.8 N·kg<sup>-1</sup>; 12%] and  $P_{\max}$  [-1.4 N·kg<sup>-1</sup>; -10%]) [231] who examined mixed-sport university-level athletes using a similar testing protocol. Of note, the backs in the current study produced 30% greater  $F_H$  compared with forwards and 12% greater  $F_H$  compared with mixed-sport athletes during initial acceleration [231], suggesting unique attributes may have been developed as a result of sporting demands. These findings support the notion that sport-specific adaptations may exist in sprint kinetics during initial acceleration.

Following initial acceleration, where a distinct separation between final contact of one foot and initial contact of the other is observed (e.g. flight), is the acceleration phase. During the acceleration phase, the non-preferred leg of the forwards produced possibly to likely small differences in  $F_V$  (-2%),  $F_H$  (-19%) and  $P_{\max}$  (-25%) compared with the preferred leg while the non-preferred leg of the backs produced likely trivial differences in  $F_V$  (0.2%) and unclear differences in  $F_H$  (-0.5%) and  $P_{\max}$  (-2%) compared with the preferred leg. During maximal velocity, the non-preferred leg of the forwards produced likely small to possibly moderate

differences in  $F_V$  (-3%),  $F_H$  (-27%) and  $P_{\max}$  (-27%) compared with the preferred leg while the non-preferred leg of the backs produced likely trivial differences in  $F_V$  (1%), likely small positive differences in  $F_H$  (9%) and unclear differences in  $P_{\max}$  (6%) compared with the preferred leg. The observation that the preferred leg produced substantially larger sprint kinetics during acceleration and maximal sprinting is of interest considering professional rugby union athletes have been found to possess superior strength in the preferred leg [177]. While the most substantial differences between legs occurred in the non-preferred leg of forwards during maximal phase sprinting, given literature [98, 114] has typically presented a 'safe' upper-limit for bilateral imbalances of <10%, both phases (acceleration and maximal velocity) present potentially dangerous imbalances in  $F_H$  and  $P_{\max}$ . It would appear that the forwards in this sample would benefit from targeted (individualised) interventions to decrease asymmetries, while the backs appear relatively symmetrical.

While this is the only study to our knowledge that has examined the differences in sprint mechanics between the preferred and non-preferred legs, researchers [97] have examined sprint kinetics and kinematics at 80% maximal effort in the right and left legs and injured and non-injured legs of Australian rules footballers. The authors [97] noted the injured leg was 46% weaker compared with the non-injured leg in absolute  $F_H$  (~46% relative  $F_H$ , due to homogenous athlete characteristics). Moreover, recent research [235] in over-ground sprinting highlights significant decrements in net  $F_H$  production (and associated performance markers) with imbalances in hamstring strength reminiscent from injury; giving further credence to the premise that accurate and detailed bilateral screening of athlete imbalances is important, and their correction may result in increases in performance markers. While some discrepancies in bilateral force production during sprinting may possibly be explained by differences in stiffness for each leg resultant of neuromuscular tasking (see the 'spring and stick' theory, as described in detail by Cavanagh et al. [236]), excessive imbalances in kinetic and kinematic profiles likely present cause for concern. In any case, mechanical asymmetries between legs may be the result of different neuromuscular tasking during sprinting efforts, as found in the current study, and could potentially affect both sprinting performance and injury risk [237].

The ability of an athlete to cover more distance at a faster rate (e.g. velocity) could result in a more advantaged offensive or defensive task (i.e. body- or field-position) which is crucial to

success in rugby union [228]. Moreover, while maximal velocity is reached less frequently in rugby codes, athletes may occasionally be required to sprint at maximal velocity following a line-break or while in pursuit of an opponent [234]. In addition to differences found in leg preference, clear and substantial differences were found between playing position. When examining global (averaged between legs)  $F_H$  during the sprint effort, backs possessed substantially greater  $F_H$  at initial acceleration (30%) but unclear differences during acceleration (2%) and maximal velocity (-6%) compared with forwards (see Figure 2). These combined kinetic findings appeared linked to split times and ultimately maximal velocity: the backs reaching 2, 5, 10 and 15 m quicker (13, 5, 2 and 0.3%, respectively) and the forwards reaching 35 and 40 m quicker (6 and 14%, respectively) with a higher maximal velocity (3%). Interestingly, while backs typically reach greater peak velocities during over-ground sprinting [228], forwards displayed higher peak velocities on the NMT. While over-ground sprint performance was not assessed in this study, these results seemingly contradict moderate correlations between NMT and over-ground sprinting [238]. We believe that these findings characterise the muscular ability of each subset (forwards and backs) that could potentially be seen during over-ground sprinting to a certain extent [239]; be it in unloaded or sprinting against resistance (e.g. contact in a tackle). An explanation for this assertion could be given that forwards possess greater posterior-chain strength [177], their superior levels of relative force and peak velocities support the notion that NMT sprinting favours heavier athletes at maximal velocities. It is possible that the relationship between NMT and over-ground sprint performance might be weakened in sporting codes featuring position-subsets with differing characteristics; however, further research in this area is warranted. It is important to note, from an injury risk point-of-view, forwards presented much greater imbalances across all phases of sprinting compared with backs. When separated by leg, backs demonstrated moderately larger  $F_H$  (10%) and slightly larger  $P_{\max}$  (11%) in the non-preferred leg during acceleration compared with the forwards' non-preferred leg. During maximal velocity sprinting however, backs produced moderately smaller  $F_V$  (-1%),  $F_H$  (-24%) and  $P_{\max}$  (-28%) in the preferred leg compared with the forwards' preferred leg. These results highlight the importance of leg-separation of kinetic results during sprinting, as while forwards may have performed better in several aspects of the NMT sprint, they possess significantly greater imbalances in key mechanics; likely placing them at greater risk of injury if left unattended.

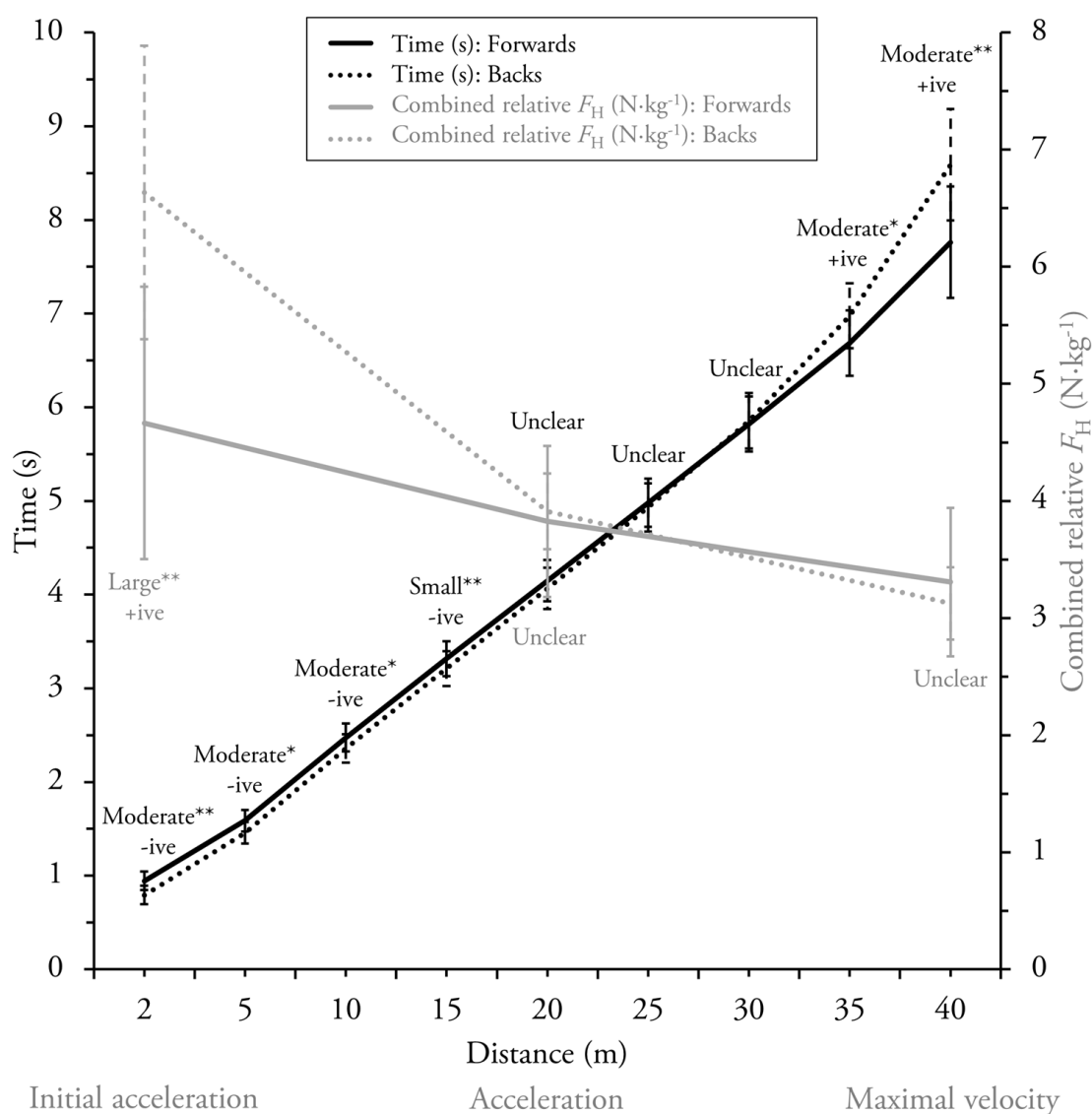


Figure 14. Sprint kinematics and kinetics.

Sprint kinematics presented as split times in seconds (s) on the primary vertical axis (left) are shown in black at distances of 2, 5, 10, 15, 20, 25, 30, 35 and 40 metres (m) and sprint kinetics presented as combined relative horizontal force (relative  $F_H$ ; Newton per kilogram [ $\text{N}\cdot\text{kg}^{-1}$ ]) during initial acceleration (steps 1-2), acceleration (steps 3-12) and maximal velocity (steps 12-22) sprinting on the secondary vertical axis (right) are shown in grey for forwards and backs; and inferences for change in the means. Small, moderate and large inference: \*possibly, 25–74%; \*\*likely, 75–94%. +ive and -ive; substantial positive and negative change of backs relative to forwards [233].

We feel it is important to acknowledge limitations in the current study to give context to the interpretations of our findings. First, this study implemented a novel division of sprint phases based on step number (e.g. initial acceleration [steps 1-2], acceleration [steps 3-12] and maximal velocity [steps 13-22]) as a prospective method for future studies to follow.

Potentially, acceleration profiles from athletes in different sporting codes (i.e. 100 m sprinters) may not be accurately fitted within our standardised step criteria due to elongated or shortened acceleration profiles [240]. Second, a substantial lack of normative data unique to sport, position and leg limit meaningful comparisons at this time. The continuation of NMT assessments using relatively homogenous populations, separated by position if applicable, and the addition of assessing each leg individually is imperative to the growth of NMT knowledge as it pertains to the generation of individualised injury prevention and athletic performance programming. Future research should determine whether individualised programming can reduce asymmetries in sprint mechanics measured via NMT ergometry, and consequently which elements in preventative programming are most important.

## Conclusion

In summary of key observations from this research: 1) the forwards' non-preferred leg produced lower relative  $F_V$ ,  $F_H$  and  $P_{\max}$  compared with the preferred leg throughout the sprint effort; suggesting a greater possibility of potentially dangerous asymmetries as a result of either training or competition demands; 2) backs produced higher relative  $F_V$ ,  $F_H$  and  $P_{\max}$  during the acceleration phases but lower values at maximal velocity, resulting in faster split times at early distances and slower split times at shorter distances compared with forwards; suggesting positional differences occur in force application with distance, and NMT sprinting may favour stronger and heavier athletes. These findings highlight a need for individual athlete assessment, or at very least separation of athletes based on position, when profiling athlete sprint kinetics and kinematics. Moreover, leg separation of sprinting kinetic data should be performed to unearth imbalances potentially missed by global measures of averaged force. It is apparent in this study's cohort that differences in sprint mechanics exist between legs and positions, however it is unknown whether these differences are comparable to other male academy-level rugby union athletes or unique to the athletes studied. Monitoring of lower-extremity sprinting asymmetries should occur intra-season in rugby union athletes to determine whether imbalances predict or influence injury risk.

## Chapter 6: Mechanical Sprinting Asymmetries Exist in Un-Injured Academy Rugby Union Athletes

This chapter comprises the following paper submitted to *Journal of Sports Sciences*.

### Reference:

Brown SR, Cross MR, Morin J-B, Samozino P, Brughelli M. Mechanical sprinting asymmetries exist in un-injured academy rugby union athletes. *J Sports Sci*. 2016:[in review].

### Author contributions:

Brown SR, 80%; Cross MR, 5%; Morin JB, 5%; Samozino P, 5%; Brughelli M, 5%.

### Overview

Horizontal force ( $F_H$ ) production is imperative during sprint acceleration. Lower-extremity asymmetries are commonly assessed in injury-prevention programming as they are thought to precede injury. However little is known regarding normative symmetry values in vertical ( $F_V$ ) and horizontal force production during sprinting in un-injured male rugby athletes. The purpose of this case-study was to determine the prevalence and magnitude of  $F_V$  and  $F_H$  symmetry while sprinting. A cross-sectional analysis of thirty male academy-level rugby union athletes implementing non-motorised treadmill ergometry was utilised to evaluate sprint kinetics from maximum  $F_H$  until maximal velocity during sprinting. There were no differences found between the legs in  $F_V$  values (ES = -0.059) whilst the non-preferred kicking leg produced less  $F_H$  than the preferred leg (ES = -0.55). Mean symmetry angle scores were substantially lower in  $F_V$  compared to  $F_H$  (1.4 vs 8.0%). Although all athletes were cleared to play by their team's medical staff, large asymmetries in  $F_H$  remained present, showing potential for athletes to "slip under the radar" of traditional injury-prevention assessments. Additionally, symmetry angle scores were extremely variable in  $F_H$  whereas they remained low in  $F_V$ . These findings highlight the importance of detailed athletic assessments for individualised programming in male rugby union athletes.

## Introduction

In a variety of sports, a component of sprinting (either acceleration or acceleration and maximal velocity [ $v_{\max}$ ]) is often utilised; requiring a unique marriage of horizontal ( $F_H$ ) and vertical ground reaction force production ( $F_V$ ) for success [228]. While Weyand [241] have demonstrated  $F_V$  as a key determinant of maximal velocity sprinting, sports like rugby union present fewer bouts of maximal sprinting and more repetitive bouts of acceleration [216]. In recent publications [225, 228, 240], authors have convincingly linked  $F_H$  capacities to acceleration performance across many sports, including rugby.

To directly measure sprint kinetics (i.e.  $F_V$  and  $F_H$ ) in each leg during a sprint effort, a non-motorised treadmill (NMT) can be utilised with reliable and repeatable methods [226]. Recently, several authors have illuminated substantial differences between the preferred and non-preferred kicking legs of academy-level rugby union athletes in lower-extremity strength on an isokinetic dynamometer [9] and force production during acceleration and maximal velocity sprinting phases on a NMT [242]; providing rationale for further investigations into lower-extremity symmetry. Lower-extremity deficits in  $F_H$  production have been shown to increase injury risk in semi-professional male Australian Rules footballers during sub-maximal sprinting [235]. Additionally, authors [98, 114, 170] have presented force asymmetry scores to gauge return-to-sport status in footballers and rugby athletes alike. Unfortunately, the specific demands of rugby may cause, aggravate or further perpetuate any lower-extremity asymmetries.

What is currently unknown is if  $F_V$  and  $F_H$  asymmetries exist while sprinting within a homogeneous and injury-free rugby cohort and if so, what might the expected levels be. Such information can be used by practitioners to more accurately guide return-to-sport decision making as well as individualised monitoring throughout development and competitive periods [170]. The purpose of this case-study was to report individual  $F_V$  and  $F_H$  symmetry angle scores among a homogeneous academy-level rugby cohort to determine the prevalence and magnitude of potential lower-extremity asymmetries during the acceleration phase of a maximal effort sprint.



## Methods

### *Athletes*

Thirty male academy (development-level) rugby union athletes volunteered as participants for this research (age =  $22 \pm 4$  y, body-height =  $1.85 \pm 0.07$  m, body-mass =  $97 \pm 11$  kg, body-mass index =  $28 \pm 3$  kg·m<sup>-2</sup>, rugby experience =  $8.6 \pm 4.2$  y, preferred leg = 24 right, 6 left). Informed consent were received from all athletes and all procedures used in this study were approved by the Auckland University of Technology Ethics Committee (13/378).

### *Design*

A cross-sectional design was used to classify leg differences in  $F_V$  and  $F_H$  using a modern NMT. Testing occurred during the athletes' off-season after ~24 h of rest. All athletes were free from injury in the previous six months, either chronic or acute, and cleared by the team's medical staff for full competitive play.

### *Procedure*

Detailed methodological procedures (including machine calibration, data verification and reliability metrics) can be found in previous research [231, 242, 243] implementing the identical NMT; but in short, following a standardised warm-up each athlete performed submaximal sprints for familiarisation and a maximal effort ~8 s sprint on a Woodway Force 3.0 (Woodway USA, Inc., Waukesha, WI, USA) NMT ergometer.  $F_V$  and  $F_H$  data were collected at 200 Hz and made relative to individual athlete body-mass. Data were analysed using a custom designed LabVIEW program (Version 14.0, National Instruments Corp., Austin, TX, USA), where discrete peak  $F_V$  and  $F_H$  data points between maximum horizontal force ( $F_{H_{\max}}$ ) and  $v_{\max}$  were meaned for the preferred and non-preferred leg (Figure 15). Leg preference was determined by the leg that the athlete preferred to kick the ball with or which they could kick the ball the furthest [9, 242].

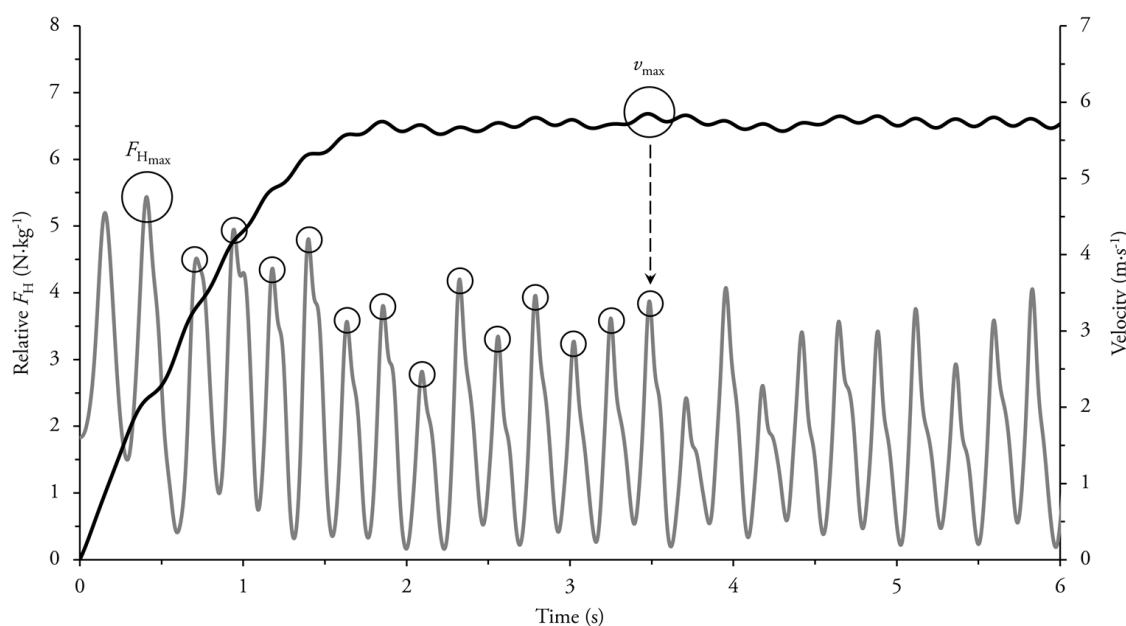


Figure 15. A maximal sprint effort and associated horizontal force.

A visual representation of a typical maximal sprint effort on the Woodway non-motorised treadmill. Relative horizontal force (Relative  $F_H$ ; newton per kilogram [ $\text{N}\cdot\text{kg}^{-1}$ ]) on the primary vertical axis is shown in grey and velocity (metres per second [ $\text{m}\cdot\text{s}^{-1}$ ]) on the secondary vertical axis is shown in black. Kinetic variables were normalised to time (seconds [s]) on the horizontal axis. Large circles represent maximum relative horizontal force ( $F_{H\max}$ ) and maximal velocity ( $v_{\max}$ ). Small circles represent discrete data points used in analysis.

Based on long-standing discrepancies of validity and practical use of symmetry index scores [96], a dimensionless symmetry angle equation [103] was considered the most clinically relevant assessment strategy to implement. However, as the purpose of this case-study was to determine the prevalence and magnitude of potential lower-extremity asymmetries, irrespective of leg, a modified symmetry angle equation was created to report an absolute relationship between the two legs (preferred leg and non-preferred leg). The modified symmetry angle equation (Equation 5) reports an absolute score (between 0 – 100%) that describes the deviation of the observed relationship between the two legs from a theoretically perfect relationship; where a score of 0% indicates perfect symmetry and 100% indicates perfect asymmetry.

### *Statistical analysis*

Means and standard deviations of relative  $F_V$  and  $F_H$  variables were presented along with the difference between the legs and an absolute symmetry angle score. Magnitude-based

inferences were utilised in this study for the authors to report on the magnitude of the difference between legs by using an Excel spreadsheet (*Post-only crossover*) found at Sportsci.org.

The magnitude of the difference was assessed by standardisation by using the preferred leg as the reference criteria as described in detail elsewhere [9]. Threshold values were <0.2, 0.2 and 0.6 representing trivial, small and moderate effects with uncertainty expressed at 90% confidence limits. Probabilities that the true value of the effect was substantially positive (+ive) and negative (-ive) were made and reported as unclear if the true effect were >5% or clear if otherwise. The scale for interpreting the probabilities was 25-74%, possibly (\*) and 75-94%, likely (\*\*).

## Results

Values of  $F_V$  were similar between the preferred ( $22 \pm 2 \text{ N}\cdot\text{kg}^{-1}$ ; range 18 – 25  $\text{N}\cdot\text{kg}^{-1}$ ) and non-preferred leg ( $22 \pm 2 \text{ N}\cdot\text{kg}^{-1}$ ; range 17 – 26  $\text{N}\cdot\text{kg}^{-1}$ ). The mean change between legs with 90% confidence limits was  $-0.55$ ;  $\pm 0.39$  with a clear and likely trivial effect ( $-0.059$ ). Conversely  $F_H$  values were larger in the preferred leg ( $4.3 \pm 1.0 \text{ N}\cdot\text{kg}^{-1}$ ; range 2.5 – 6.2  $\text{N}\cdot\text{kg}^{-1}$ ) compared to the non-preferred leg ( $3.7 \pm 0.7 \text{ N}\cdot\text{kg}^{-1}$ ; range 1.7 – 5.3  $\text{N}\cdot\text{kg}^{-1}$ ). The mean change between legs with 90% confidence limits was  $-0.13$ ;  $\pm 0.41$  with a clear and likely small negative effect ( $-0.55$ ) (Figure 16).

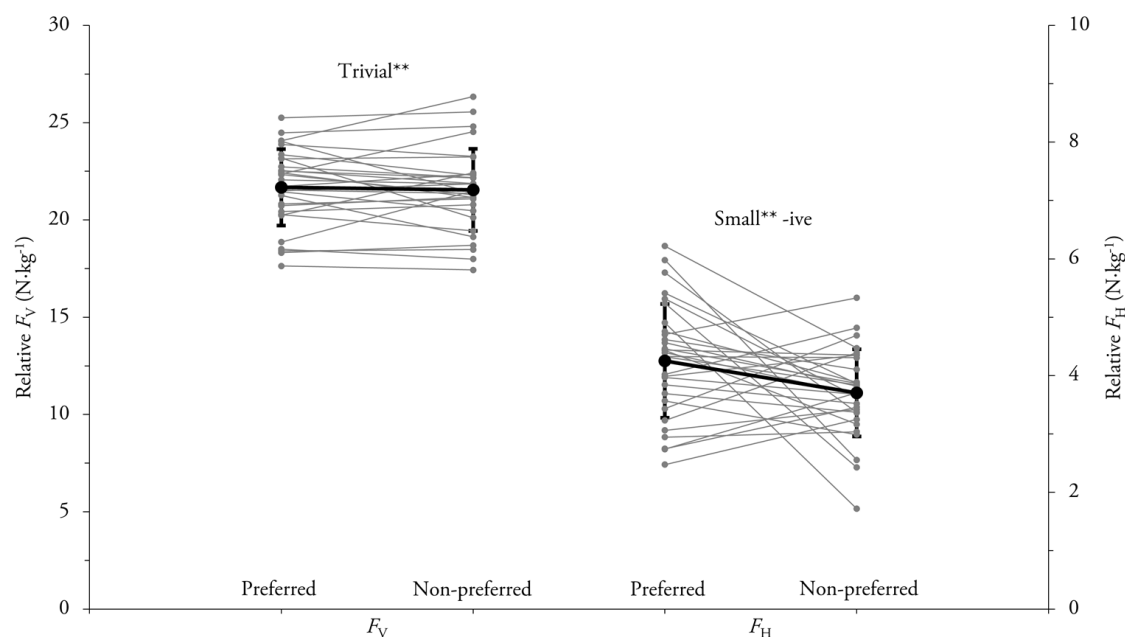
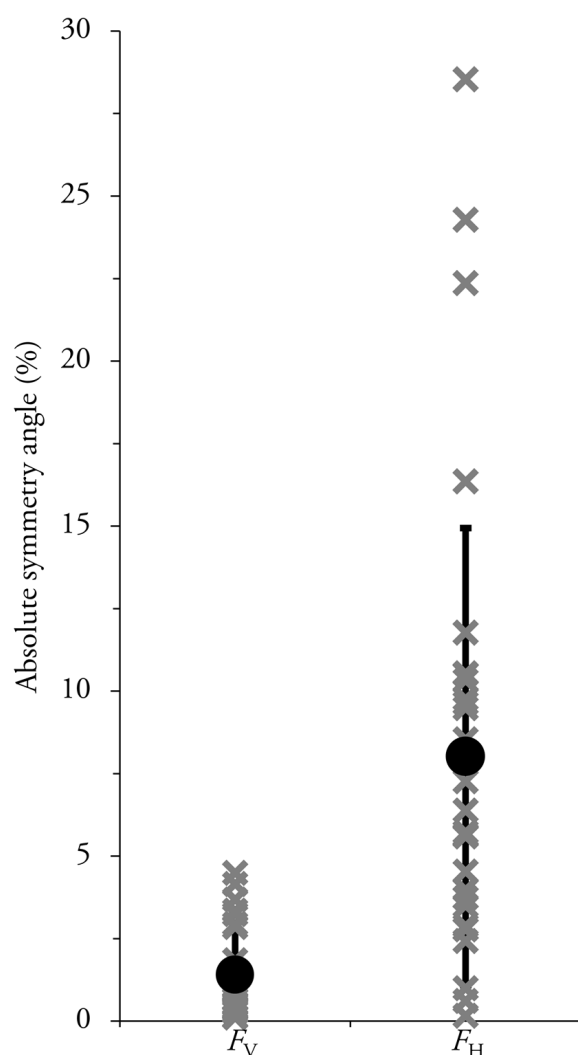


Figure 16. Individual vertical and horizontal force while sprinting.

Individual results for all rugby athletes separated by the preferred and non-preferred legs are shown in grey while means and standard deviations are shown in black. Relative vertical force (Relative  $F_V$ ; newton per kilogram [N·kg<sup>-1</sup>]) is presented on the primary vertical axis and relative horizontal force (Relative  $F_H$ ; newton per kilogram [N·kg<sup>-1</sup>]) is on the secondary vertical axis. Trivial and small inference: \*\*likely, 75–94%. -ive = substantial negative change of the non-preferred leg relative to the preferred leg.

Mean absolute asymmetry angle scores in  $F_V$  were  $1.4 \pm 1.3$  (range: 0.11 – 4.5) while  $F_H$  were  $8.0 \pm 6.9$  (range: 0.17 – 29) (Figure 17).



**Figure 17. Sprint kinetic symmetry angle scores.**

Individual asymmetry index scores for all rugby athletes (grey) separated by vertical ( $F_V$ ) and horizontal force ( $F_H$ ). Means and standard deviations are shown in black.

### Discussion

To our knowledge this is the first study to examine between leg differences and symmetry angle scores in  $F_V$  and  $F_H$  in rugby union athletes using NMT ergometry during the acceleration phase of maximal effort sprinting. To summarise, the preferred and non-preferred legs produced similar values of  $F_V$ , resulting in a low mean absolute symmetry angle score, whereas substantially different values of  $F_H$  were displayed between legs resulting in a higher mean absolute symmetry angle score (1.4% vs 8.0%, respectively).

Authors of previous research [225, 240] have convincingly demonstrated that the ability to globally produce  $F_H$  is more indicative of sprint acceleration performance than  $F_V$  capacities. While the research examining sprinting acceleration determinants on treadmill ergometers

and over-ground is robust [228, 239], little investigation exists profiling the difference in kinetic output between legs (largely as a by-product of the inability to quantify these complex variables). Moreover, no research exists investigating the mechanical determinants of asymmetries during sprinting. While speculative at this point, it is possible that kinetic asymmetries may arise from either an inability to produce total force or the lack of technical ability to apply this force in an effective manner (i.e. ratio of forces [240]). Regardless, it remains intuitive that an asymmetry between legs may lower the global effect of  $F_H$  production during a sprint effort [235] and a more detailed examination is warranted.

The athletes involved in the current research were assessed by their team's trained medical staff and reported no current injuries, chronic or acute. Listed as 'competition ready', one would assume injury risk at a low level. However, our research highlights potentially dangerous (high) levels of asymmetries may exist in mechanical sprinting capacities despite traditional means of detection, and subsequent clearance for competitive play [114]. Particularly, the extremely large range of absolute symmetry angle scores show the potential for an individual from a similar sample of male rugby athletes to present an asymmetry of between 0.17 – 29% in  $F_H$  output. The concern from a practitioner's standpoint is that these asymmetries pose a risk to performance, both as a function of decreased technical capacity to apply force (and thus sprint maximally) and as an increased risk of acute or chronic injury.

Two scenarios through which injuries may arise are: 1) increased risk reminiscent of a functionally weaker leg (i.e. activity exceeding limited capacity) or otherwise the 'stronger' leg pushing to compensate and maintain acceleration capacities, and 2) the performance of the athlete may begin to decrease (i.e. decreased ability to produce global  $F_H$ ). Further research is warranted to mitigate these theories. In any case, the fact that substantial asymmetries in kinetic capacities go undetected by traditional means should be of interest to athletes and coaching staff alike, and highlights the need for further screening / testing means to determine at risk cases.

## Conclusions

Substantial asymmetries in kinetics exist in cleared-to-play 'healthy' rugby union athletes. Given horizontal force production is paramount to the acceleration phase of sprinting, which in turn is central to rugby performance, the fact that these asymmetries exist in a seemingly healthy rugby population should be of concern, both from an injury prevention and

performance stand-point. Further, the global ability to produce  $F_H$  may be effected by an inept mechanical distribution between the legs; a trend not apparent in  $F_V$ . The direction of this investigation has prompted our research group to ponder several questions while continuing our research in this field: 1) would asymmetries determined in this dynamic task be present in an isolated strength measurement such as isokinetic dynamometry, 2) are asymmetries in  $F_H$  modifiable through individualised training programmes, and 3) will modifying these asymmetries decrease injury risk, increase performance, attain both attributes or attain neither?

## Chapter 7: An Individualised Approach to Assess the Sidestep Manoeuvre in Rugby Union Athletes: Are we Missing Individual Asymmetries by Focusing on Group Means?

This chapter comprises the following paper submitted to *American Journal of Sports Medicine*.

### Reference:

Brown SR, Hume PA, Lorimer AV, Brughelli M, Besier TF. An individualised approach to assess the sidestep manoeuvre in rugby union athletes: Are we missing individual asymmetries by focusing on group means? *Am J Sports Med*. 2016:[in review].

### Author contributions:

Brown SR, 80%; Hume PA, 5%; Lorimer AV, 5%; Brughelli M, 5%; Besier TF, 5%.

### Overview

Replicating anterior cruciate ligament (ACL) injury risk scenarios (e.g. the sidestep manoeuvre) provides a better understanding of the injury mechanisms. However, in sports like rugby union where athletes must sidestep off both legs, research on leg preference as a possible contributor to ACL injury is lacking. The appropriateness of how we then interpret ACL injury risk from the group / team data is questionable compared with the importance of individual differences and its impact on injury risk. The purpose of this study was to compare external knee abduction moments during sidestepping on each leg and to qualitatively assess the differences between group means and individual athletes. Cross-sectional study; Level of evidence 2c. Sixteen male academy-level rugby union athletes (age,  $20 \pm 3$  y; body-height  $1.9 \pm 0.1$  m; body-mass  $99 \pm 14$  kg) performed three maximal effort sidesteps ( $> 6.0\text{m}\cdot\text{s}^{-1}$ ) each on the preferred and non-preferred leg using marker-based three-dimensional motion analysis techniques. Quantitative comparisons were made between the legs while qualitative comparisons were made between the group means and the individual athletes. When sidestepping on the non-preferred leg, athletes produced 25% greater knee abduction moments (ES = 0.43) and presented modified postural adjustments associated with injury risk (extended knee [ES = -0.26; -8%], more trunk lateral flexion [ES = 0.42; 17%] and more distance between the centre-of-mass and ankle-joint-centre of the stance leg [ES = 0.97; 11%]) compared to the preferred leg. When assessing the individual athlete data,



only 9 out of 16 athletes presented a higher abduction moment in their non-preferred leg with individual asymmetries between legs ranging 2.2 and 47%. The non-preferred leg demonstrated altered mechanical properties compared to the preferred leg which are commonly associated with an increased injury risk (i.e. increased external knee abduction moment). Nearly half of the athletes showed the potential to “slip under the radar” of traditional group mean assessments.

## Introduction

Anterior cruciate ligament (ACL) injuries occur frequently in sport [75]. The sidestep is the most common manoeuvre associated with non-contact ACL injury [33]. During the stance phase of a sidestep the knee experiences applied flexion, abduction and internal rotation moments [54], which are combined loads that increase ACL strain [48]. Ligament injury occurs when the external forces exceed the mechanical properties of the tissue; which is believed to occur within the first 30% of stance phase [33, 58]. Therefore, assessment and potential interventions to reduce ACL injury have focused on reducing these key kinetic variables, particularly the applied knee abduction moment [77, 81, 83]. Kinematic variables that can contribute to increasing external knee abduction moments include smaller knee flexion angle, larger trunk lateral flexion angle, larger distance between the centre-of-mass of the body (COM) and the ankle-joint-centre (AJC) and increased speed and angle of the sidestep [82].

In rugby union, there exists a high frequency of sidestep manoeuvres with the primary goal to avoid a tackle and secondary goals to establish a better body position to break a tackle, offload the ball to another athlete or to create momentum in the next phase play [244]. While the sidestep can occur equally on either leg, the position of the defensive opponent and the intended progression of the ball carrier will inevitably determine the sidestepping leg [245]. In some instances, an athlete may favour one leg over the other during the sidestep and other sport specific movements involving a single leg (i.e. kicking, jumping, landing, etc.); thus increasing the frequency of skill on that particular leg. Continual use of a single leg, in addition to the positional requirements of rugby, may then develop or further augment a neuromuscular asymmetry between the legs; potentially affecting lower-extremity injury risk [9, 75].

During the sidestep, there is evidence to suggest that females are more likely to injure their non-preferred kicking leg and males are more likely to injure their preferred kicking leg; supporting the hypothesis that leg preference contributes to the aetiology of non-contact ACL injuries [66]. To our knowledge, there are only two [178, 246] biomechanical studies that have attempted to examine joint moments with respect to leg preference during sidestepping, providing limited support to the retrospective evidence. Brown and colleagues [178] found that female footballers (soccer) experienced greater external abduction moments

in the non-preferred leg and Marshall and colleagues [246] found the male rugby athletes experienced greater external abduction moments in the preferred leg. While the differences in knee abduction moment between legs of both studies were only small ( $> 0.2$ ), the findings align with the evidence seen by Brophy et al. [66]. As both studies incorporated different methods and analyses, any meaningful inference of the data is difficult at this time.

When assessing ACL injury risk in athletes, the sidestep manoeuvre is among the most commonly used tool by researchers. Limited research [126] has attempted to accurately replicate the sidestep seen in rugby match play. Unfortunately, the technical aspects of the movement in the laboratory setting do not always align with the practical aspects seen in the field. A lack of rugby union specific data and specifically male data in this area may cause misleading interpretations when compared with ACL injury risk research in other sporting codes and genders. Factors like sex, anthropometrics, sidestep velocity and sidestep angle are key elements that are unique to rugby union which should be accounted for in research design [75]. While the sidestep has been examined [83] in males of similar sporting codes (footballers and Australian Rules footballers), the velocities at which the task was performed were lower ( $\sim 4.6 \text{ m}\cdot\text{s}^{-1}$ ) than the match velocities commonly seen in rugby union [75].

Following traditional data collection procedures of the sidestep, information is typically reported as group means and standard deviations [75]. By using means, researchers are able to group athletes together to make meaningful inferences based on the data; i.e. difference between the means, spread of the data, etc. While this is an important structure to have when comparing 40-m sprint performance for example, group means also have the potential to miss individual variability within and between athletes. Individual responses have previously been observed in footwear comfort perception, leading authors [247] to comment on the importance of evaluating individual results when making decisions that may ultimately affect the group. When evaluating variables that are associated with injury risk (i.e. external knee abduction moment during sidestepping), missing individuals that may need further attention is counterintuitive to the very purpose of injury risk assessments [170]. While few authors [51, 54] have mentioned the ability for unique knee mechanics to be present while sidestepping, a full inclusion and subsequent dissemination of individual knee abduction moments while sidestepping among a similar athlete cohort has yet to be performed.

The purpose of this research was two-fold: firstly, we wanted to assess the sidestep manoeuvre at velocities and angles similar to what might be performed in rugby union match-play and then examine the differences in external knee abduction moment at weight acceptance between the preferred and non-preferred legs; secondly, we wanted to qualitatively compare the differences between group means and individual means of external knee abduction moment during weight acceptance. Falling in line with similar sidestepping research [82, 83, 178], we postulated that the non-preferred leg would present “at risk” mechanics compared to the preferred leg. Specifically, “at risk” was defined as larger abduction moments during weight acceptance along with less knee flexion, greater distance between the COM and AJC and more lateral trunk flexion during initial contact. We also speculated that athletes would present a range of differences in knee abduction moments between both legs during sidestepping. This final venture was proposed based on similar rugby codes research showing a substantial range of differences between legs in other biomechanical measures like strength and sprint mechanics [9, 98].

## Methods

### *Study design and athletes*

A cross-sectional design was used to compare external knee abduction moments between legs during a maximal effort sidestep ( $> 6.0\text{m}\cdot\text{s}^{-1}$ ) and assess the qualitative differences between group mean and individual data. Testing occurred during the athletes' off-season after  $\sim 24$  h of rest. At the time of this study all athletes were free from injury in the previous six months, either chronic or acute, that may have inhibited them from performing the required sidestepping task. All athletes were cleared by the team's medical staff for full competitive play.

Sixteen male academy (high-performance development) rugby athletes (mean  $\pm$  SD; age  $20 \pm 3$  y, body-height  $1.86 \pm 0.09$  m, body-mass  $99 \pm 14$  kg, body-mass index  $29 \pm 4$   $\text{kg}\cdot\text{m}^{-2}$ ) participated in this research. Athletes consisted of forwards ( $n = 12$ ) and backs ( $n = 4$ ) from European and Pacific Island descent and had an average playing experience of  $11 \pm 4$  y, encompassing  $>151$  matches played per athlete. Fifteen athletes indicated their right leg as their preferred kicking leg while one forward specified the left leg; denoted as the leg at which they preferred to kick the ball with or which they could kick the furthest with.

The *Sample-size estimation* Excel spreadsheet for use with magnitude-based inferences (found at [sportsci.org](http://sportsci.org)) was used to identify a minimum of 16 athletes to show an effect with the smallest worthwhile difference of 0.20 when using a kinetic effect size of 0.42 from similar research [178] (concurrent analysis of the collected kinetic data of the present study [248]). Constraints from many of the athletes' professional contracts resulted in only 16 "healthy and cleared-to-play" athletes available for testing. All procedures used in this study were approved by the Auckland University of Technology Ethics Committee (13/378) and all athletes provided their informed verbal and written consent prior to data collection.

### ***Data collection***

All athletes were fitted with identical, size appropriate compression clothing (Nike Pro Compression, Nike, Inc., Beaverton, OR, US) and wore the same cross-training shoes (GEL-KUROW, ASICS Ltd., Kobe, JP). Athletes performed a general self-selected lower-extremity dynamic warm-up, identical to the team's weight training, practice and game warm-up procedures. All athletes in this study performed a planned sidestepping manoeuvre in each direction [178]. While unplanned sidestepping is known to more accurately resemble match play, it also elicits substantially larger joint moments. The athletes who participated in the study played at a high calibre (the majority of which had already signed contractual agreements with professional teams). We were therefore ethically restricted in allowing them to perform unplanned sidestepping at maximal velocity; known to increase external knee abduction moments and increase the potential for ACL injury.

The sidestepping task was performed on an indoor track surface (Sportflex Super X, Mondo U.S.A. Inc., Conshohocken, PA, US) using the athlete's preferred and non-preferred leg ( $n = 15$  right,  $n = 1$  left). Athletes were given a 10-m runway in which to maximally accelerate before performing a sidestep within a designated lane (outlined via tape on the ground) located at  $45^\circ$  from the centre of the force platform and then maximally reaccelerating out to complete the task. An athlete would step with their right foot when sidestepping to the left and vice versa. Athletes were verbally and visually instructed on how to perform the sidestepping task and were allowed adequate familiarisation of the protocol. Testing began only when they felt comfortable with performing the movement at a maximal effort. When ready, athletes completed a minimum of three trials in each direction given in a random order. A successful trial consisted of athletes reaching an approach velocity of  $\geq 6.0 \text{ m}\cdot\text{s}^{-1}$ ,

striking the force platform completely with the sidestepping foot and executing the task as quickly as possible to simulate the requirements of a match situation. Sidestepping velocity was determined in real-time by a Stalker Acceleration Testing System (ATS) II radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) secured to a tripod positioned 3-m behind the starting line at a height of 1-m above the ground, approximately in-line with the athlete's COM. Tape lines the same width of the force platform (600-mm) were provided to direct athletes through the initial runway and the 45° exit paths. See Figure 18 for detailed setup configuration.

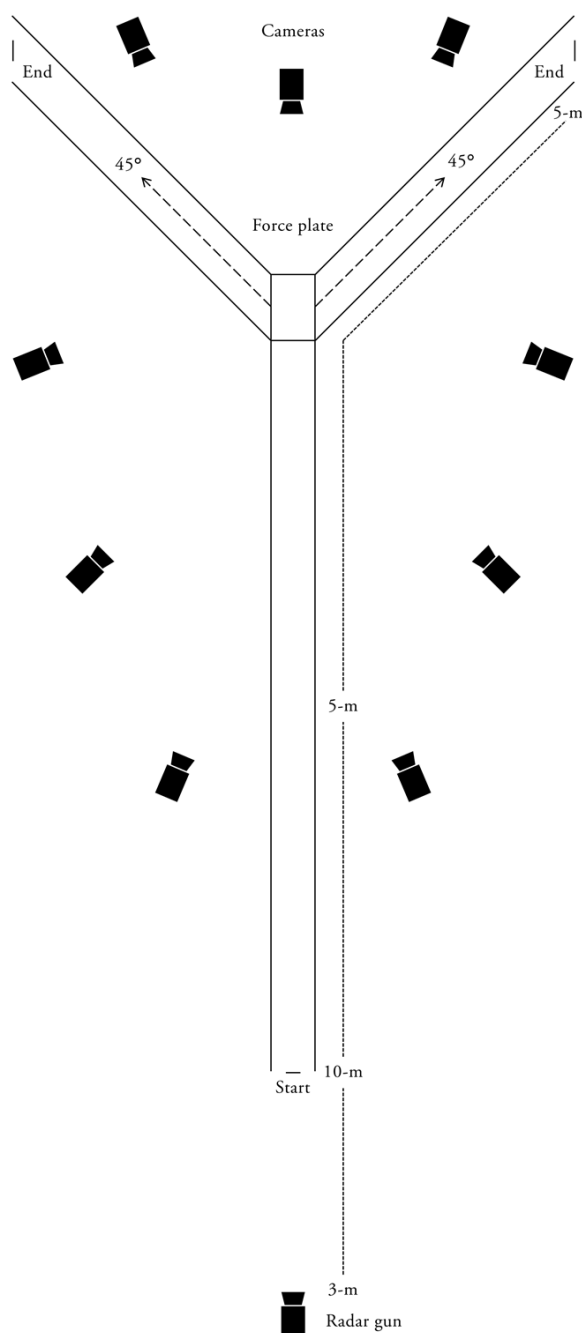
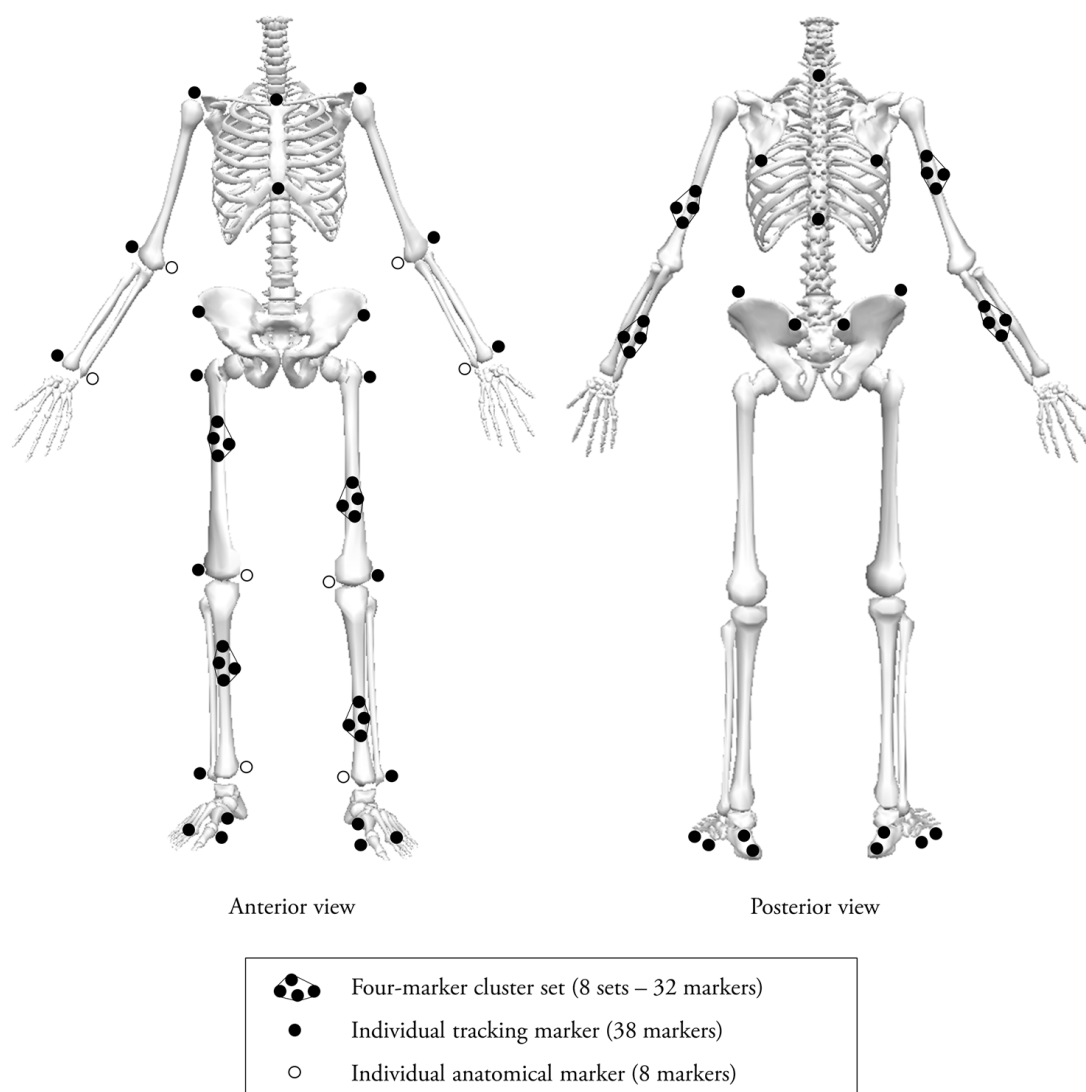


Figure 18. Experimental setup.

At the beginning of the collection, a laboratory calibration was completed to establish the capture volume and position of the nine-cameras (T10S, Vicon Motion System Ltd., Oxford, UK) relative to each other and the laboratory origin (front right corner of the force platform [Type 9287C, Kistler Instrumente AG, Winterthur, CH]). To create a three-dimensional model for analysis, the University of Western Australia (UWA) full-body marker set [82, 141, 249] was modified to include four spherical retro-reflective markers (10-mm width) on each segment to improve redundancy through the dynamic sidestepping manoeuvre (78 total). All markers were placed on anatomical locations by a highly trained, Level-3 certified ISAK anthropometrist to create the Auckland University of Technology (AUT) full-body marker set. The upper-body model (32 markers) consisted of eight single markers placed on the left / right superior border of the acromion process, superior border of the manubrium (sternal notch), inferior boarder of the xiphoid process, spinous process of the seventh cervical and tenth thoracic vertebrae and left / right inferior angle of the scapulae to create the ‘thorax’ segment and eight single markers placed on the medial / lateral epicondyles of the humerus and on the styloid processes of the ulna and radius of both arms to create the ‘upper-arm’ and ‘lower-arm’ segments. The lower-body model (46 markers) consisted of six single markers placed on the left / right iliac crest and left / right posterior / anterior superior iliac spines to create the ‘pelvis’ segment, ten single markers placed on the left / right greater trochanters, medial / lateral femoral condyles and medial / lateral malleoli of both legs to create the ‘upper-leg’ and ‘lower-leg’ segments and fourteen single markers placed on the superior / inferior posterior calcaneus, navicular tuberosity, cuboid and head of the first, third and fifth metatarsals of both feet to create the ‘foot’ segment. Additionally, four-marker cluster sets attached to thermo-moulded plastic shells were added to the upper- and lower-arm and leg segments to increase redundancy about the joints (Figure 19).



**Figure 19. The Auckland University of Technology marker set.**

Static and range-of-motion calibration trials were performed on the individual athletes using Vicon Nexus software. Elbow, wrist, knee and ankle medial markers were removed after the calibration trials were complete to allow for the dynamic movement of the testing protocol. Athlete-specific helical-axis joint centre locations for the hips and knees were calculated from the range of motion trials (hip star and squats respectively) using a custom-made MATLAB programme (R2014b, The MathWork, Inc., Natick, MA, US) [141, 250]. Synchronised three-dimensional motion (100 Hz) and ground reaction force (1000 Hz) data were filtered with the same low-pass fourth-order zero-lag Butterworth filter using a cut-off frequency of 16 Hz in Visual 3D (4.91.0, C-Motion, Inc., Germantown, MD, US) based on residual analysis and visual inspection of the kinematic and kinetic data [126].



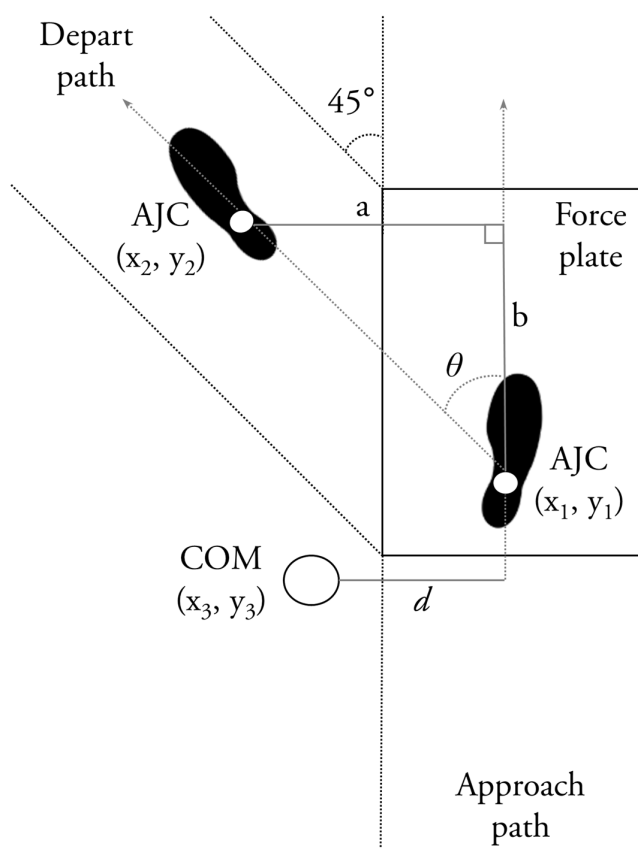


Figure 20. Sidestepping variable configuration.

Sidestepping variable configuration. a, opposite side length; b, adjacent side length; d, distance;  $\theta$ , theta or 'angle'; AJC, ankle-joint-centre; COM, centre-of-mass; (x, y), coordinates.

### *Data analysis*

Sidestepping performance variables (i.e. velocity, angle and stance time of the sidestep) were calculated in Visual 3D to allow comparison between the preferred and non-preferred leg. Sidestep velocity ( $\text{m}\cdot\text{s}^{-1}$ ) was calculated via tracking the athlete's COM before (approach) and after (depart) the stance phase. Stance time (s) was calculated from the instant vertical force rose above 10 N (initial contact) to the time vertical force dropped below 10 N (final contact). Sidestep angle ( $\theta$ ) was calculated using the x- and y-coordinates of the stance foot AJC at initial contact ( $x_1$  and  $y_1$ ) and the coordinates of the contralateral AJC at final contact ( $x_2$  and  $y_2$ ) (Figure 20 and Equation 11).

Equation 11. Sidestep angle ( $\theta$ ) =

$$\theta = \tan^{-1}\left(\frac{a}{b}\right);$$

where

$$a = |x_2 - x_1| \text{ and } b = |y_2 - y_1|.$$

Sidestepping mechanical variables (i.e. knee flexion angle, trunk lateral flexion and COM to AJC distance) were also calculated in Visual 3D during initial contact. Knee flexion angle ( $\theta$ ) was defined as the angle between the thigh and shank segments, where full knee extension represented 0° of knee flexion. Trunk lateral flexion angle was defined as the angle between the thorax (trunk) and the ground; where a straight posture represented 0° of trunk lateral flexion. The COM to AJC distance (m) is was calculated using the x-coordinates of the COM ( $x_3$ ) and the AJC ( $x_1$ ) (Figure 20 and Equation 12).

Equation 12. Distance from the COM to the AJC (m) =

$$m = |x_3 - x_1|.$$

Finally, knee abduction moments were calculated using standard, Newton-Euler inverse dynamics equations and were defined as those externally applied to the segment's distal end. Moments were normalised to body-mass and body-height ( $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) and time data were normalised to stance phase (%; from initial contact to final contact) to facilitate comparison between all athletes. Moment data were analysed during weight acceptance (the average between initial contact and the first trough in the unfiltered vertical ground reaction data [Figure 21]) [75]. Initial contact and weight acceptance phases were calculated using a custom-made MATLAB programme [178]. Individual asymmetries were calculated using a non-dimensional modified symmetry angle equation [103] to report the absolute difference of external knee abduction moments between the legs (preferred leg versus the non-preferred leg; Equation 5). This equation was chosen as it does not require an arbitrary reference leg, is unaffected by artificial inflation by near-zero numbers and is useful in determining clinically relevant information in sports science [101-103]. In-line with previous research [103], we implemented an initial 15% threshold as a means for separating the data into “acceptable” ranges of symmetry ( $< 15\%$ ) and asymmetry ( $\geq 15\%$ ) such that the interpretation of the data would change between the two groups.

### Statistical analysis

The *Post-only crossover* Excel spreadsheet employing magnitude-based inferences (found at [sports-ci.org](http://sports-ci.org)) was used to describe the standardised effects of leg preference on knee mechanics [142]. The preferred leg was chosen as the reference in this study as it is commonly chosen for analysis purposes [178]. Uncertainty in the estimates of effects on leg preference was expressed at 90% confidence limits and as probabilities that the true value of the effect was substantially negative (-ive) and positive (+ive). Qualitative probabilistic inferences regarding the true effect were then made [142]. If the probabilities of the true effect being substantially positive and negative were both >5%, the effect was expressed as unclear; otherwise the effect was clear and expressed as the non-clinical (mechanistic) magnitude of standardised effects with threshold values of 0.2, 0.6, 1.2 for small, moderate and large differences respectively [142]. The scale for interpreting the probabilities was: 25-75%, possibly (\*); 75-95%, likely (\*\*); 95-99.5%, very likely (\*\*\*); and >99.5%, most (or extremely) likely (\*\*\*\*).

### Results

Performance variables executed on the preferred and non-preferred leg are presented in Table 21. All athletes displayed similar approach velocity (ES = 0.045), depart velocity (ES = -0.057) and sidestep angle (ES = -0.19) when comparing sidestepping off the preferred and non-preferred legs. There was a small difference in absolute stance time (ES = -0.23) between the legs; further justifying the normalisation of the kinematic and kinetic data to stance time.

**Table 21. Sidestepping performance variables.**

	Preferred	Non-preferred	Non-preferred – preferred	
			Mean change; ±90% CL	Qualitative inference
Approach velocity (m·s <sup>-1</sup> )	6.5 ± 0.5	6.5 ± 0.4	0.045; ±0.083	Trivial** +ive
Stance time (s)	0.18 ± 0.03	0.18 ± 0.02	-0.0061; ±0.0046	Small* -ive
Depart velocity (m·s <sup>-1</sup> )	6.1 ± 0.5	6.1 ± 0.4	-0.027; ±0.084	Trivial** -ive
Sidestep angle (Deg)	25 ± 4	24 ± 3	-0.73; ±0.99	Trivial***

Footnote: CL, confidence limits; m, metre; s, second; Deg, degree. Values are means ± standard deviation and mean change; ±90% confidence limits. Trivial and small inference: \*possibly, 25–74%; \*\*likely, 75–94%; \*\*\*very likely, 95–99.5%. -ive and +ive = substantial negative and positive change of the non-preferred leg relative to the preferred.

Figure 21 illustrates (in grey) the small difference between the group average for knee external abduction moments during weight acceptance for the preferred leg compared to the non-preferred leg ( $0.61 \pm 0.32$  and  $0.76 \pm 0.44$  Nm·kg<sup>-1</sup>·m<sup>-1</sup>, respectively; ES = 0.43; 25%).

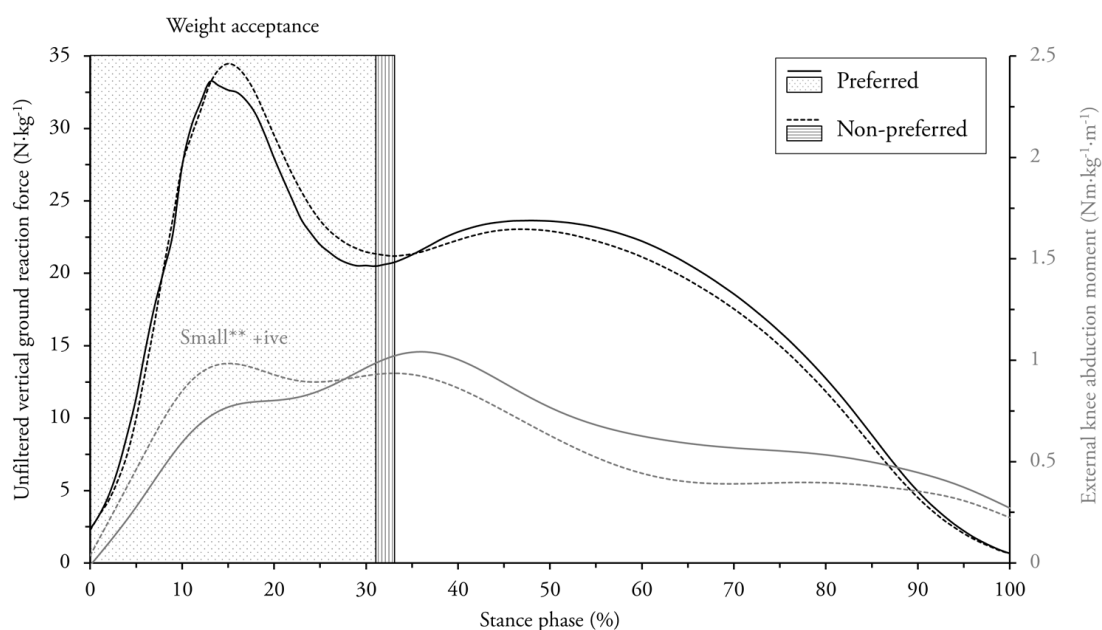


Figure 21. Group mean kinetics during sidestepping.

Group mean unfiltered vertical ground reaction force ( $\text{N}\cdot\text{kg}^{-1}$ ) during sidestepping for the preferred (solid black line) and non-preferred (dashed black line) leg. Group mean external knee abduction moments ( $\text{N}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) during sidestepping for the preferred (solid grey line) and non-preferred (dashed grey line) leg. Small inference; \*\*likely, 75–94%. +ive; substantial positive change of the non-preferred leg relative to the preferred.

All mechanical variables showed differences between the preferred and non-preferred legs as presented in Table 22. The non-preferred leg demonstrated 8% smaller knee flexion angles ( $\text{ES} = -0.26$ ), 17% larger trunk lateral flexion angles ( $\text{ES} = 0.42$ ) and 11% larger COM to AJC distance ( $\text{ES} = 0.97$ ) during initial contact of the sidestep.

Table 22. Mechanical sidestepping variables during initial contact.

	Preferred	Non-preferred	Non-preferred – preferred	
			Mean change; $\pm 90\%$ CL	Qualitative inference
Knee flexion angle (Deg)	$27 \pm 8$	$25 \pm 6$	$-2.2; \pm 1.5$	Small* -ive
Trunk lateral flexion angle <sup>a</sup> (Deg)	$14 \pm 6$	$17 \pm 6$	$2.5; \pm 1.32$	Small** +ive
COM to AJC distance (m)	$0.36 \pm 0.04$	$0.40 \pm 0.04$	$0.039; \pm 0.013$	Moderate*** +ive

Footnote: CL, confidence limits; Deg, degree; m, metre; COM, centre-of-mass; AJC, ankle-joint-centre; a contralateral to the sidestepping direction, -ive. Values are means  $\pm$  standard deviation and mean change;  $\pm 90\%$  confidence limits. Trivial and small inference: \*possibly, 25–74%; \*\*likely, 75–94%; \*\*\*very likely, 95–99.5%. -ive and +ive = substantial negative and positive change of the non-preferred leg relative to the preferred.

All sixteen athletes' individual and mean abduction moment values produced by both legs and compared to the group mean are presented in Figure 22. Seven athletes had a -ive slope (44%; larger average external knee abduction moment in the preferred leg) while nine had a +ive slope (56%; larger average external knee abduction moment in the non-preferred leg). Also within this cohort, just over half of the athletes (56%) presented “acceptable” symmetry angle scores ( $< 15\%$ ; range: 2.2 – 14), whereas the remaining 44% presented asymmetrical scores ( $\geq 15\%$ ; range: 15 – 47).

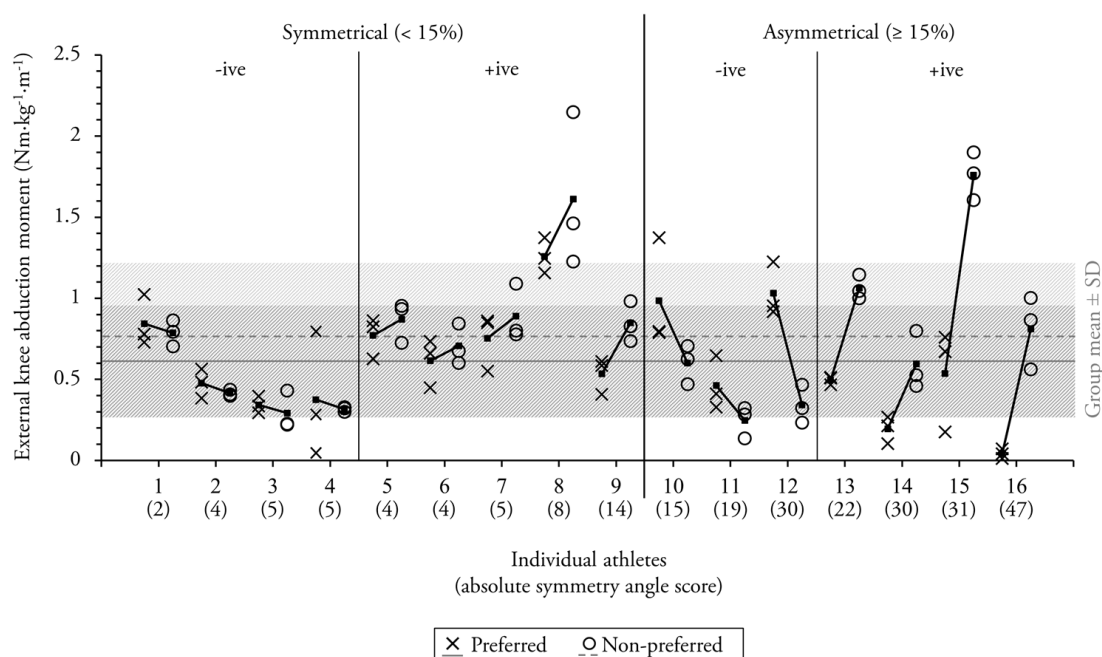


Figure 22. Individual peak knee abduction moments during sidestepping.

Individual peak external knee abduction moments ( $\text{N} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ ) during weight acceptance of sidestepping for sixteen individual male rugby athletes. Data shown (Xs and Os) are each trial of the sidestep manoeuvre performed on the preferred and non-preferred leg respectively. Solid black squares represent the average of the three trials on each leg. Solid and dashed grey bars represent group mean data for the preferred and non-preferred legs respectively. Data are presented in ascending order based on 1.) the negative (-ive) and positive (+ive) slope of the solid line connecting the average moment data of each leg [a negative slope signifies the preferred leg experienced a larger external knee abduction moment whereas a positive slope signifies the non-preferred leg experienced a larger moment]; and 2.) the absolute symmetry angle score shown in brackets beneath the athlete's number.

## Discussion

The sidestep manoeuvre is a unique movement associated with high ACL injury risk. The continued examination of sidestepping has greatly increased our knowledge of non-contact ACL epidemiology in sport and has aided in the creation of helpful injury prevention training programmes. To enhance ecological validity, the sidestepping task has become more sport-specific to replicate the typical demands the athlete would experience at the time of injury by increasing the velocity, including a ball, and affecting reaction time, decision-making and complexity, to name a few [126, 153, 251, 252]. A primary component of the current study was to replicate the faster velocity of the sidestep to closely resemble those experienced in male rugby union athletes; as such, approach velocity was constrained to  $\geq 6.0 \text{ m}\cdot\text{s}^{-1}$ . Our two-fold purpose was to examine non-contact ACL injury risk via knee abduction moment at weight acceptance in the preferred and non-preferred legs: (1) using standard quantitative techniques of obtaining group means; and (2) using a qualitative method to investigate individual variability within / between the athletes. While both methods showed differences in the defined variables, they provide different views into injury risk status and unique insight into subsequent injury prevention strategies.

To our knowledge, this is the first sidestepping study where the athletes were required to produce an approach velocity of  $\geq 6.0 \text{ m}\cdot\text{s}^{-1}$  with a subsequent maximal acceleration out of the sidestep. Rapid entry and exit from the sidestep replicates the goals of the manoeuvre during match play [244]. While the exit angle was controlled, the actual sidestep angle was calculated and reported in order to present the true angle based off foot placement. We found that the increased velocities of the task resulted in a decreased sidestep angle ( $\sim 24^\circ$ ) from the initial  $45^\circ$  pathways used to direct the athletes exit strategy. Previous literature [75] has also observed higher velocities associated with greater differences between the actual and attempted sidestep angle. During sidestepping, appropriate braking forces contribute to orientating of the COM, maintaining a constant velocity and preventing over-rotation of the body [253]. Thus a physical limitation of sidestepping is such that the angle of the sidestep is a function of the velocity of the sidestep. None-the-less, the sidestepping angle was considered a secondary performance variable compared to the overall velocity of the movement, therefore angle was not a constraint in the study design; rather, an informative addition. As a purpose of this study was to replicate the sidestep in a match-like manner, exit

velocity was monitored and quantified to assess and comment on the athletes' ability to maintain velocity following the change-of-direction; a common performance variable [254, 255]. The athletes' ability to reaccelerate after the stance phase of the sidestep was affected only marginally ( $6.1 \text{ m}\cdot\text{s}^{-1}$ ; 6.9% decrease from the approach velocity), highlighting the athletes' skill at redirecting the COM using appropriate body orientation [77, 82] and efficiency in transferring energy during the stance phase [139].

The average group external abduction moments at the knee during weight acceptance showed a small difference between legs. Brown et al. [178] reported a 19% greater external abduction moment during the weight acceptance phase of the sidestep in the non-preferred leg compared to the preferred leg in National Collegiate Athletic Association Division I female footballers. Similarly, our results show a 25% greater abduction moment for the non-preferred leg compared to the preferred leg. Brown et al. [178] surmised that the mechanical differences found between legs may have resulted in greater knee flexion velocity, greater power absorption during the braking phase (weight acceptance) and larger internal rotation angle in the non-preferred leg. The absolute magnitude of the abduction moment produced by the male rugby athletes in the current study is up to 4x greater than that produced by female footballers [178] and 2.5x greater than that of similar male athletes [75]; even when normalised to body-mass and body-height. It is proposed that the greater velocity of the side step approach and exit contributed to the increased moments.

While sidestepping on the non-preferred leg we observed a decreased knee flexion angle (a more extended stance leg), an increased trunk lateral flexion angle (leaning more towards the stance leg side) and an increased distance between the COM and AJC (the stance leg is further away from the body) compared to the preferred leg. Landing with the leg in a more extended position can increase the resultant strain at the ACL [48, 256]. Additionally, while sidestepping off the non-preferred leg, athletes showed greater trunk lateral flexion angles and a further distance between the COM and AJC compared to sidestepping on the preferred leg; both of which have been shown to increase knee abduction moments [82]. Compared to previous research [77, 82], our lateral trunk flexion angles ( $14 - 17^\circ$ , compared to  $7 - 8^\circ$ ) and COM to AJC distances ( $0.36 - 0.40 \text{ m}$ , compared to  $0.34 - 0.37 \text{ m}$ ) were slightly larger. The greater kinematic differences found in our study may also be explained by the larger body-mass (80 vs 99kg) and / or faster velocity ( $5.7 \text{ vs } 6.5 \text{ m}\cdot\text{s}^{-1}$ ) in this rugby union cohort.

Additionally, as the location of the AJC gets further away from the body, the trunk needs to laterally flex more to ensure the COM stays close to the base-of-support to maintain balance during the sidestep, explaining the increase in both variables.

Group means and standard deviations are frequently used in sports science research when describing a certain attribute of a cohort. However, an individual and detailed look at each athlete should be performed to benefit all athletes. Mündermann and colleagues [247] stated, "...subgroups of individuals exist and that the evaluation of individual results can reveal important information that may not be obtained by the analysis of group means." The current study reinforces the idea that individual differences have great potential to be masked by group means, as seen in our results. Another purpose of this research was to qualitatively compare the group means to the individual data when assessing abduction moments at weight acceptance as a surrogate for injury risk.

Presenting the data individually allows for three important observations: (1) variability within each athletes' leg (the vertical spread of the Xs and Os); (2) each athletes' deviation from the group mean (the vertical distance between the solid back squares and the grey lines); and (3) symmetry within each athlete (the positive / negative slope of the black lines). As the results show, each of these observations were unique to the athlete. An equal distribution was apparent between the number of athletes that produced larger abduction moments on their preferred leg versus those that produced larger abduction moments on their non-preferred leg (9 / 7 respectively). Athletes that were furthest outside the group mean (#8 and 15) or showed the largest asymmetry (#16) did so by producing larger abduction moments on their non-preferred leg. The larger moments experienced could have been a result of the larger kinematic alterations while sidestepping off the non-preferred leg, or perhaps the result of a greater hip abduction and / or internal rotation moments which have been found to increase knee abduction moments during sidestepping [63]. Lower-extremity strength could also play a role in the results, as hip strength (the ability to stabilise the hip / pelvis of the stance leg while decelerating) has been shown to be an important factor of body position during sidestepping [130, 257]. The influence of hip strength on sidestepping mechanics warrants further investigation as rugby union athletes have been shown to possess strength asymmetries at the hip across multiple levels of experience [9, 177].



### ***Limitations***

We feel it is important to acknowledge limitations in the current study to give context to the interpretations of our findings. First, while we attempted to improve the ecological validity of the sidestep as it pertains to male rugby union athletes, our study was still conducted in a laboratory-based setting. As such, the interpretation of the results should account for additional environmental factors such as surface, footwear and climate that may potentially affect sidestepping mechanics [258]. Second, unplanned sidestepping more accurately represents the task demands of match play [75] however, we were not ethically permitted to perform such a modification on the professionally contracted athletes in the current study due to the potential for increasing injury risk. Future authors whom are not confined with such limitations should examine a similar experimental process with the inclusion of unplanned sidestepping to gain greater insight into the importance of the neuromuscular system [126]. Third, while our sample size was sufficient enough to detect a small worthwhile change (an effect size of at least 0.20) between the legs, a larger sample may show a smaller, equal or greater variation of individual responses of knee abduction moments during the sidestep compared to the data in the current study. Fourth, we expressed the probability levels of ACL injury risk based on scaled differences in knee mechanics between the two legs. During which, the knee mechanics of the preferred leg served as the reference leg. Thus, results from this study are only comparable with ACL injury risk studies of similar statistical analyses at this time [178].

### **Conclusions**

The current study illuminated several interesting findings with regards to the sidestep manoeuvre in male rugby athletes. From a task acquisition stand-point, all athletes performed the task to a similar level of efficiency and completed the sidestep manoeuvre within the provided 45° paths at the required velocity of  $\geq 6.0 \text{ m}\cdot\text{s}^{-1}$ . Upon closer look however, the athletes presented unique postural techniques while sidestepping potentially increasing knee abduction moment in the non-preferred leg. While these unique postures have been proposed to increase ACL injury risk [82], to our knowledge there has been only one attempt where authors [178] suggested a clear distinction in knee mechanics between the preferred and non-preferred legs. Similarly, our findings suggest that the non-preferred leg may experience a greater risk of injury while sidestepping by an inability to establish an appropriate posture;

thus placing the body in an “at risk” position and directing more of the external force towards the knee and challenging its structural integrity to resist an abducted (valgus) position.

While our observations that the non-preferred leg of the *group* of athletes is at an increased risk of injury risk are correct, the interpretations can show a substantially different picture when accounting for the *individual* athlete. For example, if the group results from this study were interpreted as: ‘increase lower-extremity strength, postural stability and sidestepping technique in the non-preferred leg to decrease external knee abduction moments and injury risk’, nearly half (44%) of the athletes may have missed out on any beneficial training effect. However, if the individual results from this study were interpreted as: ‘each athlete presents a unique injury risk profile while sidestepping and must therefore be given an individualised training programme to decrease external knee abduction moments and injury risk’, the potential for a greater percentage of the group benefitting from a training effect would theoretically increase. Unfortunately, these final statements are purely speculative at this time as there is little to no research investigating the effects of individualised injury prevention training to decrease external knee abduction moments while sidestepping among a group of male rugby athletes; accounting for each leg as a unique structure with unique attributes.

Moving forward, we suggest the continuation of examining “at risk” scenarios (i.e. sidestepping) in athletes but with the inclusion of individual results to show the true spread of the data and to highlight athletes requiring special attention outside of the traditional team training prescription. Whether this information is presented within the academic journal article itself or via appendices, supplemental material or other online source (ResearchGate.net ‘Dataset’) is solely up to the discretion of the authors and / or journal editors. Further, while the inclusion of both legs in any injury risk assessment seems paramount to the complete picture of an athlete’s status to subsequently base injury prevention recommendations, research is greatly lacking in this area. Although symmetrical athletes are thought to exist (and perhaps even seen on occasion), realistically the majority of athletes (especially male rugby athletes [as seen in the current study]) will have some sort of unique asymmetry as a result of genetics, sport, previous injury or other. When assessing injury risk, our job as sports scientists or clinicians is to find the asymmetry and provide direction to strength and conditioning practitioners.

## Chapter 8: Clinical Determinants of Individual Knee Joint Loads Experienced While Sidestepping: An Exploratory Study with Male Rugby Union Athletes

This chapter comprises the following paper prepared for *British Journal of Sports Medicine*.

### Reference:

Brown SR, Hume PA, Brughelli M. Clinical determinants of individual knee joint loads experienced while sidestepping: An exploratory study with male rugby athletes. *Am J Sports Med*. 2016:[in preparation].

### Author contributions:

Brown SR, 90%; Hume PA, 5%; Brughelli M, 5%.

### Overview

Our knowledge of the relationship between biomechanical factors during / within the sidestep manoeuvre and anterior cruciate ligament (ACL) injury risk has pointed our attention to hip strength and trunk orientation. While several clinical factors have independently been linked to ACL injury risk factors, how they might collectively affect knee loading (i.e. external knee abduction moments or limb symmetry moments) during the sidestep manoeuvre is unknown. The purpose of this study was to assess the relationship of strength, balance and sprint kinetics on external knee abduction moments during sidestepping on each leg and on the symmetry score between legs. Cross-sectional study; Level of evidence 2c. Sixteen male academy-level rugby union athletes (age,  $20 \pm 3$  y; body-height  $1.86 \pm 0.09$  m; body-mass  $99 \pm 14$  kg) were assessed in single-leg: isokinetic concentric / eccentric knee and concentric hip strength, balance at two difficulty levels, vertical and horizontal force production during maximal sprinting and 3-dimensional sidestepping on the preferred and non-preferred leg. A hierarchical multiple regression analysis based on a theoretical approach of the mechanics of ACL injury risk relevant to high-performance male rugby athletes was performed. When sidestepping on the preferred leg, larger abduction moments were explained by decreased concentric hip extension strength and decreased vertical force production during maximal sprinting ( $\bar{R}^2 = 41\%$ ;  $ES = 0.64$ ); when sidestepping on the non-preferred leg, larger abduction moments were explained by increased concentric hip flexion strength ( $\bar{R}^2 = 8\%$ ;  $ES = 0.29$ ). Larger symmetry scores between the legs

(representing abduction moments) were explained by increased horizontal force production during maximal sprinting and decreased eccentric knee flexion strength ( $\bar{R}^2 = 32\%$ ; ES = 0.56). Independently, the preferred and non-preferred legs contribute to increased knee abduction moments via unique distributions of strength and / or sprint kinetics. However, the allocations of strength and sprint kinetics appear interrelated through weaker posterior muscular strength and may be modifiable through a targeted strength training approach.

## Introduction

Knee injuries are a problem in rugby union [31]. The primary issue of concern is injury to the anterior cruciate ligament (ACL) occurring in contact and non-contact scenarios. While ACL injuries may not be the most frequently diagnosed in rugby, they do cause the most damage to the athlete and club both on and off the pitch [20, 31, 259, 260]. While the mechanisms of *contact* ACL injuries are clear (contact with another athlete or equipment), *non-contact* ACL injuries are less understood [56]. Compared with straight-line running, where ACL injuries are not common, sidestepping involves single-leg deceleration combined with a change-of-direction [50]. It is during this deceleration phase (weight acceptance; ~ first 30% of stance) where the external loads placed on the knee can exceed the mechanical strength of the ACL; potentially causing injury [54]. Based on our examination [261] of tissue tolerance *in vitro* and our understanding [54] of knee loading *in vivo*, larger external loads (specifically abduction moments) at the knee during weight acceptance suggest an increased risk of ACL injury [75]. As such, a number of researchers [54, 77, 81, 83, 126, 137, 152, 178] have used the sidestep manoeuvre as a ‘gold-standard’ surrogate measure of non-contact ACL injury risk.

When considering the sidestep in the context of rugby, athletes are frequently required to rapidly decelerate their forward velocity on one leg, reorient the centre-of-mass (COM) in a new direction and then accelerate quickly. As such, attributes of single-leg strength, balance and sprint kinetics (force application) are needed to perform the task efficiently and without injury. Three-dimensional analyses of the sidestep has indicated that inappropriate postural adjustments including the distance from the COM to ankle-joint-centre (AJC), trunk lateral flexion angle and knee flexion angle can increase external knee abduction moments and subsequent injury risk [82]. Unfortunately, the contributions of strength and musculoskeletal stability assessed in a laboratory to the athletes’ ability to perform the postural adjustments needed during the sidestep in the field are not well known [77, 81, 83, 214]. Through strength and conditioning principals and / or screening and monitoring practice [81, 214, 262, 263], ACL injury prevention strategies and research have gained momentum. As such, common assessment strategies used to determine if an athlete may return-to-sport following an injury [98, 114] may also be useful for pre-injury screening to determine athlete injury risk, however, this approach has not yet been taken in rugby.

The incorporation of strength and balance training principles in injury prevention strategies is gaining popularity in sports science [264] due to its ability to protect an athlete against future injury. Lower-extremity strength stabilises the knee (to reduce anterior tibial translation) and hip (to reduce hip adduction and knee abduction) [265, 266] during deceleration and can reduce knee loads [265, 266]. Similarly, single-leg balance has been shown to reduce the rates of multiple injuries in athletes by improving proprioceptive ability and has promise in protecting the knee joint from ACL injury [214, 267]. The incorporation of a sport-specific task unique to the athlete studied (i.e. sprinting) may also be beneficial in injury risk assessments as this movement is seen in many team sports, especially rugby [7]. While a link between the ability to produce force into the ground and ACL injury has not been made, several authors [97, 235, 268] have suggested a connection between reduced sprint ability and hamstring injury in a number of sports including football (soccer), Australian rules football and rugby. Additionally, authors [269, 270] have suggested that hamstring injuries can increase the risk of ACL injury as a result of decreased kinematics and motor control to stabilise the knee joint. While purely speculative at this time, a possible association between decreased force production during a sprint effort and an increased risk of ACL injury could be made based on the common contributions of the hamstrings during sprinting and sidestepping (i.e. eccentrically absorbing kinetic energy from the swing leg during the late swing phase and then concentrically producing force into the ground while sprinting [271] and eccentrically resisting anterior tibial translation during the braking phase and then concentrically generating force into the ground while sidestepping [33]). Weak or asymmetrical concentric hamstring function may therefore indicate a reduced eccentric function to protect the knee during sidestepping; subsequently channelling more of the applied forces to the ACL.

Substantial differences in lower-extremity mechanics (i.e. strength, balance, sprinting) between the legs have been found to exist in athletes [9, 233], however, no author has examined the potential link between these factors and sidestepping. In addition to examining at each leg individually, which is paramount when assessing injury risk, examining a global measure of symmetry between the legs allows researchers to assess the differences in a clinically relevant and meaningful way. The symmetry angle has been used in similar sports analyses [101, 102] when examining kinematic and kinetic variables associated with sprinting

as it does not require an arbitrary reference leg and is unaffected by artificial inflation by near-zero numbers. The symmetry angle therefore allows for the standardisation of differences between the legs across many different types of assessments and training (for injury risk and for performance purposes alike). Used in conjunction with the examination of individual leg characteristics would provide the greatest understanding of injury risk. It is unknown if differences between the legs in one or several of these mechanical characteristics translates to differences in sidestepping mechanics. And if so, the question then becomes, will these differences increase or decrease the potential for ACL injury risk?

The current literature is not only missing any connection between laboratory-based assessments and our surrogate measure of ACL injury risk (sidestepping) but is also lacking information on how the differences between legs may influence that risk. Therefore, the aim of this study was to examine the relationship between laboratory assessments (strength, balance and sprint kinetics) and ACL injury risk (sidestep manoeuvre) among high-performance male rugby athletes. We hypothesised that the laboratory assessments would only explain a small percentage of the knee loading variance seen while sidestepping but more importantly that each leg would individually contribute unique portions of strength, balance and sprint kinetics to increased knee abduction moment. We further postulated that larger independent variable asymmetries would be related to larger dependant variable asymmetries.

## Methods

### *Athletes and study design*

Sixteen male academy (high-performance development) rugby athletes (mean  $\pm$  SD; age  $20 \pm 3$  y, body-height  $1.86 \pm 0.09$  m, body-mass  $99 \pm 14$  kg, body-mass index  $29 \pm 4$  kg·m<sup>-2</sup>) participated in this research. Athletes were forwards ( $n = 12$ ) and backs ( $n = 4$ ) from European and Pacific Island descent and had an average playing experience of  $11 \pm 4$  y, encompassing >151 matches played per athlete. Fifteen athletes indicated their right leg as their preferred kicking leg while one forward specified the left leg. At the time of this study, all athletes were free from any acute or chronic injury or illness that may have inhibited them from performing the required sidestepping task. All procedures used in this study were approved by the Auckland University of Technology Ethics Committee (13/378) and all athletes provided their informed verbal and written consent prior to data collection.

### *Data collection*

All athletes wore identical, size appropriate compression clothing (Nike Pro Compression, Nike, Inc., Beaverton, OR, US) and the same model of cross-training shoes (GEL-KUROW, ASICS Ltd., Kobe, JP). Testing took place over the course of five days. To begin, athletes performed a general self-selected lower-extremity dynamic warm-up protocol identical to the team's weight training, practice and game warm-up procedures. Following the warm-up, athletes were randomised to an assessment protocol consisting of strength, balance, sprinting and sidestepping assessments.

### *Strength assessment*

Concentric and eccentric knee and concentric hip isokinetic strength assessments were performed at  $60^{\circ}\cdot\text{s}^{-1}$  on a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA) sampling at 100 Hz. Athletes were secured to the machine in a seated position to assess unilateral knee extension / flexion strength then in a supine position to assess unilateral hip extension / flexion strength ( $0$ - $90^{\circ}$ ;  $0^{\circ}$  being full anatomical extension to  $90^{\circ}$  of flexion). Athletes were well familiarised with the required five extension and five flexion actions during the warm-up protocol at which they performed the movements at an individually perceived 50, 70 and 90% of maximum exertion. When athletes were ready and felt comfortable with the task, they performed a 100% maximum effort trial. Following the maximum trial, the contralateral joint was tested. After both legs were tested in one position (sitting or supine), athletes were re-positioned for the remaining test.

In both positions, gravity adjustments were made by determining the combined effects of leg-mass and the passive muscle tension using the HUMAC software to measure peak torque. Testing leg and position were randomly determined for each athlete and followed an identical protocol previously described in detail [177]. Investigators provided strong verbal encouragement during each trial to maximise the athletes' effort across trials. Athletes were given a 45-second rest between each familiarisation and test trial, a two-minute rest between side-to-side testing and a five-minute rest between positions to ensure adequate rest between trials and within the session.



### *Balance assessment*

Athletes were positioned on the Biodex Balance SD System (Biodex Medical Systems, Inc., Shirley, NY, USA) in the centre of the locked platform in a self-assessed “comfortable” single-leg standing position. Foot position was recorded in the system’s software and for repositioning purposes in subsequent trials. Athletes were verbally familiarised with the testing protocol and when ready performed a single-leg balance assessment at either Level-8 (more stable) or Level-2 (less stable) for three trials lasting 20-seconds each. Once the assessment on one leg was completed the contralateral leg was tested using the aforementioned procedures. Once both legs were assessed, the test was repeated using the remaining stability level.

All athletes were instructed to perform the tests barefoot, eyes open, both arms across the chest, maintain slight knee flexion ( $\sim 15^\circ$ ) in the standing leg with  $0^\circ$  and  $90^\circ$  flexion for the contralateral hip and knee respectively and to not let the two legs touch whilst attempting to keep the platform as stable as possible [272]. The order of leg and stability level were randomised for all athletes. Visual and audio feedback / encouragement were not provided to any athlete during any of the balance tests. Athletes were given a 45-second rest between side-to-side testing and a five-minute rest between positions to ensure adequate rest between trials and within the session.

### *Sprint assessment*

The sprint assessment was performed on a Woodway Force 3.0 (Woodway USA, Inc., Waukesha, WI, USA) NMT ergometer collecting vertical ground reaction force data ( $F_V$ ) and horizontal propulsive force data ( $F_H$ ) via a load cell attached to a non-elastic tether sampling at 200 Hz. Athletes were secured to a vertical strut at the rear of the treadmill with a non-elastic tether connected to a belt around their waist. The athletes then performed a standardised familiarisation, consisting of variable speed jogging ( $\sim 2 \text{ m}\cdot\text{s}^{-1}$  for  $\sim 120$ -seconds), three submaximal sprints ( $\sim 8$ -seconds at 50, 70 and 80% of athlete’s estimated maximum velocity), and a single short maximal trial ( $\sim 3$ -seconds). When athletes were ready and felt comfortable with the sprinting task, they performed a  $\sim 8$ -seconds maximal velocity sprint from a ‘blocked’ starting stance [231].

Athletes performed two trials with a 5-minute rest between trials. The trial with the highest peak velocity was selected for subsequent analysis. Athletes started all trials from a staggered stance with their preference of lead-leg forward, the likes of which were recorded to allow determination of left / right, and accordingly preferred / non-preferred leg comparisons. Investigators provided strong verbal encouragement during each trial to maximise the athletes' effort across trials.

### *Sidestep assessment*

The sidestepping task was performed on an indoor track surface (Sportflex Super X, Mondo U.S.A. Inc., Conshohocken, PA, US) using the athlete's preferred and non-preferred kicking leg ( $n = 15$  right,  $n = 1$  left). Athletes were given a 10-metre runway at which to maximally accelerate in before performing a sidestep into a  $45^\circ$  angle channel and then maximally reaccelerating out to complete the task. Specifically, an athlete would step with their right foot when sidestepping to the left and vice versa. Athletes were verbally and visually instructed on how to perform the sidestepping task and were allowed adequate familiarisation of the protocol. Testing began only when they felt comfortable with performing the movement at a maximal effort.

When ready, athletes completed a minimum of three trials in each direction given in a random order. A successful trial consisted of athletes reaching an approach velocity of  $\geq 6.0 \text{ m}\cdot\text{s}^{-1}$  as determined in real-time by a Stalker Acceleration Testing System (ATS) II radar device (Model: Stalker ATS II, Applied Concepts, Dallas, TX, USA) positioned 2-metres behind the start position, striking the force platform completely with the sidestepping foot and executing the task as quickly as possible to closely simulate the requirements of a match situation. Tape lines the same width of the force platforms (600-millimetres) were provided to direct athletes through the initial runway and the  $45^\circ$  exit paths.

At the beginning of the collection, a laboratory calibration was completed to establish the capture volume (collection area) and position of the nine-cameras (T10S, Vicon Motion System Ltd., Oxford, UK) relative to each other and the laboratory origin (front right corner of the force platform [Type 9287C, Kistler Instrumente AG, Winterthur, CH]). Once the capture volume was established, static and range-of-motion calibration trials were performed on the individual athletes using Vicon Nexus software. To create a three-dimensional model for analysis, 78 spherical retro-reflective markers (10-millimetre width) were placed on

specific anatomical locations by a highly trained, Level-2 certified ISAK anthropometrist to create a full-body marker set and model. Knee and ankle medial markers were removed after the static calibration trial was completed to allow for the dynamic movement of the testing protocol. Clusters were comprised of four markers and placed on the segments to increase redundancy for marker tracking.

### *Data analyses*

Custom-made LabVIEW (Version 14.0, National Instruments Corporation, Austin, TX, USA) and Matlab (R2014b, The MathWorks, Inc., Natick, MA, US) programmes were created to analyse all data. Isokinetic data in the form of torque-angle curves were filtered with a fourth-order polynomial and separated into extension and flexion actions (where the first repetition of each action were removed) before the mean peak torque and angle of peak torque were extracted for the preferred and non-preferred legs. Stability index data from the balance assessment were generated within the Biodex software using the mean of the three trials performed. Data were presented as overall, anterior-posterior and medial-lateral scores and were separated by the preferred and non-preferred legs. Sprint kinetic data were filtered with a dual low-pass Butterworth filter at 10 Hz and separated into initial acceleration (steps 1 and 2), acceleration, (steps 3-12) and maximal velocity (steps 13-22) based on the force output readings. Within the acceleration and maximal velocity phases, data were separated by the preferred and non-preferred legs and the mean peak horizontal force were extracted.

Three-dimensional motion (100 Hz) and ground reaction force (1000 Hz) data from the sidestepping task were filtered with a low-pass fourth-order zero-lag Butterworth filter using a cut-off frequency of 16 Hz in Visual 3D (4.91.0, C-Motion, Inc., Germantown, MD, US) based on residual analysis and visual inspection of the kinematic and kinetic data. Athlete-specific helical-axis joint centre locations for the hips and knees were calculated from the range of motion trials (hip star and squats respectively) using Matlab [141, 250]. Knee moment data were calculated using standard inverse dynamics equations and were defined as those externally applied to the segment's distal end. Moments were normalised to body-mass and body-height ( $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) and time data were normalised to stance phase (%; from initial contact to final contact) to facilitate comparison between all athletes.

Stance time was calculated by detecting the ground contact via ground reaction force data using a 10 N threshold. Performance variables were calculated in Visual 3D to allow

comparison between the preferred and non-preferred sidestep. Initial contact was defined as the discreet point when the unfiltered vertical ground reaction force exceeded 10 N and weight acceptance as the average between initial contact and the first trough in the unfiltered vertical ground reaction data. Initial contact and weight acceptance phases were calculated using Matlab using a method similar to that applied elsewhere [178].

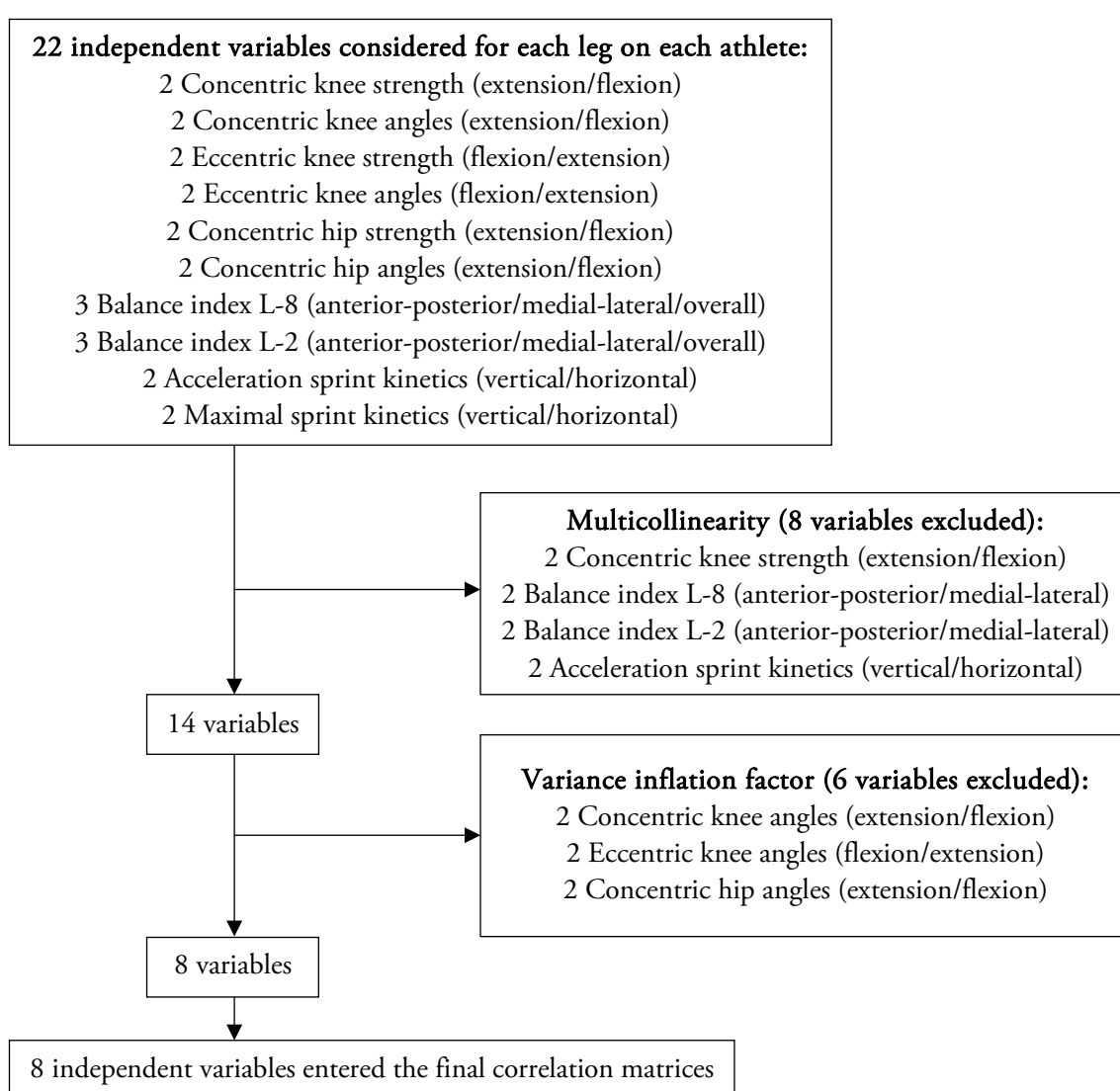
Individual symmetry angle scores were calculated for all variables using a modified non-dimensional relationship (Equation 5) [103]. This equation was chosen as it does not require an arbitrary reference leg, is unaffected by artificial inflation by near-zero numbers and is useful in determining clinically relevant information in sports science [101-103]. The resulting score (between 0 – 100%) reflects the absolute percentage difference between the legs; where 0% indicates perfect symmetry and 100% indicates perfect asymmetry.

### *Statistical analyses*

The independent variables of interest were based on assessing the athletes' concentric / eccentric strength at the knee and concentric strength at the hip, the ability to maintain single-leg balance at multiple difficulty settings and sprint kinetics (vertical and horizontal force production) during acceleration and maximal sprinting. Previous rugby research examining differences between legs in injury risk assessments [98, 177, 246] were also considered. The principles of magnitude-based inferences were implemented in this study rather than traditional significance testing to identify mechanistically important determinants of increased knee loads and to provide a more detailed interpretation of the findings [273].

Correlation matrices were separately produced and analysed for the independent variables within the theoretical model mentioned above which pertained to the preferred leg, the non-preferred leg and the symmetry angle (the absolute difference between the two legs [range: 0 – 100%]). Checks for multicollinearity and variance inflation factor (Pearson  $r \geq 0.8$  and  $VIF > 5$ ) were used to identify which variable(s), if any, contributed to collinearity [274]. Any variable(s) identified as contributing to colinearity was closely assessed to determine if its absence in the subsequent regression model would negatively affect the initial theoretical approach (Figure 23). After removal of collinear variables, all remaining variables entered a new correlation matrix where they were correlated with the dependant variable. Mean and standard deviation, goodness of fit presented as Pearson correlation coefficient ( $r$ ) and co-

efficient of determination ( $R^2$ ) were produced for each model. The scale of thresholds used for interpreting the mechanistic importance of the individual variable correlations were < 0.10 (trivial), 0.10 (small), 0.30 (moderate), 0.50 (large), 0.70 (very large), 0.90 (nearly perfect) and 1.0 (perfect) correlations [142]. Based on this scale, only moderate or higher ( $\geq 0.3$ ) correlations were considered mechanistically important for the subsequent multiple regression equation and a minimum of a 5:1 ratio of athletes to independent variables (16 athletes = a maximum of four independent variables) were implemented to account for a lack of generalisability (shrinkage) and inflated error rates due to the study's smaller sample size [275].



**Figure 23. Statistical analysis flow-chart.**

The two criteria listed above were used in determining which independent variables would continue on to the hierarchical multiple regression equation. Each variable entered the equation in a separate block in descending order of mechanistic importance (highest to lowest

Pearson  $r$ ). The adjusted  $R^2$  ( $\bar{R}^2$ ) of each variable was then assessed as it entered the model as a final means to ensure that the increasing contribution of the independent variables was not a result of chance but rather that each variable that entered the equation was improving the model and providing an unbiased estimate of the population  $R^2$ . If the  $\bar{R}^2$  decreased with the inclusion of a new independent variable, the actual contribution of that variable was less than what was expected by chance alone and was therefore removed from the final equation.

Following the statistical process, unstandardised and standardised coefficients ( $B$  and  $\beta$ , respectively) for the individual independent variables and  $R^2$ ,  $\bar{R}^2$ , standard error of the estimate (SEE [in raw units of the dependant variable]) and inference based on the square-root of the  $\bar{R}^2$  were presented for the overall model to describe the magnitude of the observed relationship [276]. This statistical process was performed for the three unique models (Model 1: Preferred leg; Model 2: Non-preferred leg and Model 3: Symmetry angle) to fit the theoretical approach established for this study. All correlation and regression analyses were performed in Statistical Analysis System (version 9.4, SAS Institute Inc., Cary, NC, US).

## Results

Descriptive information (mean  $\pm$  standard deviation,  $r$  and  $R^2$ ) of the initial correlation matrices pertaining to the three groups are presented in Table 23. Large negative (concentric hip extension torque [-0.56]) and moderate negative ( $F_V$  during maximal sprinting [-0.40], eccentric knee extension torque [-0.38] and concentric hip flexion torque [-0.31]) correlations were observed with knee abduction moment at weight acceptance during the sidestep manoeuvre in Group 1: Preferred leg. Moderate positive (concentric hip flexion torque [0.37]) and negative ( $F_V$  during maximal sprinting [-0.33]) correlations were observed in Group 2: Non-preferred leg. Large positive ( $F_H$  during maximal sprinting [0.58]) and moderate positive ( $F_V$  during maximal sprinting [0.46]) and moderate negative (eccentric knee flexion torque [-0.40] and concentric hip flexion torque [0.37]) correlations were observed in Group 3: Symmetry angle. All other variables did not meet the minimum requirements: presented small or trivial correlation coefficients ( $< 0.30$ ) and / or exceeded the 5:1 ratio of athletes to independent variables.

**Table 23. Correlation matrices.**

Theoretical approach	Variable	Group 1: Preferred leg			Group 2: Non-preferred leg			Group 3: Symmetry angle		
		Mean $\pm$ SD	r	R <sup>2</sup> (%)	Mean $\pm$ SD	r	R <sup>2</sup> (%)	Mean $\pm$ SD	r	R <sup>2</sup> (%)
Injury risk (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )	Knee abduction moment at weight acceptance during sidestepping	0.65 $\pm$ 0.31			0.77 $\pm$ 0.45			15 $\pm$ 13		
	Eccentric knee flexion torque	240 $\pm$ 64	0.17	3	228 $\pm$ 51	-0.012	< 1	5.9 $\pm$ 2.4	-0.40 <sup>3</sup>	16
Strength (N·m)	Eccentric knee extension torque	154 $\pm$ 35	-0.38 <sup>3</sup>	15	140 $\pm$ 38	0.027	< 1	5.0 $\pm$ 5.7	-0.057	< 1
	Concentric hip extension torque	325 $\pm$ 96	-0.56 <sup>1</sup>	31	313 $\pm$ 65	0.040	< 1	4.4 $\pm$ 3.3	0.22	5
	Concentric hip flexion torque	170 $\pm$ 40	-0.31 <sup>4</sup>	10	173 $\pm$ 37	0.37 <sup>1</sup>	14	3.7 $\pm$ 3.3	-0.37 <sup>4</sup>	14
Balance (Deg)	Dynamic postural stability index L8	1.9 $\pm$ 0.7	-0.062	< 1	2.2 $\pm$ 0.8	0.13	2	12 $\pm$ 10	-0.37	14
	Dynamic postural stability index L2	5.9 $\pm$ 2.4	0.19	4	6.5 $\pm$ 2.3	0.14	2	9.4 $\pm$ 8.4	-0.16	2
Sprint kinetics (N·kg <sup>-1</sup> )	Vertical force during maximal sprinting	25 $\pm$ 2	-0.40 <sup>2</sup>	16	24 $\pm$ 2	-0.33 <sup>2</sup>	11	1.8 $\pm$ 1.4	0.46 <sup>2</sup>	21
	Horizontal force during maximal sprinting	3.3 $\pm$ 0.8	0.050	< 1	3.0 $\pm$ 0.5	0.12	2	4.7 $\pm$ 4.3	0.58 <sup>1</sup>	34

Footnote: Correlation matrices for the relationship between the independent variables in the theoretical approach and the dependant variable (knee abduction moment at weight acceptance during the sidestep manoeuvre) among the three groups, n = 16. N, newton; m, metre; kg, kilogram; Deg, degree. Values are means  $\pm$  standard deviation; Pearson correlation coefficient (r); coefficient of determination as a percent (R<sup>2</sup> [%]). Numerical superscript represents the largest Pearson correlation coefficients which satisfies the effect threshold value of  $\geq 0.30$  (representing a moderate magnitude of the effect), presented in descending order. \*Note: while some of the independent variables listed above met the initial inclusion criteria (r  $\geq 0.3$  and 5:1 ratio of athletes to independent variables), these variables were subsequently removed as their inclusion lowered the R<sup>2</sup> of the overall model.\*

The hierarchical multiple regression analysis equations for the three models are presented in detail in Table 24. In Model 1: Preferred leg, concentric hip extension torque was entered first and explained 33% of the adjusted variation in knee abduction moment and  $F_V$  during maximal sprinting was entered second and explained an additional 8%. Eccentric knee extension torque (originally entered third) and concentric hip flexion torque (originally entered fourth) lowered the  $\bar{R}^2$  (-4% and -1%, respectively) when entered into the model so were therefore removed from the final model. The combination of concentric hip extension torque and vertical force during maximal sprinting explained a large percentage (41%; inference: 0.64) of the total adjusted variation in knee abduction moment at weight acceptance in the preferred leg during sidestepping. In Model 2: Non-preferred leg, concentric hip flexion torque was entered first and explained 8% of the variation.  $F_V$  during maximal sprinting (originally entered second) lowered the  $\bar{R}^2$  (-1%) when entered into the model so were therefore removed from the final model. Concentric hip flexion torque in explained a small percentage (8%; inference: 0.29) of the total variation in knee abduction moment at weight acceptance in the non-preferred leg during sidestepping. In Model 3: Symmetry angle,  $F_H$  during maximal sprinting was entered first and explained 29% of the variation and eccentric knee flexion torque was entered second and explained an additional 3%.  $F_V$  during maximal sprinting (originally entered second) and concentric hip flexion torque (originally entered fourth) lowered the  $\bar{R}^2$  (-3% and -2%, respectively) when entered into the model so were therefore removed from the final model. The combination of  $F_H$  during maximal sprinting and eccentric knee flexion torque explained a large percentage (32%; inference: 0.56) of the total variation in knee abduction moment at weight acceptance in the symmetry angle during sidestepping.



Table 24. Hierarchical multiple regression analysis.

		Independent variable characteristics		Overall model characteristics				
		Block	B	β	R <sup>2</sup> (%)	̄R <sup>2</sup> (%)	SEE (raw)	Inference
Model 1:	Preferred leg (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )				49	41	0.24	Large
		1: Concentric hip extension torque	-0.0020	-0.61				
		2: Vertical force during maximal sprinting	-0.051	-0.34				
Model 2:	Non-preferred leg (Nm·kg <sup>-1</sup> ·m <sup>-1</sup> )				15	8	0.42	Small
		1: Concentric hip flexion torque	0.0045	0.38				
Model 3:	Symmetry angle (%)				42	32	11	Large
		1: Horizontal force during maximal sprinting	1.6	0.52				
		2: Eccentric knee flexion torque	-1.6	-0.29				

Footnote: Hierarchical multiple regression analysis for the prediction of knee abduction moment at weight acceptance during the sidestep manoeuvre among the three theoretical models,  $n = 16$ . B, unstandardised coefficient;  $\beta$ , standardised coefficient;  $R^2$ , coefficient of determination;  $\bar{R}^2$ , coefficient of determination adjusted for degrees of freedom; SEE, standard error of the estimate; N, newton; m, metre; kg, kilogram; %, percent. Mechanistic inferences are based on the square-root of the adjusted correlation coefficient. Small and large inference:  $0.10 - < 0.30$  and  $0.50 - < 0.70$ , respectively.

## Discussion

The relationship between internal factors and knee loads during sidestepping has been previously described [277, 278] providing valuable information on the mechanics of knee loading within a group of athletes. To the best of our knowledge, the current study is the first to aid in our understanding of the primary characteristics of the sidestep with current laboratory assessment strategies used to evaluate injury risk in athletes [98, 114] and then observe that relationship with knee loading during the sidestep. The aim of this study was to determine which assessment tools provide the greatest explanation for increased knee loading. We assessed components of lower-extremity single-leg strength at the knee and hip, single-leg balance and single-leg sprint kinetics. Based on this approach, we analysed the unique relationships within the preferred leg, the non-preferred leg and the symmetry angle (difference between the legs); wherein the sidestepping manoeuvre can be / is performed on either leg and that each leg may present distinctive attributes from each other. The three modelled relationships (preferred leg, non-preferred leg and symmetry angle) describe the individual and collective contribution of specific independent variables in predicting increased knee loading. Based on our findings, we can infer that knee loading in the preferred kicking leg is influenced by weak lower-extremity posterior strength (specifically hip extension [glutes]), and knee loading in the non-preferred kicking leg is marginally influenced by strong lower-extremity anterior strength (specifically hip flexion [hip flexors]); confirming that each leg possesses unique mechanical characteristics. We can also infer from our results that larger asymmetries in  $F_H$  during maximal sprinting influence larger asymmetries in knee loading, suggesting a potential link between sprint kinetics and ACL injury risk.

Just under half of the variance (41%) in larger external knee abduction moment at weight acceptance of sidestepping was explained by lower levels hip extension strength (glutes & hamstrings) and  $F_V$  during maximal sprinting in the preferred leg alone. When performing a sidestep, the athlete must first decelerate the body before reorienting the COM in a new direction. It is during the weight acceptance phase where the knee and hip move into greater degrees of flexion by eccentrically lengthening the quadriceps, hamstrings and glutes to accept the mass of the athlete and decelerate their forward velocity. Adequate strength in these muscle groups has been found [84, 265] to provide the appropriate joint stability and to

protect the ACL and other soft tissues. Specifically, a lack of adequate strength and control at the hip has been targeted [130, 257] as a main contributor to larger moments experienced at the knee within the sidestep manoeuvre. It is thought [265] that stronger hip muscles can better resist high levels of externally applied loads, causing internal rotation and adduction of the femur, subsequently aiding in the reduction of internal rotation and abduction of the knee. With this thought in mind, we can infer that the athletes in our cohort whom possessed lower levels of hip extensor strength also presented larger knee abductor moments while sidestepping. In addition, lower levels of eccentric knee extension strength and hip flexion strength also showed moderate correlations ( $r = -0.31 - -0.38$ ) with larger knee abductor moments. While these last two variables were disallowed in the final model, they do support the suggestion that 1) posterior-chain strength, and 2) total strength at the hip are vital components in reducing larger external loads in the preferred leg during the sidestep.

Another interesting finding in the preferred leg was that lower levels of  $F_V$  during maximal sprinting contributed to higher levels of knee abduction moments during the sidestep. When considering the spring-mass model [279], a stiff lower-extremity will produce the greatest  $F_V$  due to the rigidity of the model in transferring energy compared to a compliant lower-extremity which will absorb more energy by greater degrees of flexion across the lower-extremity joints. However, as many of the events in rugby are not cyclic (sidestepping, jumping, kicking, etc.), each leg may present a different stiffness profile. This may be the case in the current study as only the preferred leg presented a relationship between lower  $F_V$  and larger knee moments; potentially suggesting that the preferred leg in rugby athletes acts as the “stick” leg (absorbing more energy) [97, 279]. Additionally, if the glutes in a particular athlete are weak and yet are still required to activate, control and aid in decelerating the body, the athlete may in fact require more time at which to flex the hip or a longer ROM of hip flexion in order to accomplish the task. Therefore, weaker glutes and lower  $F_V$  may be inherently linked as a function of each other. However, as there was no collinearity between the two variables and the expected contribution of each variable greater than randomness alone (e.g. the  $\bar{R}^2$  did not decrease), we can assume that hip extension strength and  $F_V$  during maximal sprinting each contribute to the characteristics of the preferred leg during sidestepping.

The non-preferred leg presented a unique model to that of the preferred leg where only 8% of the variance seen in higher levels of knee abduction moment was explained by higher levels of hip flexion strength (hip flexors). The non-preferred leg acts as the stance leg to stabilise the body while performing the action of kicking a ball and therefore may experience a greater frequency of single-leg loading at the knee and hip. However, as the athlete does not change direction during the kick, the deceleration phase may be much shorter and require less joint flexion in the knee and hip [280]. If this were the case, the higher frequency of muscular loading would potentially be localised to the anterior-chain musculature (i.e. quadriceps and hip flexors). While the hamstrings and glutes may be strong in these athletes, the hip flexors (or other quadriceps) may be stronger than normal. Stronger levels of hip flexor strength could add to an athlete being quad-dominate or essentially throw off the ideal balance of the hamstrings to quadriceps ratio at the knee and / or at the hip [9, 177]. The aforementioned connection between strong hip flexors and larger knee abduction moments are purely speculative at the time as this measure of strength only provides a small examination of the relationship. What is more important to take note of is that the non-preferred leg (stance leg) is not affected by lower levels of posterior-chain strength as was the preferred leg. Additionally, the mechanics of the non-preferred leg may be better explained within the sidestep manoeuvre itself rather than by the assessments outside of the movement. Unfortunately, preferred versus non-preferred leg mechanical determinates within the sidestep has not yet been examined in the literature and was not within the scope of the current study; we can therefore only speculate at this time.

Very little research has been performed using symmetry angle scores and even less outside of walking, jogging and sprinting activities; however, its importance and contribution to our understanding of individual differences is well established [101-103]. As such, in addition to assessing the unique characteristics of each leg in terms of raw variables, we also deemed the inclusion of assessing the difference between the legs as equally important to acquire the complete picture of our athletes' injury risk status. As such, we ran a third model using our symmetry angle scores in an attempt to answer the question, "If asymmetries exist in traditional assessment measures of strength, balance and sprint kinetics, would they also exist in knee abduction moments as a measure of ACL injury risk?" We found that larger symmetry angle scores in  $F_H$  during maximal sprinting and smaller symmetry angle scores in

eccentric knee flexion strength (quadriceps) explained 32% of the variance of larger symmetry angle scores in knee abduction moments. Hip extension strength has recently been shown to impact  $F_H$  and subsequently sprint velocity [227]. Decreases in  $F_H$  have also been found pre- and post-injury in footballers and rugby athletes [268]. While both of these studies produced a measure of force production (the summation of both legs) via COM acceleration and position, it can be asserted that the net force is the product of the contribution of the right and left legs (or preferred and non-preferred in the context of the current study). Therefore, a decrease in net  $F_H$  could be the result of a decrease in only one leg, which would present a larger symmetry angle score. If an athlete possessed a larger asymmetry in  $F_H$ , this would inform us that one of the legs is potentially not operating as efficiently (or at the same level) as the other. If the leg which produced the lower  $F_H$  is doing so because it lacks the strength, then it could be speculated that the same ‘weak’ leg would lack the posterior-chain strength to support the lower-extremity joints during a sidestep. While an imbalance in  $F_H$  while sprinting can potentially increase injury risk is a very novel and interesting finding, more research needs to be conducted to substantiate or refute these assertions.

Another interesting finding in the symmetry angle model was that eccentric knee flexion strength (quadriceps) also had an impact on knee abduction moment while sidestepping. Eccentric quadriceps strength, alongside eccentric hamstring strength, is required while decelerating in a sidestep to control and stabilise the knee joint. However, the findings from the current study should not be interpreted as ‘more symmetry (a score closer to zero) in eccentric quadriceps strength equals larger knee abduction moments’, as the symmetry angle scores do not describe the magnitude of the eccentric strength in detail. For example, both legs could produce extremely low (preferred = 123 N·m and non-preferred = 128 N·m) or high (preferred = 325 N·m and non-preferred = 343 N·m) levels of strength yet both would produce a low symmetry angle scores (low = 1.3 and high = 1.7). The eccentric quadriceps strength would still need to be assessed alongside the eccentric hamstrings strength to complete the picture. Along the same lines, if the athlete in the example above possesses the high level of eccentric quad strength, and also possesses low (preferred = 150 N·m and non-preferred = 159 N·m) or high (preferred = 207 N·m and non-preferred = 216 N·m) levels of eccentric hamstrings strength, the end message would be substantially different as the ratio between the musculature would tell two unique stories (low = 0.46 and high = 0.64). This

was the case when the raw data was examined and the eccentric hamstrings strength was assessed in conjunction with the symmetrical levels of eccentric quad strength.

### ***Limitations***

We feel it is important to acknowledge several limitations in the current study to give context to the interpretations of our findings. First, the theoretical approach that we implemented in this study was thought to best represented the most fundamental characteristics of the sidestep manoeuvre; consisting of strength, balance and sprint kinetics. However, we can also acknowledge the unavoidable potential for other authors to see differently and potentially using alternative assessment tools which they feel might better characterise the sidestep. As presence of unique views from researcher to researcher is unavoidable, we also ensured that our assessment tools within our theoretical approach were also within the boundaries of typical field- and laboratory-based research and practical return-to-sport decision making to aid in the carryover of previous and future work [98, 114]. Second, as our sample size was smaller ( $n = 16$ ) than typically desired for regression analyses ( $n > 50$ ), we used a very strict statistical model and interpretation process to focus on the true importance of the model. We felt that is was the appropriate step to insure that we obtained meaningful results based on our sample population, thus allowing us to propose the most accurate considerations available without the influence of data inflation, error or chance. Third, as the purpose (and theoretical approach) of this study was to examine the relationship between select assessment tools and knee loading during the sidestep of each leg, the results from this study are unique to: 1) male rugby union athletes; 2) leg division using the preferred and non-preferred kicking leg definition; and 3) external knee abduction moments during the sidestep manoeuvre; relevant to the individual athlete's body-mass and body-height. As specific as this study may seem, the information resulting from our results provides valuable information regarding injury risk factors in rugby at which to build upon with future research potentially examining female and / or professional rugby using the theoretical model found in this study.

### **Conclusions**

Our stepwise regression analysis of lower-extremity differences in knee moments during sidestepping in male rugby athletes showed that the preferred and non-preferred kicking legs possess unique attributes. The attributes between the legs also appear interrelated and may be modifiable through a targeted strength training approach. For example, both legs

presented a relationship with increased knee loading through weaker posterior muscular strength (glutes and hamstrings) or stronger anterior muscular strength (hip flexors and quads), providing valuable information into the importance of appropriate levels of strength about the hip. We therefore suggest the incorporation of hip strength testing in all forthcoming research related to ACL injury risk. Additionally, we would like to introduce the possibility of greater knee abduction asymmetry during sidestepping (increased ACL injury risk) with greater asymmetry in  $F_H$  during maximal sprinting.

In summary, when assessing athletes for injury risk factors, practitioners / clinicians should incorporate a multicomponent assessment strategy combining elements of single-leg strength at the knee and hip and single-leg sprint kinetics during maximal sprinting (if available). The interpretation of such a testing strategy would identify single-leg values lower than pre-established norms and / or asymmetries between the legs. An individualised or “targeted” strength training programme could then be created for the athlete to work on increasing strength and / or decreasing asymmetries where needed. Follow-up assessments could then determine the effectiveness of the programme and any subsequent modifications needed for the progression. Future research is greatly needed in the area of individualised training programmes to determine their effectiveness in reducing injury risk and / or increasing performance in athletes.

**Section 3:**  
**The Next Step towards**  
**Lower-Extremity Assessment Strategies**



## **Chapter 9: A Lower-Extremity Multi-Component Assessment Strategy for Individualised ACL Injury Prevention and Athletic Performance in Rugby Union: A New Framework**

This chapter comprises the following paper prepared for *Journal of Athletic Training*.

### **Reference:**

Brown SR, Brughelli M, Hume PA. A lower-extremity multi-component assessment strategy for individualised ACL injury prevention and athletic performance in rugby union: A new framework. *J Athl Train*. 2016:[in preparation].

### **Author contributions:**

Brown SR, 90%; Brughelli M, 5%; Hume PA, 5%.

### **Overview**

Differences between the preferred and non-preferred legs of rugby athletes exist in laboratory assessments of strength, balance, sprint kinetics and three-dimensional sidestepping. As important as these differences are, there is currently no normative data that practitioners can use for comparison when working with their own rugby athletes. Additionally, there is currently no framework to structure clinical injury prevention assessments specific to rugby athletes. The purpose of this commentary was to provide 1) normative data values and ranges from the cross-sectional studies conducted in this thesis, 2) normative symmetry values and ranges from the cross-sectional studies conducted in this thesis, 3) a new theoretical model on injury risk assessment in rugby athletes, and 4) a framework to guide future rugby research. Data and symmetry scores accumulated from several published cross-sectional studies were compiled as means, standard deviations, ranges, medians and inner-quartile ranges. Variables showing a relationship with increased ACL injury risk, combined with current laboratory-based research, were compiled to form the basis of the theoretical model. This theoretical model was then used to create an injury assessment framework. Strength at the knee and hip as well as sprint kinetics showed the strongest relationships with knee abduction moments during sidestepping. Isokinetic strength at the knee and the hip combined with sprint kinetic assessments during maximal velocity should be combined in a multi-component strategy to assess injury risk in rugby athletes. A framework has been created to conduct such a theoretical model wherein athletes enter an assessment loop, have

their data compared with normative data of their peers, are assessed on their symmetry values and are deemed “clear to continue team training” or “require individualised programming”. Athletes can continue within the loop until their data are within acceptable ranges to aid in decreasing injury risk.

## ACL injury and sidestepping

The sidestep manoeuvre is a common action performed in rugby. Non-contact anterior cruciate ligament (ACL) injuries often occur during the sidestep which is one of the most substantial injuries in sport. The link between the manoeuvre and ACL injury can be found in the aetiology and mechanism of the injury itself. Ligament injury occurs when the external forces exceed the mechanical properties of the tissue; which is believed to occur within the first 30% of stance phase known as ‘weight acceptance’ [33, 58]. The mechanisms are complicated due to the multifaceted function of the knee consisting of flexion / extension, abduction (valgus) / adduction (varus) and internal / external rotation [75].

The knee experiences applied flexion, abduction and internal rotation moments [54] during the sidestep. When combined, these loads can increase ACL strain [48]. Our understanding of tissue tolerance has grown and is supported through *in vitro* [261] and *in vivo* [54] ACL research. The athlete requires adequate levels of lower-extremity strength to stabilise the knee, control the hip and decelerate the body, balance to stabilise and re-orientate the centre-of-mass and sprint kinetics to apply the appropriate force contribution and reaccelerate in the new direction. Inadequacies in lower-extremity strength and sprint kinetics have been linked with increased knee abduction moments during weight acceptance of sidestepping [281].

In the context of how sidestepping relates to ACL injury in rugby, our proposed theoretical model has developed consisting of knee and hip strength measures and of vertical and horizontal force ( $F_V$  and  $F_H$ , respectively) application while sprinting. Interestingly, components of this proposed theoretical model for assessing ACL injury risk in injured athletes have been seen before [98, 114] in research as a return-to-sport assessment strategy. Common and validated laboratory-based tools such as dynamometers and instrumented treadmills have been used to assess lower-extremity function as it pertains to injury risk / re-injury [98, 114, 170, 172].

Where we are falling short is that instead of utilising a model to assess and monitor uninjured / healthy athletes, many researchers attempt to use single field-based screening assessments to predict ACL injuries. Minimal success in these predictions is suggested [282, 283] to result from a lack of theoretical support (specificity) [283], incomplete validation [282] and improper dissemination of the findings; practically the opposite of what is shown to work. When it comes to assessing an uninjured / healthy athlete, perhaps our goal as researchers

could be to assess the mechanical components associated with ACL injury risk and potentially *fix* the issues that need attention instead of trying to *predict* the injury all together. To accomplish this goal, normative values of the assessment tools being used are needed within a specific population in order to better guide the researcher to identify injury risk and where any deficits may reside on the athlete. A more informed researcher may then translate that information to the coaching staff to aid their decision-making on whether the athlete can play or not. Normative values have not yet been presented for lower-extremity strength and / or sprint kinetic measures for rugby athletes.

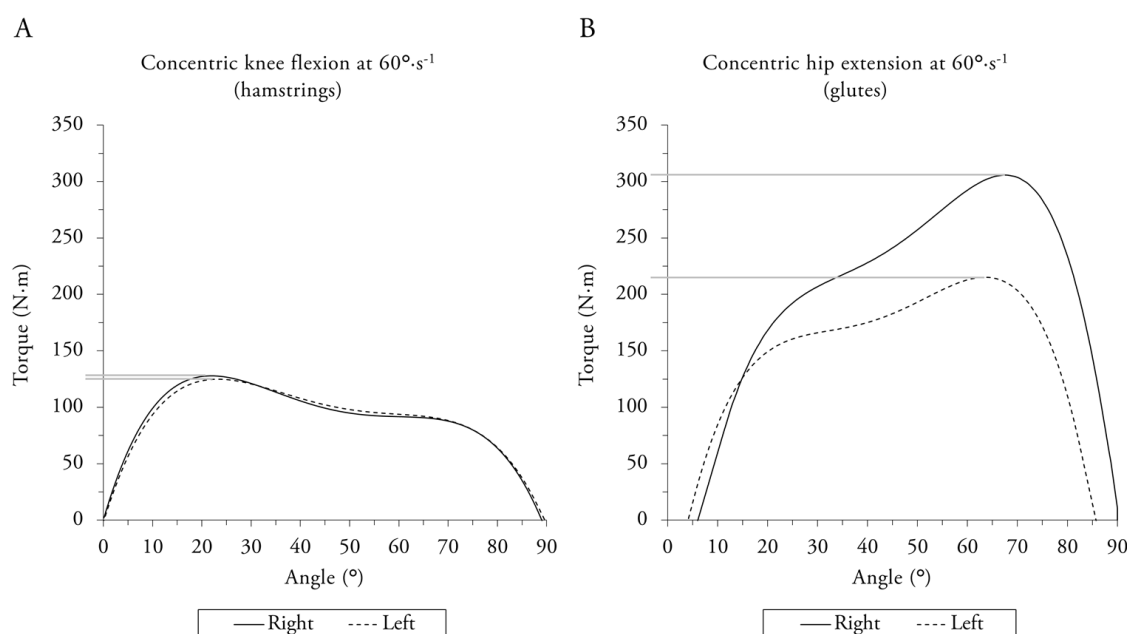
### **What assessment tools should we use?**

#### ***Single-component***

There are many types of lower-extremity assessment components available including visual screening (MSC [284] or FMS [285]), assessing hamstring flexibility [286], lumbopelvic stability [287], strength [177], balance [213], sprint kinetics [98] and Magnetic Resonance Imaging (MRI) [288] to name a few. However, in rugby athletes lower-extremity strength and sprint kinetics are the most common assessments in detecting increased ACL injury risk. When used individually, these assessments can be performed easily (requiring only one researcher) and quickly (< 30 min). Thus a researcher can assess multiple athletes or an entire team in a short time and provide rapid results. Additionally, each assessment can provide objective and reliable information to the researcher and can aid in a more educated direction for subsequent programming on an individual basis.

Using only one assessment can limit additional interactions that may need to be included to see the bigger picture. Figure 24 shows an example of how important information can be missed using a single-component strategy. If only assessing concentric strength about the knee during flexion, a researcher might be able to determine that the athlete possesses a lack of strength in the hamstrings. A subsequent recommendation may be to concentrically strengthen the posterior-chain by means of squats, glute-activation, etc. Important factors such as eccentric strength may be overlooked. Similarly, if that same athlete was only assessed at the knee, the interaction of biarticular muscles would not be included in the analysis; potentially missing important information as to the exact location of the strength deficit. To reinforce this point, authors in a similar isokinetic study found more than 30% of the athletes assessed would not have been identified with strength imbalances if only a concentric

protocol were used instead of the multi-speed and multi-action protocol that was used [112]. Along the same lines, when using sprint kinetics as an individual assessment, a clear asymmetry might be evident following the assessment. Whether this asymmetry is a result of a lack of strength or improper force application cannot be determined on the basis of just one assessment.



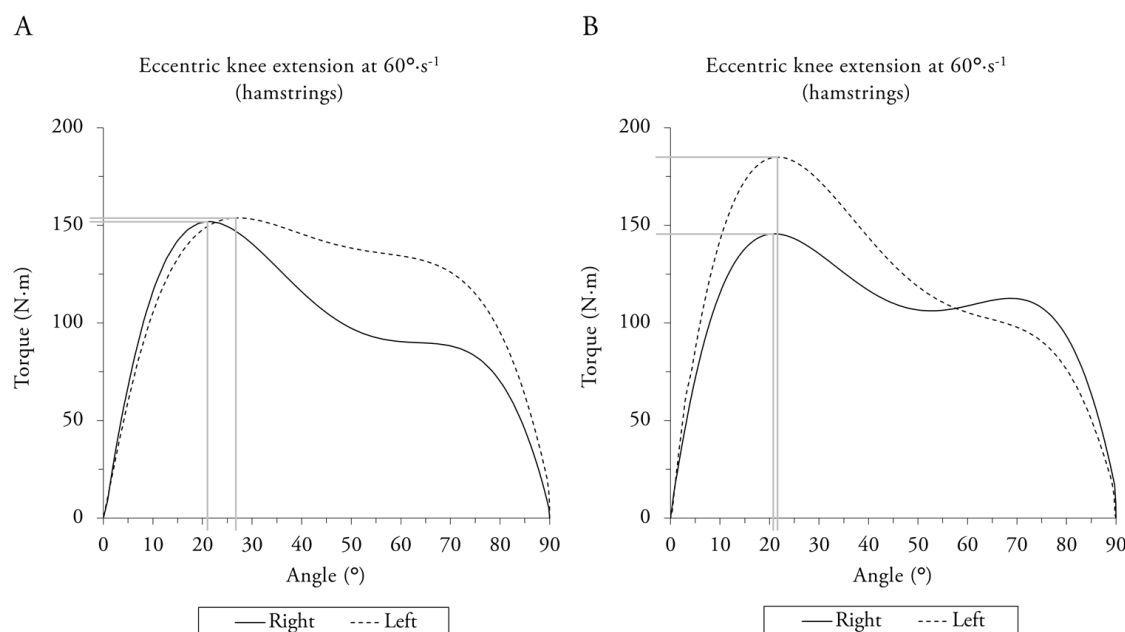
**Figure 24. Isokinetic asymmetries example one.**

An example of a typical graph examining side-to-side asymmetries during concentric A) knee flexion with no apparent difference in peak torque (2%); and B) hip extension with a large difference in peak torque (42%).

### *Multi-component*

The multi-component assessment strategy is not a new idea. Several authors [114, 289] have proposed various algorithms with multiple assessments in order to progress an athlete back to sport following an injury. However, very few studies implemented multi-component assessment strategies with the purpose of informing individualised training in previously injured [98] or un-injured populations. Essentially, a multi-component strategy is one that incorporates more than one essential component. Our recommendation for the components used on rugby athletes include: concentric AND eccentric isokinetic strength at the knee AND hip, AND sprint kinetics during acceleration AND maximal velocity. When combined in a collective fashion or a 'holistic approach', each assessment can add valuable information to the big picture. Figure 25 illustrates an example of how a multi-component strategy can

assist a researcher in their final analysis. When assessing the strength of an athlete, determining the angle of peak torque along with the peak torque may help in the identification of injury risk factors not otherwise noticed [9]. It has been suggested that the inability to produce force at long muscle lengths may increase the risk of hamstring injury while sprinting [290].



**Figure 25. Isokinetic asymmetries example two.**

An example of a typical graph examining side-to-side asymmetries during eccentric knee extension where A) the peak torque is similar (1%) but the angle of peak torque is different (23%); and B) the peak torque is different (21%) but the angle of peak torque is similar (2%).

When assessing a rugby league athlete's return-to-sport status as a case-study for example, we combined isokinetic strength about the knee and the hip with sprint kinetics in an attempt to determine whether he had a "normal" level of strength for each leg and at each joint (compared to his peers playing the same position) [98]. By using this multi-component assessment strategy, we were able to recommend a more targeted programme based on his individual deficits in hopes of returning the athlete to play as safely as possible while minimising the potential for future injury (either as a re-injury or a new injury). The physiotherapy staff implemented an individualised rehabilitation program based on his individual deficits. After returning for a second assessment, the athlete improved in strength and sprint kinetic asymmetries. In the following season, no major lower-extremity injuries were noted in this athlete and he eventually made it back the top level of his sport.

Unfortunately, the use of multiple tools for assessment purposes requires more instruments, more time and an extended knowledge of those tools or additional researchers; all of which decrease the ease of practicality and increase cost [112]. While an isokinetic assessment for the knee takes < 30 min, by including the hip, time can easily double to ~ 60 min. Further including sprint kinetics adds another ~ 30 min; creating a ~ 90 min total assessment time. Structuring a multi-component assessment around an individual remains simple with one clinician and an easy turn-over of results. Structuring a multi-component assessment around a team of 35 athletes will require several clinicians and several days of processing the data. Admittedly, not all teams can make this a reality, even with good resources and during the off- or pre-season periods. However, for those that can, useful information can be developed and then fed back into the team's staff to guide the decisions around field training and strength programming.

### So where do we begin? Normative values

#### *Athletes*

The data used in developing the model and framework were derived from fifty-two male rugby athletes. Athletes consisted of European, Pacific Island and Asian descent and had an average playing experience that encompassed > 151 rugby matches played per athlete. Detailed characteristics can be found in Table 25 including the separation of forwards and backs. Lower-extremity strength and sprint kinetic data were among a battery of assessments used to provide rationale in this commentary.

All procedures used in this study were approved by the Auckland University of Technology Ethics Committee (13/378) and all athletes provided their informed verbal and written consent prior to data collection.

**Table 25. Athlete characteristics used in developing the framework.**

	Forwards ( <i>n</i> = 26)	Backs ( <i>n</i> = 26)	Combined ( <i>n</i> = 52)
Age (y)	20 ± 1	23 ± 4	21 ± 3
Body-height (m)	1.85 ± 0.11	1.83 ± 0.05	1.84 ± 0.08
Body-mass (kg)	100 ± 10	90 ± 7	95 ± 10
Body-mass index (kg·m <sup>-2</sup> )	29 ± 3	27 ± 2	28 ± 3
Rugby experience (y)	11 ± 5	9 ± 6	10 ± 5
Preferred kicking leg	right = 24, left = 2	right = 20, left = 6	right = 44, left = 8

Footnote: y, year; m, metre; kg, kilogram; m, metre. Values are means ± standard deviation.

All data were collected on both legs and subsequently divided into 'preferred' and 'non-preferred' legs. In-line with previous research [9, 233], this classification was based on the self-reported leg that the individual athlete preferred to kick the ball with or which leg they could kick the furthest with. Additionally, data were divided into 'forwards' and 'backs' based on the self-reported position that that individual athlete played most frequently. Raw data were entered into SAS software to produce group statistical characteristics including the median, inner-quartile range and range of the data. Traditional Box-plots with whiskers and frequency graphs were created to visually show the unbiased spread of the raw data as outliers are known to skew the mean and inflate the standard deviation.

### *Lower-extremity strength norms*

Isokinetic concentric and eccentric strength at the knee and concentric strength at the hip were assessed at  $60^{\circ}\cdot s^{-1}$  via a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA). Detailed methods are reported elsewhere [9].



Table 26. Normative raw data for knee and hip strength.

			Preferred		Non-preferred	
			Median (IQR)	Range	Median (IQR)	Range
Knee	Concentric extension (quadriceps)	Forwards	248 (205 – 285)	159 – 379	216 (199 – 239)	161 – 301
		Backs	222 (195 – 240)	158 – 285	211 (187 – 235)	126 – 352
	Concentric flexion (hamstrings)	Forwards	138 (122 – 146)	81 – 169	128 (109 – 133)	100 – 165
		Backs	112 (104 – 128)	99 – 138	121 (112 – 127)	81 – 197
	Eccentric flexion (quadriceps)	Forwards	239 (215 – 280)	194 – 329	241 (207 – 255)	143 – 317
		Backs	244 (178 – 290)	135 – 343	238 (204 – 258)	123 – 328
	Eccentric extension (hamstrings)	Forwards	161 (139 – 175)	105 – 216	141 (124 – 159)	85 – 215
		Backs	152 (122 – 173)	66 – 206	151 (126 – 159)	60 – 170
Hip	Concentric extension (glutes)	Forwards	316 (290 – 370)	196 – 551	320 (282 – 379)	199 – 477
		Backs	327 (261 – 370)	164 – 445	315 (271 – 375)	187 – 444
	Concentric flexion (hip flexors)	Forwards	165 (144 – 183)	127 – 249	179 (140 – 196)	122 – 232
		Backs	156 (144 – 189)	116 – 222	155 (137 – 176)	108 – 217

Footnote: Normative raw data for isokinetic strength at 60°·s<sup>-1</sup> at the knee and hip, presented as a newton-metre (N·m). Data are separated into the preferred and non-preferred legs and by forwards (n = 26) and backs (n = 26) Values are presented as the median (inner-quartile range [quartile 1 – quartile 3]) and the range of the population.

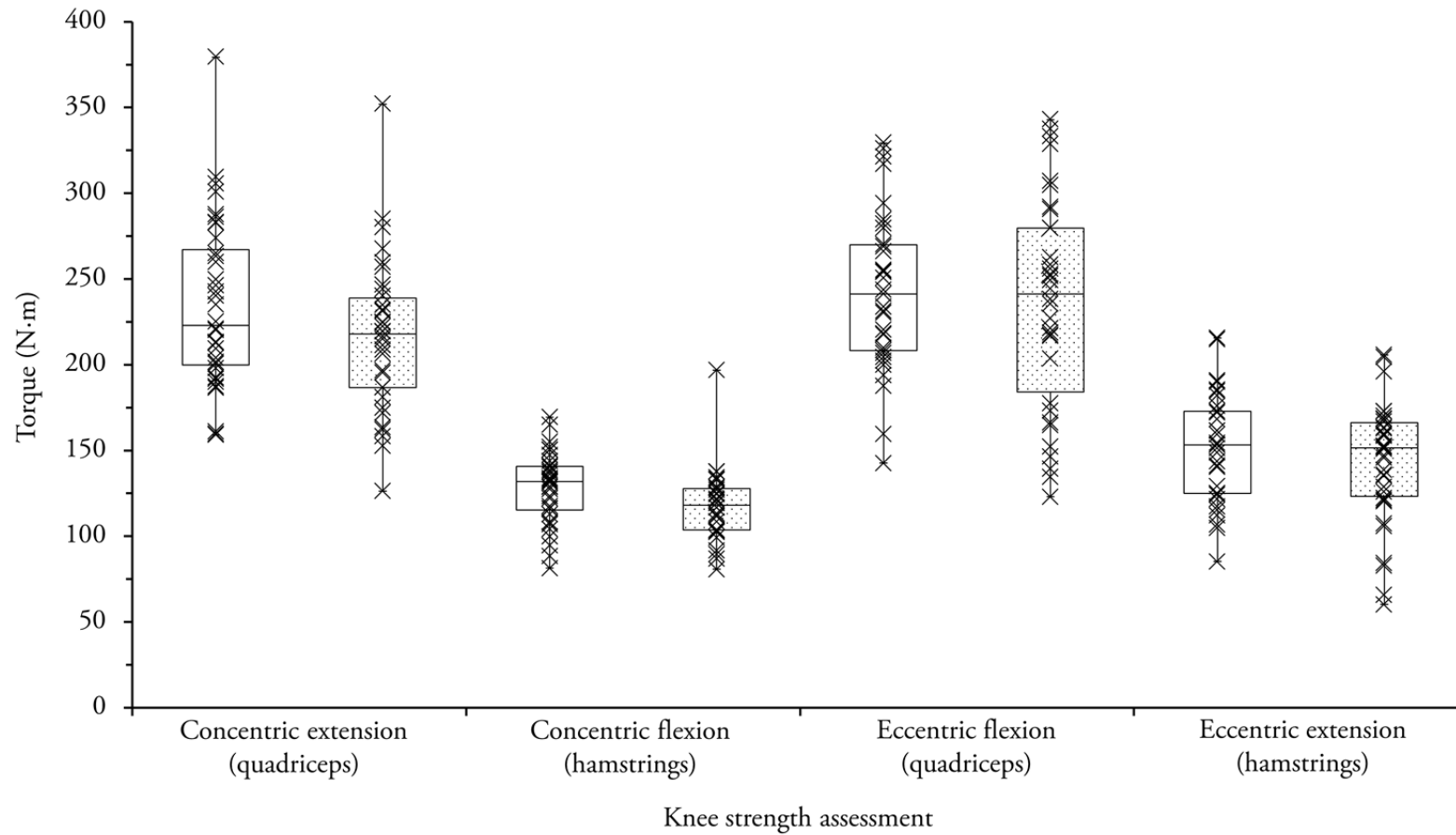
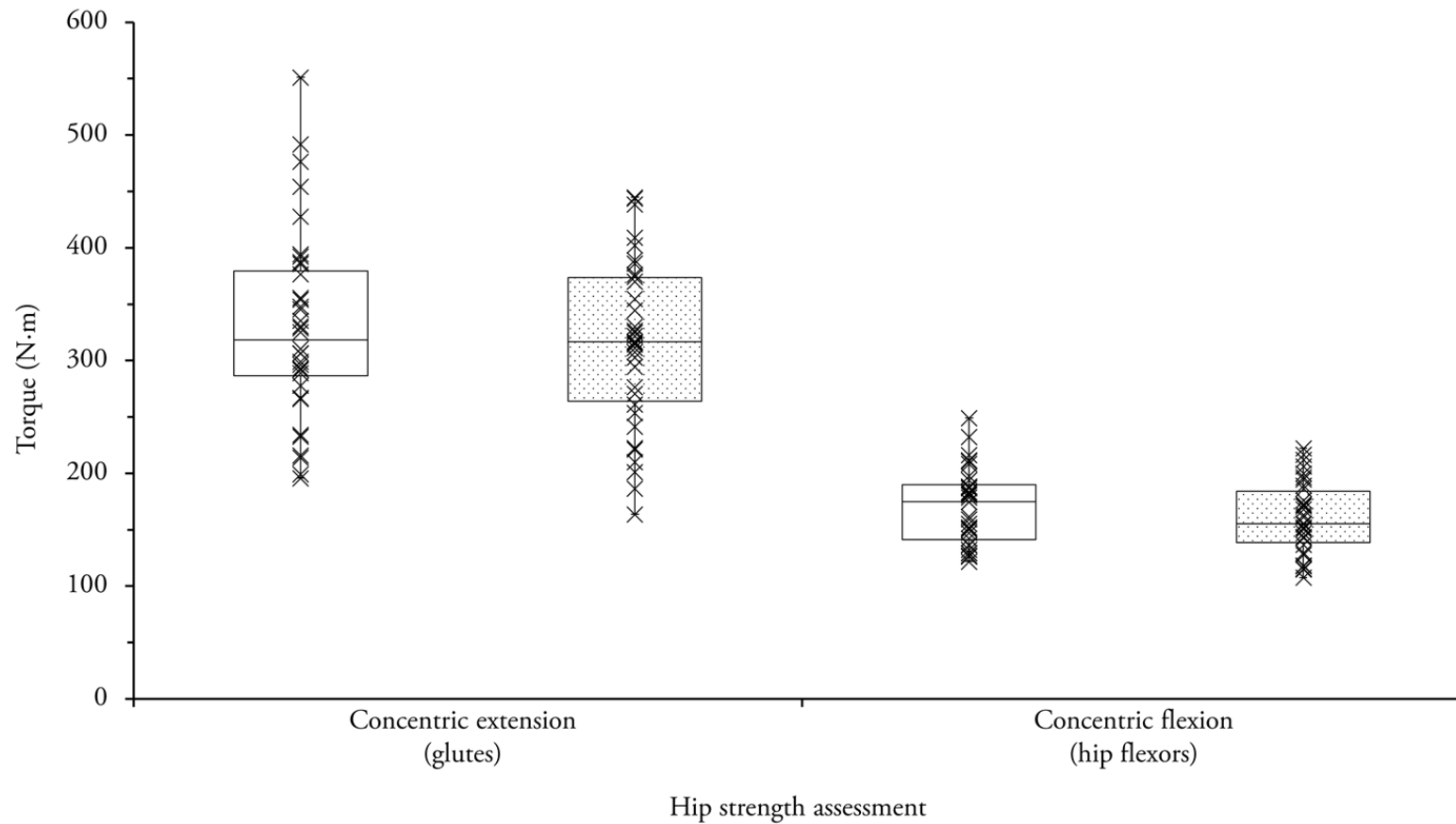


Figure 26. Normative raw data for knee strength.

Normative raw data for isokinetic strength at  $60^{\circ}\cdot s^{-1}$  at the knee, presented as a newton-metre (N·m). Data are combined with the preferred and non-preferred legs and separated by forwards (n = 26, samples = 52; white Box-plots) and backs (n = 26, samples = 52; dotted Box-plots). Xs represent individual athlete data within the Box-plots.



**Figure 27. Normative raw data for hip strength.**

Normative raw data for isokinetic strength at 60°·s<sup>-1</sup> at the hip, presented as a newton-metre (N·m). Data are combined with the preferred and non-preferred legs and separated by forwards (n = 26, samples = 52; white Box-plots) and backs (n = 26, samples = 52; dotted Box-plots). Xs represent individual athlete data within the Box-plots.

*Sprint kinetic norms*

Vertical and horizontal force ( $F_V$  and  $F_H$ , respectively) at acceleration and maximal velocity sprinting were assessed via a Woodway non-motorised instrumented treadmill (Force 3.0, Woodway USA, Inc., Waukesha, WI, USA). Detailed methods are reported elsewhere [233].

Table 27. Normative raw data for sprint kinetics.

			Preferred		Non-preferred	
			Median (IQR)	Range	Median (IQR)	Range
Acceleration	$F_V$	Forwards	22 (21 – 22)	19 – 23	20 (20 – 21)	18 – 25
		Backs	22 (19 – 23)	18 – 26	22 (20 – 23)	18 – 25
	$F_H$	Forwards	3.9 (3.5 – 4.7)	2.5 – 5.9	3.7 (3.2 – 3.9)	2.2 – 5.0
		Backs	4.0 (3.5 – 4.3)	2.8 – 5.1	3.9 (3.7 – 4.2)	3.2 – 4.6
Maximal velocity	$F_V$	Forwards	24 (23 – 25)	22 – 27	23 (22 – 24)	21 – 27
		Backs	22 (21 – 25)	19 – 29	23 (22 – 24)	19 – 28
	$F_H$	Forwards	3.2 (2.9 – 4.3)	2.4 – 5.7	3.1 (2.5 – 3.5)	1.9 – 3.9
		Backs	3.0 (2.8 – 3.3)	1.9 – 4.0	3.2 (3.0 – 3.5)	2.1 – 4.3

Footnote: Normative raw data for sprint kinetics at acceleration and maximal velocity, presented as a newton per kilogramme of body-mass ( $\text{N}\cdot\text{kg}^{-1}$ ). Data are separated into the preferred and non-preferred legs and by forwards ( $n = 26$ ) and backs ( $n = 26$ ). Values are presented as the median (inner-quartile range [quartile 1 – quartile 3]) and the range of the population.

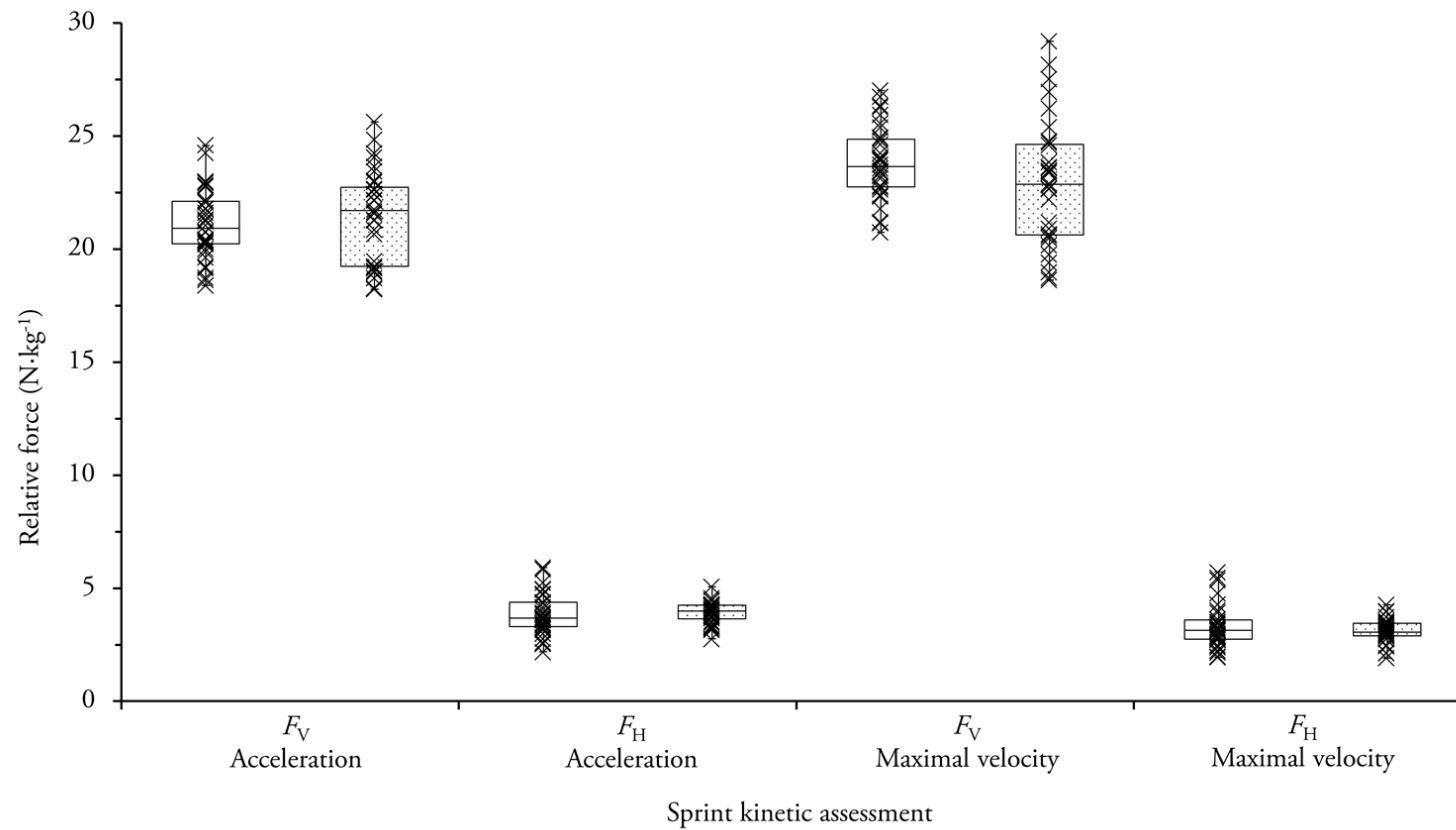


Figure 28. Normative raw data for sprint kinetics.

Normative raw data for sprint kinetics at acceleration and maximal velocity, presented as a newton per kilogramme of body-mass (N·kg<sup>-1</sup>). Data are combined with the preferred and non-preferred legs and separated by forwards ( $n = 26$ , samples = 52; white Box-plots) and backs ( $n = 26$ , samples = 52; dotted Box-plots). Xs represent individual athlete data within the Box-plots.

In addition to comparing an athlete with normative data, comparison between legs has also been shown to aid in the completeness of the athlete's status. Asymmetries found in strength and sprint kinetics for example, have been linked with asymmetries in ACL injury risk while sidestepping [281]. Researchers [9, 85, 105, 178, 182, 233, 291, 292] have found worthwhile differences between the legs in a number of laboratory assessments including (but not limited to) strength, balance, sprinting, hopping, landing, kicking and sidestepping. These differences have unfortunately been described in many different ways over the years, each with varying faults and limitations. To-date, only one equation measuring the difference between the legs has provided clinically relevant information in a sports science context whilst not requiring an arbitrary reference leg and is unaffected by artificial inflation by near-zero numbers [101-103]. This equation is known as the symmetry angle and it has been used to describe naturally occurring asymmetries in gait [96], running [111] and sprinting [101] activities over the past decade. However, similarly to the non-existent normative values in knee and hip strength or sprint kinetics, there are also no normative symmetry angle values in the literature that are unique to rugby.

### **What is normal in rugby? Normative symmetry values**

#### ***The symmetry angle***

Symmetry was calculated using a non-dimensional modified symmetry angle equation (Equation 5) [103] to report the absolute difference between the legs (preferred leg versus the non-preferred leg). The modified equation provides an absolute score between 0 – 100% describing the deviation of the observed relationship between the two legs from a theoretically perfect relationship [101-103]. A score of 0% indicates perfect symmetry and 100% indicates perfect asymmetry; aiding researchers and clinicians to make clinically important and relevant observations among a variety of assessments.

Symmetry angle scores were entered into SAS software to produce inner-quartile ranges. However, as symmetry scores can only range between 0 – 100% and very little is known regarding the most desired amount of symmetry, symmetry scores were broken-up into 25<sup>th</sup> percentile groups (similar to a Box-plot with whiskers) to describe a balanced four-section scale consisting of symmetrical, 0 – 25%; slightly symmetrical, > 25 – 50%; slightly asymmetrical, > 50 – 75%; and asymmetrical, > 75 – 100%. While this division has not been

used extensively before in research (especially in rugby research), the authors thought that it best suited the current data in providing useful information to guide our recommendations.

### *Lower-extremity strength symmetry norms*

An athlete's lower-extremity strength can reside within a range of values. However, an important factor that is commonly overlooked is whether the value of each leg is similar to one another. As with any population, a range is expected to exist which describes where each athlete sits on the continuum. Table 28 shows the knee and hip symmetry continuum, separated by playing position, by bracketing the athletes into four balanced sections consisting of 25% of the sample population. By looking at the sample population in this way, we are able to point-out new threshold values pertaining to unique assessments depending on the grouping that we are targeting. For instance, concentric knee  $ABS\theta_{SYM}$  for the forwards and backs were both relatively low percentages with  $< 2$ ,  $< 5$ ,  $< 8$  and  $< 16\%$  for 25, 50, 75 and 100% of the sample population, respectively. Eccentric knee  $ABS\theta_{SYM}$  however, was slightly different between forwards and backs; with forwards presenting almost double the  $ABS\theta_{SYM}$  across all percentages compared to the backs. These data show us that forwards may be experiencing unequal eccentric stimuli as a result of playing position. Perhaps the unilateral eccentric loading that is causing the larger  $ABS\theta_{SYM}$  occurs at the scrum, ruck and / or maul wherein large forces are generated and received by athlete.

Interestingly,  $ABS\theta_{SYM}$  were relatively low for the majority of forwards and backs with  $\sim 1$ ,  $< 3$ ,  $< 6$  for 25, 50 and 75% of the sample population, respectively. The upper 25% of just the forwards showed  $ABS\theta_{SYM}$  in concentric extension strength of  $\sim 11\%$  whereas the upper 25% of both forwards and backs showed  $ABS\theta_{SYM}$  in concentric flexion strength of  $\sim 11\%$ . These figures become important when trying to understand what normal symmetry looks like in rugby athletes and where important thresholds should reside.

When forwards and backs are combined (Figure 29),  $ABS\theta_{SYM}$  for the knee were  $< 3$ ,  $< 5$ ,  $< 8$  and  $< 18\%$  for 25, 50, 75 and 100%, respectively and  $\sim 1$ ,  $< 3$ ,  $< 5$  and  $< 11\%$  for 25, 50, 75 and 100%, respectively for the hip. With this information, we can say that 50% of the population have  $< 5\%$  knee  $ABS\theta_{SYM}$  and  $< 3\%$  hip  $ABS\theta_{SYM}$ . If these values then become the new thresholds, any athlete above these percentages (our upper 50% of the sample population) would need individual attention.

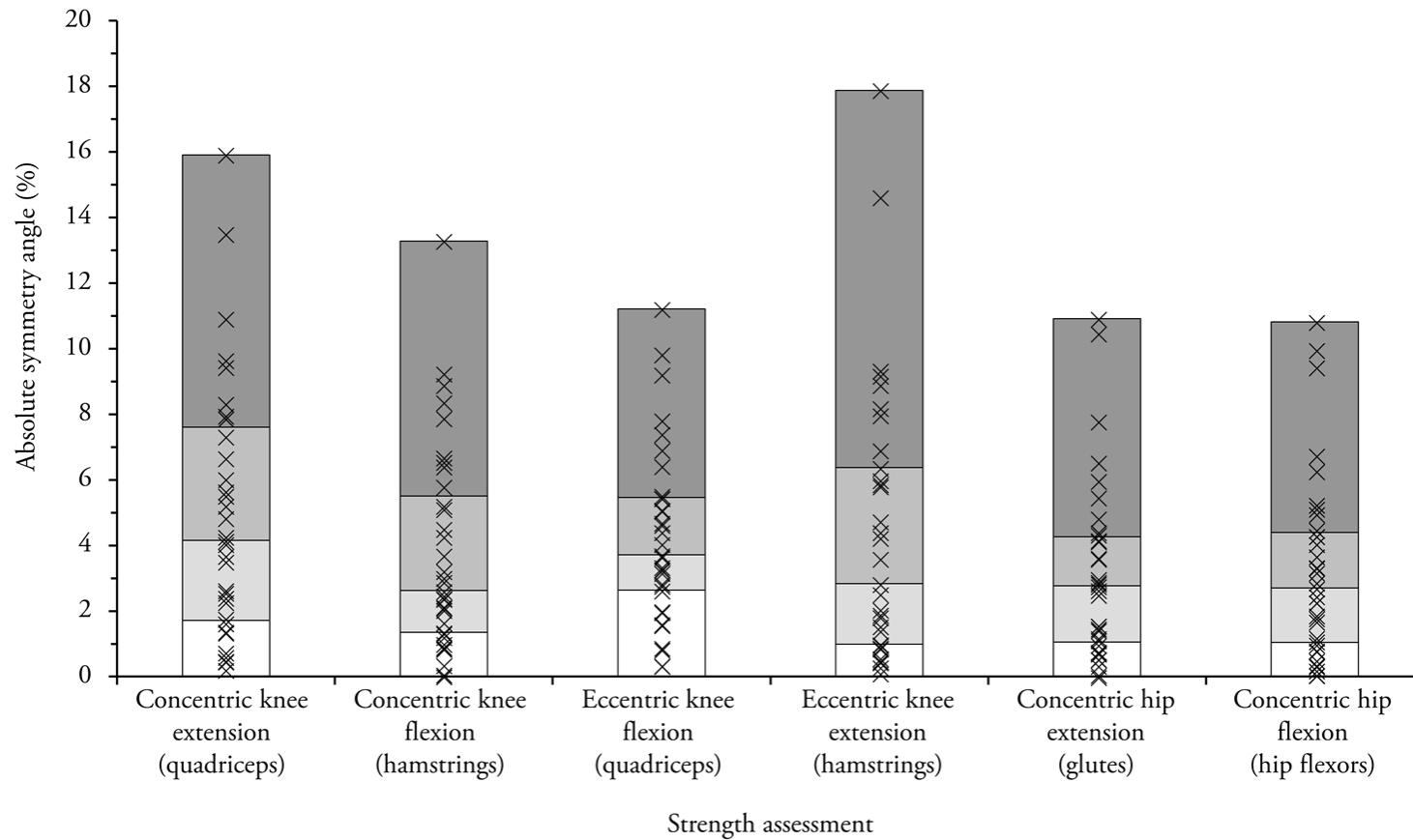


What's more interesting, yet still unknown, is whether these asymmetries are easily modifiable and whether the difficulty of modification changes among the brackets or among the athletes. For example, would an athlete that has a 5%  $ABS\theta_{SYM}$  in eccentric hamstring strength find the difficulty of dropping down to < 3% more than, less than or equal to an athlete with a 16%  $ABS\theta_{SYM}$ ? None-the-less, having normative  $ABS\theta_{SYM}$  in rugby athletes is a starting point to help answer these questions.

Table 28. Normative symmetry angle scores for knee and hip strength.

			Absolute symmetry angle (%)			
			Symmetrical (0 – 25%)	Slightly symmetrical (> 25 – 50%)	Slightly asymmetrical (> 50 – 75%)	Asymmetrical (> 75 – 100%)
Knee	Concentric extension (quadriceps)	Forwards	1.9	4.5	7.7	15.9
		Backs	1.6	4.1	6.7	10.9
	Concentric flexion (hamstrings)	Forwards	1.3	2.8	6.3	9.3
		Backs	1.4	2.4	5.1	13.3
	Eccentric flexion (quadriceps)	Forwards	2.9	4.9	7.0	11.2
		Backs	2.6	3.7	4.7	9.2
	Eccentric extension (hamstrings)	Forwards	1.7	4.6	7.4	17.9
		Backs	0.6	1.9	5.8	9.3
Hip	Concentric extension (glutes)	Forwards	0.9	2.8	5.9	10.9
		Backs	1.1	2.8	4.1	4.8
	Concentric flexion (hip flexors)	Forwards	1.1	3.0	5.1	10.8
		Backs	1.0	2.3	4.1	10.0

Footnote: Normative symmetry angle scores for isokinetic strength at  $60^{\circ}\cdot s^{-1}$  at the knee and hip, presented as a percentage (%). Data are separated into the preferred and non-preferred legs and by forwards ( $n = 26$ ) and backs ( $n = 26$ ). Values are presented as absolute symmetry angle scores within the four brackets of the population.



**Figure 29. Normative symmetry angle scores for knee and hip strength.**

Normative symmetry angle scores for isokinetic strength at  $60^{\circ}\cdot s^{-1}$  at the knee and hip, presented as a percentage (%). Data are combined forwards and backs ( $n = 52$ ). Xs represent individual athlete data.

### *Sprint kinetic symmetry norms*

Unlike the similar  $ABS\theta_{SYM}$  seen among the different muscles in lower-extremity strength assessments, sprint kinetic  $ABS\theta_{SYM}$  were shown to be quite unique to orientation; especially in  $F_H$  as seen in Table 29. During acceleration and maximal velocity sprinting,  $F_V$   $ABS\theta_{SYM}$  for the forwards and backs were very low at  $< 1.5$ ,  $< 2.1$ ,  $< 2.8$  and  $< 4.3\%$  for 25, 50, 75 and 100% of the population, respectively. However,  $F_H$  during acceleration (forwards:  $< 3.4$ ,  $< 6.3$ ,  $< 7.9$  and  $< 24\%$  and backs:  $< 2.3$ ,  $< 4.1$ ,  $< 8.8$  and  $< 11\%$ ) and maximal velocity (forwards:  $< 2.5$ ,  $< 4.4$ ,  $< 12$  and  $< 28\%$  and backs:  $< 2.4$ ,  $< 5.7$ ,  $< 9.2$  and  $< 24\%$ ) was quite different between positions.

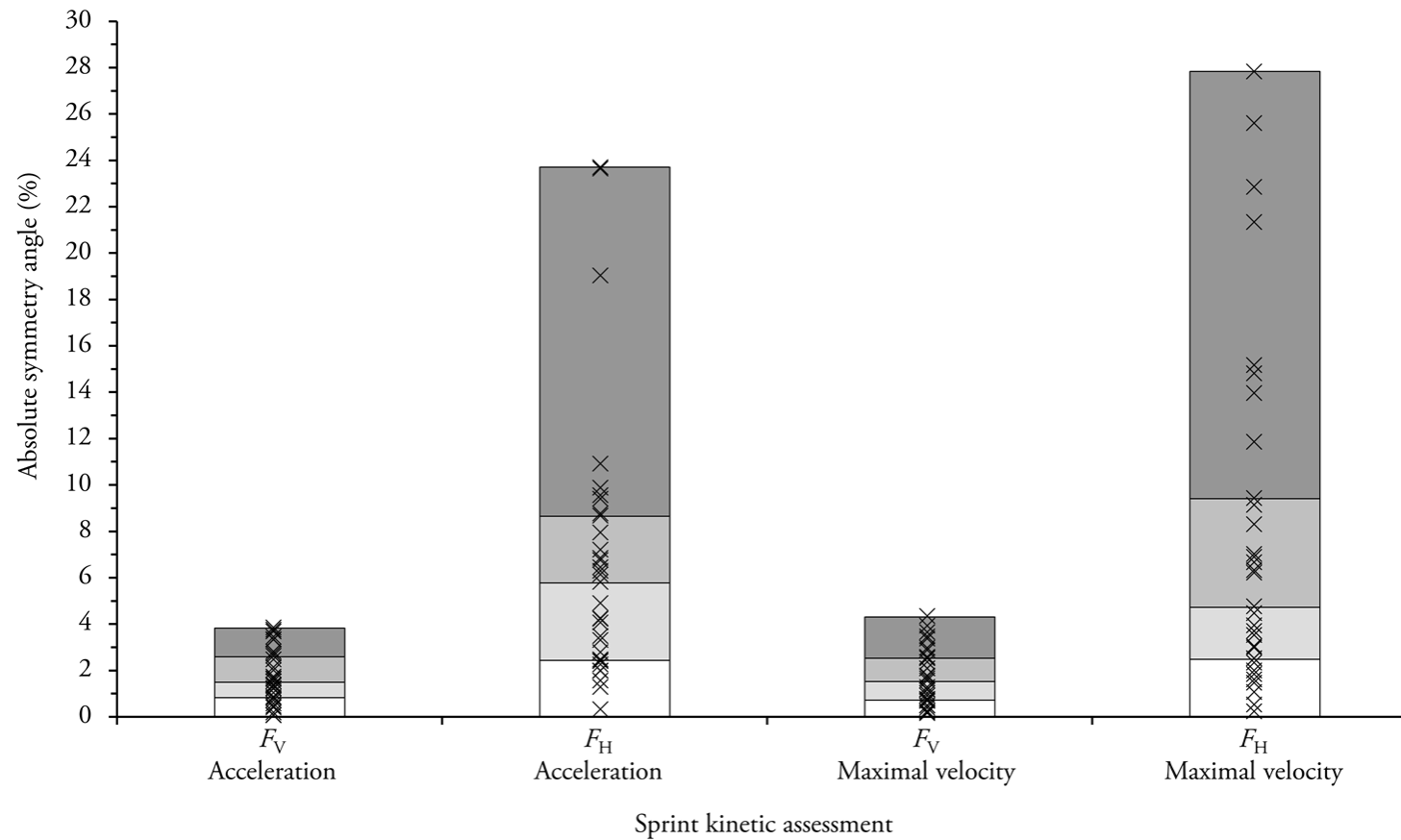
Again, when forwards and backs are combined (Figure 30),  $ABS\theta_{SYM}$  for  $F_V$  remain low ( $< 0.8$ ,  $< 1.5$ ,  $< 2.6$  and  $< 4.3\%$ ) for acceleration and maximal velocity whereas  $F_H$  are quite high ( $< 2.5$ ,  $< 5.8$ ,  $< 9.4$  and  $< 28\%$ ). Similarly to the lower-extremity strength  $ABS\theta_{SYM}$ , important thresholds can be seen in the data indicating that several athletes are far removed from the majority of others during acceleration and may potentially be at a greater risk of injury. During maximal velocity sprinting, even more athletes present large asymmetries in  $F_H$  where this is not the case in  $F_V$ .

These findings are somewhat expected when considering the mechanical contribution of the legs to sprint performance, wherein each leg can apply a distribution of  $F_V$  and  $F_H$  during ground contact. It appears that all athletes in this data set can produce somewhat symmetrical  $F_V$  during acceleration and maximal velocity sprinting as  $F_V$  is mainly determined by body-mass, vertical velocity at contact and mechanical stiffness. However some athletes may lack the technical ability to apply  $F_H$  in an effective manner (in at least one of the legs) [240]. Larger  $ABS\theta_{SYM}$  in  $F_H$  is suggested [233] to negatively affect global  $F_H$  and subsequent sprint performance [235] and has also been linked with larger  $ABS\theta_{SYM}$  in knee abduction moments [281].

Table 29. Normative symmetry angle scores for sprint kinetics.

			Absolute symmetry angle (%)			
			Symmetrical (0 – 25%)	Slightly symmetrical (> 25 – 50%)	Slightly asymmetrical (> 50 – 75%)	Asymmetrical (> 75 – 100%)
Acceleration	$F_V$	Forwards	1.3	2.1	2.8	3.8
		Backs	0.5	1.1	1.5	3.3
	$F_H$	Forwards	3.4	6.3	7.9	23.7
		Backs	2.3	4.1	8.8	10.9
Maximal velocity	$F_V$	Forwards	1.5	2.0	2.5	4.3
		Backs	0.7	0.9	1.6	3.6
	$F_H$	Forwards	2.5	4.4	11.8	27.8
		Backs	2.4	5.7	9.2	21.3

Footnote: Normative symmetry angle scores for sprint kinetics at acceleration and maximal velocity, presented as a percentage (%). Data are separated into the preferred and non-preferred legs and by forwards ( $n = 26$ ) and backs ( $n = 26$ ). Values are presented as absolute symmetry angle scores within the four brackets of the population.



**Figure 30. Normative symmetry angle scores for sprint kinetics.**

Normative symmetry angle scores for sprint kinetics at acceleration and maximal velocity, presented as a percentage (%). Data are combined forwards and backs ( $n = 52$ ). Xs represent individual athlete data.

Assessing symmetry in the lower-extremities is important as it has been linked to decreased performance [293] and increased risk of injury in a number of sports and tasks [112]. Assessment strategies are used to inform where an athlete lays within a continuum of a specific progression. In most cases, assessment strategies are called upon by medical staff to evaluate an athlete's injury risk status. When performed in the correct fashion, assessments can be objective and reliable; showing clear outcomes [98].

So what happens following an initial assessment, where the athlete has been compared with normative data and symmetry angle scores? In many cases, the answer is, “nothing”. The time following an assessment may well be the most important window for the athlete in terms of how they correct a deficit and / or decrease an asymmetry. For these purposes, individualised training has been recommended to provide advantageous results [98, 170, 294].

### **How can this model assist rugby athletes? Training for one or more**

#### ***Team training***

Generalised training programmes are most commonly found among larger team sports due to their ability to cater to many athletes. In most cases, a strength and conditioning coach can design a single programme to administer to the entire team (or at least divided by general playing position; i.e. forwards and backs in rugby). Throughout the programme, the strength and conditioning staff will know where every athlete is relative to the training progression (i.e. strength, speed, power, etc.) and can assist as need. Additionally, larger groups of athletes are able to train in sub-groups as all will have the same exercises with one of the minor setbacks being the potential for having different loads. This system is most commonly utilised in American football programmes with up to 100 athletes during the off-season receiving the same programme.

Generalised training programmes often overlook individual deficiencies in strength or technique due to the large number of athletes they cater to. As an example using a typical American football team, the weakness of the few will be overshadowed by the gains of the many. Or in some cases, the athletes starting with a ‘slight asymmetry’ may negatively develop into an ‘asymmetry’ and further increase the issues with improper muscle compensations or poor technique.

### *Individualised training*

Individual training targets an athlete's weakness with the hopes of decreasing the potential risks of injury. Brughelli et al. [172] assessed an athlete's isokinetic strength following a third right hamstring muscle strain and found a very large angle of peak torque of  $46^\circ$  and a major asymmetry in  $F_H$  during sprinting (non-published data). The athlete was given a training intervention of eccentric exercises to improve the angle of peak torque to a longer muscle length. Improvements were found in as little as one week and continued through the 32-week intervention. By the end of the intervention the angle of peak flexion torque in the right hamstring decreased by 66% and the between leg asymmetry of angle of peak torque decreased from 53% to 16%. Additionally, small improvements (5%) were made in the angle of peak extension torque in the right and left legs.

Another example of the benefits of individualised training is the work by Croisier et al. [112] examining 462 professional footballers with isokinetic measures. Just over half (246 footballers; 53%) were found to have "normal" preseason isokinetic profiles while the remaining 47% (216 footballers) were identified with substantial strength disorders during preseason. The footballers identified with strength disorders were grouped into three subsets: no specific compensating training, specific compensating training without verifying normalisation and compensating training with parameter normalisation. Following the season, ten hamstring injuries were noted in the "normal" group (4.1% injury frequency). Interestingly, the group that performed subsequent compensating training until the parameter was normalised had an injury rate of 5.7% whereas the group that performed compensating training without verifying normalisation had an injury frequency of 11%. The group that did no compensating training had an injury frequency of 16.5%. The authors concluded that footballers with untreated strength imbalances were 4 to 5 times more likely to sustain a hamstring injury when compared to a "normal" strength profile. The authors recommended the use of specific training following isokinetic assessments to identify and address any preseason muscle imbalances and / or dysfunction in muscle performance.

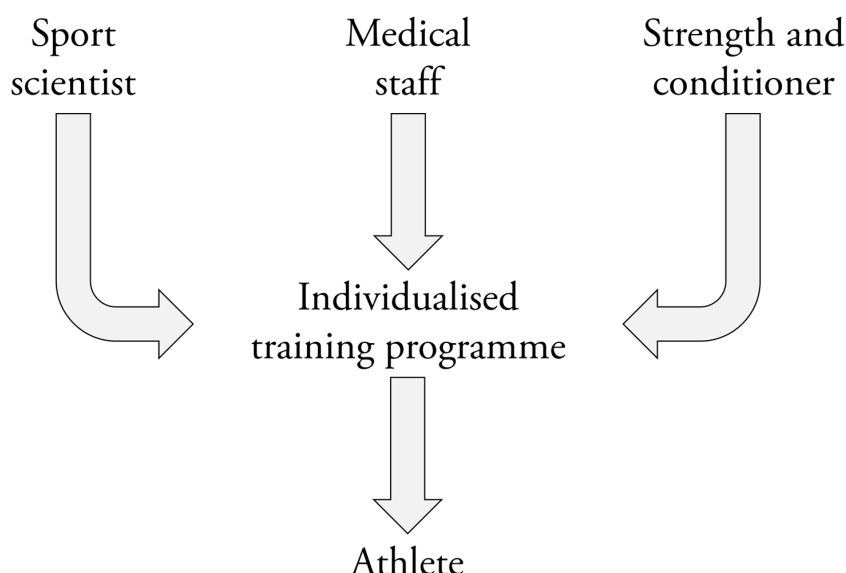
Individualised training does possess several inherent difficulties that have yet to be rectified in a practical setting. Similar to the multi-component assessment strategy, individualised programming takes personnel, time and knowledge. Firstly, in most instances, individualised programming requires more than a single strength and conditioning coach. Rather, effective



programming requires the collaborative minds of a physiotherapist, medical doctor (or similar), sport scientist and a strength and conditioner (Figure 31). The sport scientist would assess an athlete or athletes and determine the areas that need individual attention. They would translate this information to the medical staff whom would decide which exercises were most appropriate and would yield the greatest effect. The preferred exercises would be recommended to the strength and conditioning coach whom would then create a practical training schedule moulded around the available time in the athlete's schedule while not interfering with field-training, watching match footage, attending meetings, etc.

Secondly, this system takes time to work through. While the turn-around on assessment data can be rapid, the interpretation and translation to the medical staff may take hours or days. Once left with the medical personnel, deciding upon the most appropriate exercise actions to take may take some time; especially if the decisions are evidence-based and require multiple readings through academic journals. Finally, the ease of writing a few training programmes to cater to the many would not be present. The strength and conditioning coach would need to write, explain and coach individual programmes based on the recommendations from the medical staff. The difficulty of this process increases with the number of athletes in general and grows with the number of athletes with discrepancies that need attention.

Lastly, a certain degree of knowledge should be required in this programming loop; that is, everyone involved should be following evidence-based recommendations as closely as possible during the assessments, exercise prescription and exercise training. Sports science has evolved so much over the past decade that simply "winging-it" is just not good enough. A high level of thought should be put into the process to attend to academic rigor and practicality.



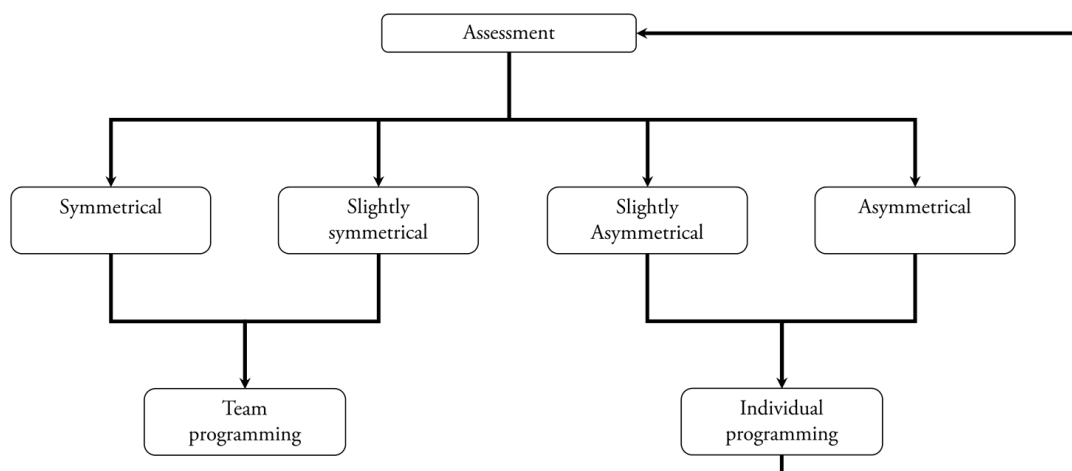
**Figure 31. Proposed collective contribution of rugby staff.**

Recent evidence [98, 177] suggests that multi-component assessment strategies provide a translucent picture of the athlete wherein interactions exist between legs, joints and muscles. At the moment, ideas relating to lower-extremity assessments and how they are linked with increased ACL injury risk is non-substantial [281, 295]. A well-established framework is also missing from the literature to illustrate the possible course of action moving forward in assessing rugby athletes.

### **How can I put this model into action?**

Similar to the frameworks [114, 118, 296] that have come before this commentary, the Preliminary Rugby Evaluation for Programming (PREP) Framework was established to use the most useful information mentioned above in a collective fashion to aid in minimising lower-extremity deficits and asymmetries. The major difference resides in the timing of the assessment; which should occur *before* an injury occurs and not *after*; if it can be helped. The premise of this framework is: (1) assess a group of athletes, preferably a team, during the off- or pre-season for any asymmetries using a multi-component strategy; (2) the athletes with ‘symmetrical’ or ‘slightly symmetrical’ differences between the legs are permitted to return-to-sport under a generalised training regime provided by the staff, the athletes with ‘slightly asymmetrical’ or ‘asymmetrical’ differences proceed to an individualised training programme aimed at improving the deficits and / or asymmetries to within a ‘normal’ range; (3) reassess the athletes that were found to possess deficits to determine if the targeted training was successful or if an altered / new individualised training programme needs to occur; (4)

continue to monitor and reassess the athletes as necessary. An easy to follow schematic of the PREP Framework is illustrated in Figure 32.



**Figure 32. Preliminary Rugby Evaluation for Programming Framework.**

The PREP Framework is our research team’s latest attempt to assess the risk of injury in rugby athletes by targeting important deficits potentially unseen by a coach’s eye or by a single-component assessment and working towards fixing them. This framework is not a means to predict or completely prevent injury, especially in contact sports like rugby. As such, injuries specific to the sport will occur. In these cases, quantifiable and vital baseline data will have been collected on the athlete at which the team’s medical personnel can then use, in addition to post-injury return-to-sport algorithms, to best guide the athlete to a safe and prolonged return to the playing field. Additionally, similar playing position and team norms can be used as benchmarks to aid in this process. Finally, athletes at lower levels of play or academy teams can be directed by these position or team norms in an attempt to “reach the next level” and to make a more “well-rounded” athlete.

Little to no research using this framework has been implemented in the literature. Therefore, the next logical step in the progression of implementing the PREP Framework is to assess it in the real-world through detailed individual and team case studies and eventually through well designed randomised controlled trials. This research will help determine which assessment components are best suited for specific sports as well as improve our understanding of lower-extremity asymmetries and deficits.

### ***Limitations***

It should be noted that the thoughts generated in this commentary were lacking several major components of return-to-sport. Additional components that should be included in return-to-sport decisions consist of games per week, traveling, load management, fatigue and most importantly sport psychology. While our group wholeheartedly subscribes to the importance of laboratory assessments and the comparison of quantitative outcomes, we have not forgotten the value of qualitative measures that are not so black and white such as competency, autonomy and relatedness [297]. It is recommended that the PREP framework be used in conjunction with a sports psychologist or councillor, when available, in returning an athlete to sport following an injury.

## Chapter 10: Summary and Conclusions

The aim of the PhD research was to answer the question, “Does lower-extremity symmetry matter for anterior cruciate ligament injury risk in male rugby union athletes?” To answer this question, it was necessary to first address how ACL injury occurs, how prevalent sidestepping is in rugby, the mechanical components of the sidestep and the best methods to calculate symmetry. An extensive review of the literature and synthesis of results (Chapters 1 and 2) led to the findings that: (1) rugby is the most played contact sport in the world, (2) rugby incurs a lot of injuries, specifically to the ACL, (3) ACL injury occurs during the weight acceptance phase of sidestepping, (4) sidestepping is a very common manoeuvre in rugby, (5) sidestepping requires elements of strength, balance and sprint kinetics, and (6) asymmetries in these elements have been independently linked with increased ACL injury risk. A theoretical model was then formulated based on the characteristics of the sidestep manoeuvre and how ACL injury occurs during the weight acceptance phase. The model incorporated components of strength, balance and sprint kinetics assessed on each leg and taking into consideration playing position (forwards and backs).

A group of rugby athletes was then profiled for the elements identified for the theoretical model through cross-sectional studies. Information pertaining to leg differences and player position between was provided for strength (Chapter 3), balance (Chapter 4), sprint kinetics (Chapters 5 and 6) and sidestepping (Chapter 7). Substantial differences between the legs were present in many of the measures used. The non-preferred leg generally: (1) was weaker in strength, (2) had worse single-leg balance, (3) produced less force during sprinting, and (4) displayed a greater theoretical risk of ACL injury during sidestepping compared to the preferred leg. Additionally, backs tended to: (1) be weaker in strength, (2) have better single-leg balance, (3) produce more force during sprinting and sprint faster, and (4) possess less asymmetries across all measures compared to the forwards. The cross-sectional studies drew our attention to the non-preferred leg of forwards potentially being at a greater risk of injury.

To better understand the potential link between these assessments and injury risk, a regression model (Chapter 8) was formulated to determine whether each leg was influenced by strength, balance and sprint kinetics to the same degree or if they were unique from one another. The model showed that injury risk for: (1) the preferred leg was explained by gluteal strength and vertical force production during sprinting, and (2) the non-preferred leg was

explained by hip flexors and vertical force production during sprinting. Additionally, larger the asymmetries in horizontal force production during sprinting and eccentric quadriceps strength explained larger the asymmetries in ACL injury risk. While these findings are not causative, there is some initial evidence that each leg contributes to increased ACL injury risk via unique distributions of strength and / or sprint kinetics. These findings indicate there should be focus on weak posterior muscular strength as a primary factor needing attention for ACL injury risk reduction.

The general discussion in Chapter 9 provided: (1) normative strength and sprint kinetic data, (2) normative symmetry scores, (3) pros and cons of assessment components and training recommendations, and (4) a new framework to use with rugby athletes in future ACL injury assessments. The review of thesis findings suggests that levels of symmetry vary substantially from athlete to athlete and from measure to measure.

So does lower-extremity symmetry matter for anterior cruciate ligament injury risk in male rugby union athletes? The answer based on the evidence presented in this thesis is yes. Asymmetries in strength and sprint kinetics do potentially have an effect on increasing the risk of ACL injury in rugby athletes. While balance has previously been linked to increased risk of injury, this relationship was not supported in this thesis.

## References

1. Year in Review 2014. 2015 ed: World Rugby at;; 2014. p. <http://www.worldrugby.org/documents/annual-reports>.
2. Year in Review 2015. 2016 ed: World Rugby at;; 2015. p. <http://publications.worldrugby.org/yearinreview2015/en/1-1>.
3. Quarrie KL, Handcock P, Toomey MJ, Waller AE. The New Zealand rugby injury and performance project. IV. Anthropometric and physical performance comparisons between positional categories of senior A rugby players. *Br J Sports Med*. 1996;30(1):53-6.
4. Gabbett TJ. Incidence of injury in semi-professional rugby league players. *Br J Sports Med*. 2003;37(1):36-43.
5. Scott AC, Roe N, Coats AJS, Piepoli MF. Aerobic exercise physiology in a professional rugby union team. *Int J Cardiol*. 2003;87(2-3):173-7.
6. Bathgate A, Best JP, Craig G, Jamieson M. A prospective study of injuries to elite Australian rugby union players. *Br J Sports Med*. 2002;36(4):265-9.
7. Duthie GM, Pyne DB, Marsh DJ, Hooper SL. Sprint patterns in rugby union players during competition. *J Strength Cond Res*. 2006;20(1):208-14.
8. Sedeaud A, Marc A, Schipman J, Tafflet M, Hager J-P, Toussaint J-F. How they won Rugby World Cup through height, mass and collective experience. *Br J Sports Med*. 2012;46(8):580-4.
9. Brown SR, Brughelli M, Bridgeman LA. Profiling isokinetic strength by leg preference and position in rugby union athletes. *Int J Sports Physiol Perform*. 2016;11(4):500-7.
10. Quarrie KL, Hopkins WG, Anthony MJ, Gill ND. Positional demands of international rugby union: Evaluation of player actions and movements. *J Sci Med Sport*. 2013;16(4):353-9.
11. Jones NMP, Mellalieu SD, James N. Team performance indicators as a function of winning and losing in rugby union. *Int J Perform Anal Sport*. 2004;4(1):61-71.
12. Fuller CW, Molloy MG, Bagate C, Bahr R, Brooks JHM, Donson H, et al. Consensus statement on injury definitions and data collection procedures for studies of injuries in rugby. *Br J Sports Med*. 2007;41(5):862-7.
13. Ball S, Halaki M, Orr R. Training volume and soft tissue injury in professional and non-professional rugby union players: A systematic review. *Br J Sports Med*. 2016:[in press].
14. Kaux J-F, Julia M, Delvaux F, Croisier J-L, Forthomme B, Monnot D, et al. Epidemiological review of injuries in rugby union. *Sci Period Res Tech Sport*. 2015;3(1):21-9.
15. Williams S, Trewartha G, Kemp S, Stokes K. A meta-analysis of injuries in senior men's professional rugby union. *Sports Med*. 2013;43(10):1043-55.
16. Bird YN, Waller AE, Marshall SW, Alsop JC, Chalmers DJ, Gerrard DF. The New Zealand Rugby injury and Performance Project: V. Epidemiology of a season of rugby injury. *Br J Sports Med*. 1998;32(4):319-25.
17. Garraway M, Macleod D. Epidemiology of rugby football injuries. *Lancet*. 1995;345(8963):1485-7.
18. Fuller CW, Brooks JHM, Cancea RJ, Hall J, Kemp SPT. Contact events in rugby union and their propensity to cause injury. *Br J Sports Med*. 2007;41(12):862-7.
19. Brooks JHM, Kemp SPT. Recent trends in rugby union injuries. *Clin Sports Med*. 2008;27(1):51-73.
20. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: Part 1 match injuries. *Br J Sports Med*. 2005;39(10):757-66.
21. Kaplan KM, Goodwillie A, Strauss EJ, Rosen JE. Rugby injuries: A review of concepts and current literature. *Bull NYU Hosp Jt Dis*. 2008;66(2):86-93.
22. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. *Am J Sports Med*. 2005;33(4):524-30.
23. Seward H, Orchard J, Hazard H, Collinson D. Football injuries in Australia at the elite level. *Med J Aust*. 1993;159(5):298-301.

24. King DA, Hume PA, Milburn P, Gianotti S. Rugby league injuries in New Zealand: A review of 8 years of Accident Compensation Corporation injury entitlement claims and costs. *Br J Sports Med.* 2009;43(8):595-602.
25. Turner AP, Barlow JH, Heathcote-Elliott C. Long term health impact of playing professional football in the United Kingdom. *Br J Sports Med.* 2000;34(5):332-6.
26. Gianotti SM, Marshall SW, Hume PA, Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *J Sci Med Sport.* 2009;12(6):622-7.
27. Agel J, Evans TA, Dick R, Putukian M, Marshall SW. Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train.* 2007;42(2):270-7.
28. Anderson SJ, Griesemer BA, Johnson MD, Martin TJ, McLain LG, Rowland TW, et al. Injuries in youth soccer: A subject review. *Pediatrics.* 2000;105(3):659-61.
29. Árnason Á, Gudmundsson Á, Dahl HA, Jóhannsson E. Soccer injuries in Iceland. *Scand J Med Sci Sports.* 1996;6(1):40-5.
30. Dick R, Putukian M, Agel J, Evans TA, Marshall SW. Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train.* 2007;42(2):278-85.
31. Dallalana RJ, Brooks JHM, Kemp SPT, Williams AM. The epidemiology of knee injuries in English professional rugby union. *Am J Sports Med.* 2007;35(5):818-30.
32. Donnelly CJ, Elliott BC, Ackland TR, Doyle TLA, Besier TF, Finch CF, et al. An anterior cruciate ligament injury prevention framework: Incorporating the recent evidence. *Res Sports Med: Int J.* 2012;20(3-4):239-62.
33. Cochrane JL, Lloyd DG, Buttfield A, Seward H, McGivern J. Characteristics of anterior cruciate ligament injuries in Australian football. *J Sci Med Sport.* 2007;10(2):96-104.
34. Silvers HJ. Play at your own risk: Sport, the injury epidemic, and ACL injury prevention in female athletes. *J Intercolleg Sport.* 2009;2(1):81-98.
35. Hutson MA. *Sports Injuries: Recognition and Management.* Third ed. Oxford, UK: Oxford University Press; 2001.
36. Kennedy JC, Hawkins RJ, Willis RB, Danylchuck KD. Tension studies of human knee ligaments: Yield point, ultimate failure, and disruption of the cruciate and tibial collateral ligaments. *J Bone Joint Surg Am.* 1976;58(3):350-5.
37. Norwood Jr LA, Cross MJ. The intercondylar shelf and the anterior cruciate ligament. *Am J Sports Med.* 1977;5(4):171-6.
38. Blackburn TA, Craig E. Knee anatomy: A brief review. *Phys Ther.* 1980;60(12):1556-60.
39. Starkey C, Brown SD. *Examination of Orthopedic & Athletic Injuries.* Fourth ed. Philadelphia, PA: F.A. Davis Company; 2015.
40. Fu FH, Harner CD, Johnson DL, Miller MD, Woo SLY. Biomechanics of knee ligaments: Basic concepts and clinical application. *J Bone Joint Surg Am.* 1993;75(11):1716-27.
41. Ryder SH, Johnson RJ, Beynnon BD, Ettlinger CF. Prevention of ACL injuries. *J Sport Rehabil.* 1997;6(2):80-96.
42. Norris CM. *Sports Injuries: Diagnosis and Management.* Third ed. Oxford, UK: Butterworth Heinemann; 2004.
43. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-29.
44. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, et al. Mechanisms for noncontact anterior cruciate ligament injuries. *Am J Sports Med.* 2010 November 1, 2010;38(11):2218-25.
45. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med.* 2007;41(Suppl 1):i47-i51.



46. Boden BP, Sheehan FT, Torg JS, Hewett TE. Non-contact ACL injuries: Mechanisms and risk factors. *J Am Acad Orthop Surg.* 2010;18(9):520-7.
47. Crichton KJ. Common Knee Problems in Sport: Their Assessment, Management and Prevention: Australian Sports Medicine Federation and Syntex Australia Limited; 1989.
48. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930-5.
49. McLean SG, Huang X, Su A, van den Bogert AJ. Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech.* 2004;19(8):828-38.
50. Andrews JR, McLead WD, Ward T, Howard K. The cutting mechanism. *Am J Sports Med.* 1977;5(3):111-21.
51. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: Potential for injury in women. *Med Sci Sports Exerc.* 1999;31(7):959-68.
52. McLean SG, Myers PT, Neal RJ, Walters MR. A quantitative analysis of knee joint kinematics during the sidestep cutting maneuver. Implications for non-contact anterior cruciate ligament injury. *Bull Hosp Joint Dis.* 1998;57(1):30-8.
53. Cross MJ, Gibbs NJ, Bryant GJ. An analysis of the sidestep cutting manoeuvre. *Am J Sports Med.* 1989;17(3):363-6.
54. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc.* 2001;33(7):1168-75.
55. Woo SL-Y, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex: The effects of specimen age and orientation. *Am J Sports Med.* 1991 June 1, 1991;19(3):217-25.
56. Van den Bogert AJ, McLean SG. Keynote address I. ACL injuries: Do we know the mechanisms? *J Orthop Sports Phys Ther.* 2007;37(2):A8-A9.
57. Olsen O-E, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *Am J Sports Med.* 2004;32(4):1002-12.
58. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, et al. Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *Am J Sports Med.* 2007;35(3):359-67.
59. Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: Abnormalities in hip and ankle kinematics. *Am J Sports Med.* 2009;37(2):252-9.
60. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med.* 2009;43(6):417-22.
61. Boden BP, Dean GS, Feagin Jr JA, Garrett Jr WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-8.
62. Cachupe WJC, Shifflett B, Kahanov L, Wughalter EH. Reliability of Biodex Balance System measures. *Meas Phys Educ Exerc Sci.* 2001;5(2):97-108.
63. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clin Biomech.* 2005;20(8):863-70.
64. McNair PJ, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J.* 1990;103(901):537-9.
65. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: The long-term functional disability in athletically active individuals. *J Bone Joint Surg Am.* 1983;65(2):154-62.
66. Brophy RH, Silvers HJ, Gonzales T, Mandelbaum BR. Gender influences: The role of leg dominance in ACL injury among soccer players. *Br J Sports Med.* 2010;44(10):694-7.
67. Ferretti A, Papandrea P, Conteduca F, Mariani PP. Knee ligament injuries in volleyball players. *Am J Sports Med.* 1992;20(2):203-7.

68. Faunø P, Jakobsen BW. Mechanism of anterior cruciate ligament injuries in soccer. *Int J Sports Med.* 2006;27(1):75-9.
69. Feagin Jr JA, Lambert KL. Mechanism of injury and pathology of anterior cruciate ligament injuries. *Orthop Clin North Am.* 1985;16(1):41-5.
70. Boden BP, Griffin LY, Garrett WE, Jr. Etiology and prevention of noncontact ACL injury. *Physician Sportsmed.* 2000;28(4):53-60.
71. Kimura Y, Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, Toh S. Mechanisms for anterior cruciate ligament injuries in badminton. *Br J Sports Med.* 2010;44(15):1124-7.
72. Cahill N, Lamb K, Worsfold P, Headey R, Murray S. The movement characteristics of English Premiership rugby union players. *J Sports Sci.* 2013;31(3):229-37.
73. Suárez-Arrones LJ, Portillo LJ, González-Ravé JM, Muñoz VE, Sanchez F. Match running performance in Spanish elite male rugby union using global positioning system. *Isokinet Exerc Sci.* 2012;20(2):77-83.
74. Vanrenterghem J, Venables E, Pataky T, Robinson MA. The effect of running speed on knee mechanical loading in females during side cutting. *J Biomech.* 2012;45(14):2444-9.
75. Brown SR, Brughelli M, Hume PA. Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. *Sports Med.* 2014;44(11):1573-88.
76. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech.* 2006;21(1):41-8.
77. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading. *Am J Sports Med.* 2009;37(11):2194-200.
78. Imwalle LE, Myer GD, Ford KR, Hewett TE. Relationship between hip and knee kinematics in athletic women during cutting maneuvers: A possible link to noncontact anterior cruciate ligament injury and prevention. *J Strength Cond Res.* 2009;23(8):2223-30.
79. Besier TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc.* 2001;33(7):1176-81.
80. Kaila R. Influence of modern studded and bladed soccer boots and sidestep cutting on knee loading during match play conditions. *Am J Sports Med.* 2007;35(9):1528-36.
81. Cochrane JL, Lloyd DG, Besier TF, Elliott BC, Doyle TLA, Ackland TR. Training affects knee kinematics and kinetics in cutting maneuvers in sport. *Med Sci Sports Exerc.* 2010;42(8):1535-44.
82. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. *Med Sci Sports Exerc.* 2007;39(10):1765-73.
83. Donnelly CJ, Elliott BC, Doyle TLA, Finch CF, Dempsey AR, Lloyd DG. Changes in knee joint biomechanics following balance and technique training and a season of Australian football. *Br J Sports Med.* 2012 Oct;46(13):917-22.
84. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc.* 2003;35(1):119-27.
85. Maulder PS, Bradshaw EJ, Hume PA. Dominant limb asymmetry greater than 10% during unanticipated agility performance is associated with prospective injury occurrence. *New Zealand Sports Medicine and Science Conference.* Wellington, NZL; 2010.
86. Shultz SJ, Schmitz RJ, Benjaminse A, Collins M, Ford K, Kulas AS. ACL Research Retreat VII: An update on anterior cruciate ligament injury risk factor identification, screening, and prevention. March 19-21, 2015; Greensboro, NC. *J Athl Train.* 2015;50(10):1076-93.
87. Faude O, Junge A, Kindermann W, Dvorak J. Risk factors for injuries in elite female soccer players. *Br J Sports Med.* 2006;40(9):785-90.
88. Matava MJ, Freehill AK, Grutzner S, Shannon W. Limb dominance as a potential etiologic factor in noncontact anterior cruciate ligament tears. *J Knee Surg.* 2002;15(1):11-6.
89. Negrete RJ, Schick EA, Cooper JP. Lower-limb dominance as a possible etiologic factor in noncontact anterior cruciate ligament tears. *J Strength Cond Res.* 2007;21(1):270-3.
90. Hart NH, Nimphius S, Weber J, Spiteri T, Rantalainen T, Dobbins M, et al. Musculoskeletal asymmetry in football athletes: A product of limb function over time. *Med Sci Sports Exerc.* 2016:[in press].

91. Hewett TE, Myer GD. Reducing knee and anterior cruciate ligament injuries among female athletes. A systematic review of neuromuscular training interventions. *J Knee Surg.* 2005;18(1):82-8.
92. Coughlan GF, Delahunt E, O'Sullivan E, Fullam K, Green BS, Caulfield BM. Star excursion balance test performance and application in elite junior rugby union players. *Phys Ther Sport.* 2014;15(4):249-53.
93. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311-9.
94. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Surg Am.* 2012;94(9):769-76.
95. Myklebust G, Steffen K. Anterior cruciate ligament injuries: Prevention strategies. *Sports Injuries.* 2015.
96. Herzog W, Nigg BM, Read LJ, Olsson E. Asymmetries in ground reaction force patterns in normal human gait. *Med Sci Sports Exerc.* 1989;21(1):110-4.
97. Brughelli M, Cronin J, Mendiguchia J, Kinsella D, Nosaka K. Contralateral leg deficits in kinetic and kinematic variables during running in Australian rules football players with previous hamstring injuries. *J Strength Cond Res.* 2010;24(9):2539-44.
98. Brown SR, Brughelli M. Determining return-to-sport status with a multi-component assessment strategy: A case study in rugby. *Phys Ther Sport.* 2014;15(3):211-5.
99. Hodt-Billington C. Measures of symmetry in gait: Methodological principles and clinical choices: University of Bergen; 2012.
100. Big Count 2006: Statistical Summary Report by Association. 2007 ed: Fédération Internationale de Football Association (FIFA); 2007. p. <http://www.fifa.com/mm/document/fifafacts/bcoffsurv/statsumrepassoc%5f10342.pdf>.
101. Exell TA, Gittoes MJR, Irwin G, Kerwin DG. Gait asymmetry: Composite scores for mechanical analyses of sprint running. *J Biomech.* 2012;45(6):1108-11.
102. Exell TA, Irwin G, Gittoes MJR, Kerwin DG. Implications of intra-limb variability on asymmetry analyses. *J Sports Sci.* 2012;30(4):403-9.
103. Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: A novel, robust method of quantifying asymmetry. *Gait Posture.* 2008;27(4):622-7.
104. Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *J Manipulative Physiol Ther.* 1987;10(4):172-6.
105. Exell TA. Lower-Limb Biomechanical Asymmetry in Maximal Velocity Sprint Running: Cardiff Metropolitan University; 2010.
106. Allard P, Lanchance R, Aissaoui R, Duhaime M. Simultaneous bilateral 3-D able-bodied gait. *Hum Movement Sci.* 1996;15(3):327-46.
107. Sadeghi H, Allard P, Duhaime M. Functional gait asymmetry in able-bodied subjects. *Hum Movement Sci.* 1997;16(2-3):243-58.
108. Sadeghi H, Allard P, Prince F, Labelle H. Symmetry and limb dominance in able-bodied gait: A review. *Gait Posture.* 2000;12(1):34-45.
109. Masani K, Kouzaki M, Fukunaga T. Variability of ground reaction forces during treadmill walking. *J Appl Physiol.* 2002;92(5):1885-90.
110. Frayne D. Kinetic Asymmetries During Submaximal and Maximal Speed Running: University of Massachusetts Amherst; 2014.
111. Zifchock RA, Davis I, Hamill J. Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *J Biomech.* 2006;39(15):2792-7.
112. Croisier J-L, Ganteaume S, Binet J, Genty M, Ferret J-M. Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *Am J Sports Med.* 2008;36(8):1469-75.
113. Croisier J-L, Forthomme B, Namurois M-H, Vanderthommen M, Crielaard J-M. Hamstring muscle strain recurrence and strength performance disorders. *Am J Sports Med.* 2002;30(2):199-203.

114. Mendiguchia J, Brughelli M. A return-to-sport algorithm for acute hamstring injuries. *Phys Ther Sport*. 2011;12(1):2-14.
115. Dauty M, Potiron-Josse M, Rochcongar P. Consequences and prediction of hamstring muscle injury with concentric and eccentric isokinetic parameters in elite soccer players. *Ann Readapt Med Phys*. 2003;46(9):601-6.
116. van Mechelen W, Hlobil H, Kemper HCG. Incidence, severity, aetiology and prevention of sports injuries: A review of concepts. *Sports Med*. 1992;14(2):82-99.
117. van Mechelen W, Hlobil H. How can sports injuries be prevented? . Oosterbeek (The Netherlands): National Institute For Sports Health Care; 1987.
118. Finch C. A new framework for research leading to sports injury prevention. *J Sci Med Sport*. 2006;9(1-2):3-9.
119. Peterson L, Junge A, Chomiak J, Graf-Baumann T, Dvorak J. Incidence of football injuries and complaints in different age groups and skill-level groups. *Am J Sports Med*. 2000;28(5 Suppl):S51-S7.
120. Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SLY. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32(4):395-400.
121. Starkey C, Brown SD, Ryan JL. Examination of Orthopedic and Athletic Injuries. Third ed. Philadelphia, PA: F.A. Davis Company; 2009.
122. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J Bone Joint Surg Am*. 1990;72(4):557-67.
123. Nordin M, Frankel VH. Basic Biomechanics of the Musculoskeletal System. 4th ed. Baltimore, MD: Lippincott Williams & Wilkins; 2012.
124. Mihata LCS, Baeautler AL, Boden BP. Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: Implications for anterior cruciate ligament mechanism and prevention. *Am J Sports Med*. 2006;34(6):445-55.
125. Winter DA. Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons, Inc.; 2009.
126. Lee MJC, Lloyd DG, Lay BS, Bourke PD, Alderson JA. Effects of different visual stimuli on postures and knee moments during sidestepping. *Med Sci Sports Exerc*. 2013;45(9):1740-8.
127. Cortes N, Blount E, Ringleb S, Onate JA. Soccer-specific video simulation for improving movement assessment. *Sports Biomech*. 2011;10(1):22-34.
128. Medina JM, McKeon PO, Hertel J. Rating the levels of evidence in sports-medicine research. *Athl Ther Today*. 2006 Sep;11(5):38-41.
129. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol*. 2001;11(4):263-8.
130. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech*. 2004;19(10):1022-31.
131. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc*. 2002;34(9):1408-13.
132. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med*. 2002 March 1, 2002;30(2):261-7.
133. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745-50.
134. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res*. 2005;19(2):394-9.
135. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res*. 2002;Aug(401):162-9.

136. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech.* 2001;16(5):438-45.
137. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc.* 2004;36(6):1008-16.
138. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med.* 2003;31(3):449-56.
139. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: A review of resistance training studies. *Sports Med.* 2008;38(12):1045-63.
140. Helms ER, Zinn C, Rowlands DS, Brown SR. A systematic review of dietary protein during caloric restriction in resistance trained lean athletes: A case for higher intakes. *Int J Sport Nutr Exerc Metab.* 2013:[in press].
141. Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech.* 2003;36(8):1159-68.
142. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-12.
143. Beaulieu ML, Lamontagne M, Xu L. Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: A gender comparison. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(8):968-76.
144. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *Am J Sports Med.* 2007;35(11):1888-900.
145. Garrett WE, Yu B. Keynote address II. Anterior cruciate ligament injury mechanisms and risk factors. *J Orthop Sports Phys Ther.* 2007 Feb;37(2):A10-A1.
146. Wu J-L, Seon JK, Gadikota HR, Hosseini A, Sutton KM, Gill TJ, et al. In situ forces in the anteromedial and posterolateral bundles of the anterior cruciate ligament under simulated functional loading conditions. *Am J Sports Med.* 2010 Mar;38(3):558-63.
147. Hewett TE, Myer GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med.* 2005;33(4):492-501.
148. Høy K, Lindblad BE, Terkelsen CJ, Helleland HE. Badminton injuries: A prospective epidemiological and socioeconomic study. *Br J Sports Med.* 1994;28(4):276-9.
149. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes. Part 1, mechanisms and risk factors. *Am J Sports Med.* 2006;34(2):299-311.
150. Jorrakate C, Vachalathiti R, Vongsirinavarat M, Sasimontongkul S. Lower extremity joint posture and peak knee valgus moment during side-step cutting performed by males and females. *J Phys Ther Sci.* 2011;23(4):585-9.
151. Beaulieu ML, Lamontagne M, Xu L. Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers. *Med Sci Sports Exerc.* 2008;40(10):1795-804.
152. Sigward SM, Pollard CD, Havens KL, Powers CM. Influence of sex and maturation on knee mechanics during side-step cutting. *Med Sci Sports Exerc.* 2012;44(8):1497-503.
153. Chan MS, Huang CF, Chang JH, Kernozek TW. Kinematics and kinetics of knee and hip position of female basketball players during side-step cutting with and without dribbling. *J Med Biol Eng.* 2009;29(4):178-83.
154. McLean SG, Walker KB, van den Bogert AJ. Effect of gender on lower extremity kinematics during rapid direction changes: An integrated analysis of three sports movements. *J Sci Med Sport.* 2005;8(4):411-22.
155. Houck JR, Duncan A, De Haven KE. Knee and hip angle and moment adaptations during cutting tasks in subjects with anterior cruciate ligament deficiency classified as noncopers. *J Orthop Sports Phys Ther.* 2005;35(8):531-40.

156. Benoit DL, Ramsey DK, Lamontagne M, Xu L, Wretenberg P, Renström P. Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait Posture*. 2006;24(2):152-64.
157. Kuntze G, Sellers WI, Mansfield NJ. Bilateral ground reaction forces and joint moments for lateral sidestepping and crossover stepping tasks. *J Sports Sci Med*. 2009;8(1):1-8.
158. Houck JR, Yack HJ. Associations of knee angles, moments and function among subjects that are healthy and anterior cruciate deficient (ACLD) during straight ahead and crossover cutting activities. *Gait Posture*. 2003;18(1):126-38.
159. Houck JR, Duncan A, De Haven KE. Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait Posture*. 2006;24(3):314-22.
160. Patla AE, Adkin A, Ballard T. Online steering: Coordination and control of body center of mass, head and body reorientation. *Exp Brain Res*. 1999;129(4):629-34.
161. Donnelly CJ, Lloyd DG, Elliott BC, Reinbolt JA. Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: Implications for ACL injury risk. *J Biomech*. 2012;45(8):1491-7.
162. Markolf KL, Mensch JS, Amstutz HC. Stiffness and laxity of the knee - The contributions of the supporting structures. A quantitative in vitro study. *J Bone Joint Surg Am*. 1976;58(5):583-94.
163. Seering WP, Piziali RL, Nagel DA, Schurman DJ. The function of the primary ligaments of the knee in varus-valgus and axial rotation. *J Biomech*. 1980;13(9):785-94.
164. Quatman CE, Hewett TE. The anterior cruciate ligament injury controversy: is "valgus collapse" a sex-specific mechanism? *Br J Sports Med*. 2009;43(5):328-35.
165. Wascher DC, Markolf KL, Shapiro MS, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part I: The effect of multiplane loading in the intact knee. *J Bone Joint Surg Am*. 1993;75(3):377-86.
166. Cerulli G, Benoit DL, Lamontagne M, Caraffa A, Liti A. In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: Case report. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(5):307-11.
167. Vaz L, Abade E, Fernandes HM, Reis VM. Cross-training in rugby: A review of research and practical suggestions. *Int J Perform Anal Sport*. 2013;13(1):225-37.
168. Gamble P. Physical preparation for elite-level rugby union football. *Strength Cond J*. 2004;26(4):10-23.
169. Brughelli M, Cronin J, Nosaka K. Muscle architecture and optimum angle of the knee flexors and extensors: A comparison between cyclists and Australian rules football players. *J Strength Cond Res*. 2010;24(3):717-21.
170. Brown SR, Brughelli M. Assessment strategies for individualised injury prevention in sport. *N Z J Sports Med*. 2014;41(2):78-9.
171. Brown SR, Brughelli M, Hume PA, King D, Gill N, Craighead H, et al. Multi-disciplinary perspectives on the use of lower-extremity injury assessments for a rugby player's return-to-play. *N Z J Sports Med*. 2014;41(1):30.
172. Brughelli M, Nosaka K, Cronin J. Application of eccentric exercise on an Australian rules football player with recurrent hamstring injuries. *Phys Ther Sport*. 2009;10(2):75-80.
173. Coombs R, Garbutt G. Developments in the use of the hamstring/quadiceps ratio for the assessment of muscle balance. *J Sports Sci Med*. 2002;1(3):56-62.
174. Dvir Z, Eger G, Halperin N, Shklar A. Thigh muscle activity and anterior cruciate ligament insufficiency. *Clin Biomech*. 1989;4(2):87-91.
175. Dauty M, Potiron-Josse M, Rochcongar P. Identification of previous hamstring muscle injury by isokinetic concentric and eccentric torque measurement in elite soccer player. *Isokinet Exerc Sci*. 2003;11(3):139-44.
176. Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *J Orthop Sports Phys Ther*. 2008;38(8):457-64.

177. Brown SR, Brughelli M, Griffiths PC, Cronin JB. Lower-extremity isokinetic strength profiling in professional rugby league and rugby union. *Int J Sports Physiol Perform*. 2014;9(2):358-61.
178. Brown SR, Wang H, Dickin DC, Weiss KJ. The relationship between leg preference and knee mechanics during sidestepping in collegiate female footballers. *Sports Biomech*. 2014;13(4):351-61.
179. Nuzzo R. Statistical errors. *Nature*. 2014;506(7487):150-2.
180. Sterne JAC, Smith GD. Sifting the evidence-what's wrong with significance tests? *Br Med J*. 2001;322(7280):226-31.
181. Hopkins WG. A scale of magnitudes for effect statistics. *A New View of Statistics* 2002 [cited; Available from: ]
182. Daneshjoo A, Rahnema N, Mokhtar AH, Yusof A. Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players. *J Hum Kinet*. 2013;36(1):45-53.
183. Rahnema N, Lees A, Bambaecichi E. A comparison of muscle strength and flexibility between the preferred and non-preferred leg in English soccer players. *Ergonomics*. 2005;48(11-14):1568-75.
184. Brito J, Figueiredo P, Fernandes L, Seabra A, Soares JM, Krstrup P, et al. Isokinetic strength effects of FIFA's "The 11+" injury prevention training programme. *Isokinet Exerc Sci*. 2010;18(4):211-5.
185. Malý T, Zahálka F, Malá L. Isokinetic strength, ipsilateral and bilateral ratio of peak muscle torque in knee flexors and extensors in elite young soccer players. *Acta Kinesiologica*. 2010;4(2):17-23.
186. Jones PA, Bampouras TM. A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *J Strength Cond Res*. 2010;24(6):1553-8.
187. Kim D, Hong J. Hamstring to quadriceps strength ratio and noncontact leg injuries. A prospective study during one season. *Isokinet Exerc Sci*. 2011;19(1):1-6.
188. Daneshjoo A, Mokhtar AH, Rahnema N, Yusof A. The effects of injury preventive warm-up programs on knee strength ratio in young male professional soccer players. *PLoS ONE*. 2012;7(12):e50979.
189. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, Newton RU. Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. *J Strength Cond Res*. 2014;28(9):2415-23.
190. Brockett CL, Morgan DL, Proske UWE. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc*. 2004;36(3):379-87.
191. Brockett CL, Morgan DL, Proske UWE. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Med Sci Sports Exerc*. 2001;33(5):783-90.
192. Mackey C, O'Sullivan K, O'Connor A, Clifford A. Altered hamstring strength profile in Gaelic footballers with a previous hamstring injury. *Isokinet Exerc Sci*. 2011;19(1):47-54.
193. Herzog W, Guimaraes AC, Anton MG, Carter-Erdman KA. Moment-length relations of rectus femoris muscles of speed skaters/cyclists and runners. *Med Sci Sports Exerc*. 1991;23(11):1289-96.
194. Savelberg HHCM, Meijer K. Contribution of mono- and biarticular muscles to extending knee joint moments in runners and cyclists. *J Appl Physiol*. 2003;94(6):2241-8.
195. Schifftan GS, Ross LA, Hahne A, J. The effectiveness of proprioceptive training in preventing ankle sprains in sporting populations: A systematic review and meta-analysis. *J Sci Med Sport*. 2015;18(3):238-44.
196. Hrysomallis C. Balance ability and athletic performance. *Sports Med*. 2011;41(3):221-32.
197. Emery CA. Is there a clinical standing balance measurement appropriate for use in sports medicine? A review of the literature. *J Sci Med Sport*. 2003;6(4):492-504.
198. McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part I: Can deficits be detected with instrumented testing? *J Athl Train*. 2008;43(3):293-304.
199. Testerman C, Vander Griend R. Evaluation of ankle instability using the Biodex Stability System. *Foot Ankle Int*. 1999;20(5):317-21.
200. Aydoğ E, Bal A, Aydoğ ST, Çakci A. Evaluation of dynamic postural balance using the Biodex Stability System in rheumatoid arthritis patients. *Clin Rheumatol*. 2006;25(4):462-7.

201. Mohammadirad S, Salavati M, Ebrahimi Takamjani I, Akhbari B, Sherafat S, Mazaheri M, et al. Intra and intersession reliability of a postural control protocol in athletes with and without anterior cruciate ligament reconstruction: A dual-task paradigm. *Int J Sports Phys Ther.* 2012;7(6):627-36.
202. Ras J, Threethambal P. Injury incidence and balance in rugby players. *Pak J Med Sci.* 2014;30(6):1346-50.
203. Riemann BL, Davies GJ. Limb, sex, and anthropometric factors influencing normative data for the Biodex Balance System SD athlete single leg stability test. *Athl Train Sports Health Care.* 2013;5(5):224-32.
204. Huurnink A, Fransz DP, Kingma I, Hupperets MDW, van Dieën JH. The effect of leg preference on postural stability in healthy athletes. *J Biomech.* 2014;47(1):308-12.
205. Gstöttner M, Neher A, Scholtz A, Millonig M, Lember S, Raschner C. Balance ability and muscle response of the preferred and non-preferred leg in soccer players. *Motor Control.* 2009;13(2):218-31.
206. Arnold BL, Schmitz RJ. Examination of balance measures produced by the Biodex Stability System. *J Athl Train.* 1998;33(4):323-7.
207. Verhagen EALM, Bay K. Optimising ankle sprain prevention: A critical review and practical appraisal of the literature. *Br J Sports Med.* 2010;44(15):1082-8.
208. Gioftsidiou A, Malliou P, Pafis G, Beneka A, Godolias G, Maganaris CN. The effects of soccer training and timing of balance training on balance ability. *Eur J Appl Physiol.* 2006;96(6):659-64.
209. Platzner H-P, Raschner C, Patterson C. Performance-determining physiological factors in the luge start. *J Sports Sci.* 2009;27(3):221-6.
210. Platzner H-P, Raschner C, Patterson C, Lember S. Comparison of physical characteristics and performance among elite snowboarders. *J Strength Cond Res.* 2009;23(5):1427-32.
211. Fong DT-P, Hong Y, Chan L-K, Yung PS-H, Chan K-M. A systematic review on ankle injury and ankle sprain in sports. *Sports Med.* 2007;37(1):73-94.
212. McGuine TA, Greene JJ, Best T, Levenson G. Balance as a predictor of ankle injuries in high school basketball players. *Clin J Sport Med.* 2000;10(4):239-44.
213. Trojian TH, McKeag DB. Single leg balance test to identify risk of ankle sprains. *Br J Sports Med.* 2006;40(7):610-3.
214. Hübscher M, Zech A, Pfeifer K, Hänsel F, Vogt L, Banzer W. Neuromuscular training for sports injury prevention: A systematic review. *Med Sci Sports Exerc.* 2010;42(3):413-21.
215. McHugh MP, Tyler TF, Tetro DT, Mullaney MJ, Nicholas SJ. Risk factors for noncontact ankle sprains in high school athletes: The role of hip strength and balance ability. *Am J Sports Med.* 2006;34(3):464-70.
216. Cunniffe B, Proctor W, Baker J, Davies B. An evaluation of the physiological demands of elite rugby union using global positioning system tracking software. *J Strength Cond Res.* 2009;23(4):1195-203.
217. King T, Jenkins D, Gabbett T. A time-motion analysis of professional rugby league match-play. *J Sports Sci.* 2009;27(3):213-9.
218. Gabbett T. Physiological and anthropometric characteristics of elite women rugby league players. *J Strength Cond Res.* 2007;21(3):875-81.
219. Gabbett TJ. A comparison of physiological and anthropometric characteristics among playing positions in junior rugby league players. *Br J Sports Med.* 2005;39(9):675-80.
220. Gabbett TJ. A comparison of physiological and anthropometric characteristics among playing positions in sub-elite rugby league players. *J Sports Sci.* 2006;24(12):1273-80.
221. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: Part 2 training Injuries. *Br J Sports Med.* 2005;39(10):767-75.
222. Quarrie KL, Wilson BD. Force production in the rugby union scrum. *J Sports Sci.* 2000;18(4):237-46.
223. Simperingham KD, Cronin JB, Ross A. Advances in sprint acceleration profiling for field-based team-sport athletes: Utility, reliability, validity and limitations. *Sports Med.* 2016.



224. Samozino P, Rabita G, Dorel S, Slawinski J, Peyrot N, Saez de Villarreal E, et al. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Sports*. 2015;26(6):648-58.
225. Rabita G, Dorel S, Slawinski J, Saez de villarreal E, Couturier A, Samozino P, et al. Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scand J Med Sci Sports*. 2015;25(5):583-94.
226. Lakomy HKA. The use of a non-motorized treadmill for analysing sprint performance. *Ergonomics*. 1987;30(4):627-37.
227. Morin J-B, Gimenez P, Edouard P, Arnal P, Jiménez-Reyes P, Samozino P, et al. Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Front Physiol*. 2015;6(404):1-14.
228. Cross MR, Brughelli M, Brown SR, Samozino P, Gill ND, Cronin JB, et al. Mechanical properties of sprinting in elite rugby union and rugby league. *Int J Sports Physiol Perform*. 2015;10(6):695-702.
229. Harriss DJ, Atkinson G. Ethical standards in sport and exercise science research: 2016 update. *Int J Sports Med*. 2015;36(14):1121-4.
230. de Lacey J, Brughelli ME, McGuigan MR, Hansen KT. Strength, speed and power characteristics of elite rugby league players. *J Strength Cond Res*. 2014;28(8):2372-5.
231. Cross MR, Brughelli ME, Cronin JB. Effects of vest loading on sprint kinetics and kinematics. *J Strength Cond Res*. 2014;28(7):1867-74.
232. Mann RV, Murphy A. The mechanics of sprinting and hurdling. 2015 ed. USA: CreateSpace Independent Publishing Platform; 2015.
233. Brown SR, Brughelli M, Cross MR. Profiling sprint mechanics by leg preference and position in rugby union athletes. *Int J Sports Med*. 2016;37(11):890-7.
234. Austin D, Gabbett T, Jenkins D. The physical demands of Super 14 rugby union. *J Sci Med Sport*. 2011;14(3):259-63.
235. Mendiguchia J, Samozino P, Martinez-Ruiz E, Brughelli M, Schmikli S, Morin J-B, et al. Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *Int J Sports Med*. 2014;35(8):690-5.
236. Cavanagh PR, Pollock ML, Landa J. A biomechanical comparison of elite and good distance runners. *Ann N Y Acad Sci*. 1977;301:328-45.
237. Flanagan EP, Harrison AJ. Muscle dynamics differences between legs in healthy adults. *J Strength Cond Res*. 2007;21(1):67-72.
238. Highton JM, Lamb KL, Twist C, Nicholas C. The reliability and validity of short-distance sprint performance assessed on a nonmotorized treadmill. *J Strength Cond Res*. 2012;26(2):458-65.
239. Morin J-B, Sève P. Sprint running performance: Comparison between treadmill and field conditions. *Eur J Appl Physiol*. 2011;111(8):1695-703.
240. Morin J-B, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour J-R. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol*. 2012;112(11):3921-30.
241. Weyand PG, Sandell RF, Prime DNL, Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol*. 2010;108(4):950-61.
242. Brown SR, Cross MR. Sprint kinetics and kinematics on a non-motorised treadmill are unique to position in rugby athletes. 20th annual Congress of the European College of Sport Science. Malmö, SWE; 2015.
243. Brughelli M, Cronin J, Chaouachi A. Effects of running velocity on running kinetics and kinematics. *J Strength Cond Res*. 2011;25(4):933-9.
244. Sayers MGL, Washington-King J. Characteristics of effective ball carries in Super 12 rugby. *Int J Perform Anal Sport*. 2005;5(3):92-106.
245. Wheeler KW, Askew CD, Sayers MG. Effective attacking strategies in rugby union. *Eur J Sport Sci*. 2010;10(4):237-42.

246. Marshall B, Franklyn-Miller A, Moran K, King E, Richter C, Gore S, et al. Biomechanical symmetry in elite rugby union players during dynamic tasks: An investigation using discrete and continuous data analysis techniques. *BMC Sports Sci Med Rehabil.* 2015;7(13):1-13.
247. Mündermann A, Stefanyshyn DJ, Nigg BM. Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. *Med Sci Sports Exerc.* 2001;33(11):1939-45.
248. Hopkins WG. Estimating sample size for magnitude-based inferences. *Sportscience.* 2006;10:63-70.
249. Lloyd DG, Alderson J, Elliott BC. An upper limb kinematic model for the examination of cricket bowling: A case study of Mutiah Muralitharan. *J Sports Sci.* 2000;18(12):975-82.
250. Piazza SJ, Okita N, Cavanagh PR. Accuracy of the functional method of hip joint center location: Effects of limited motion and varied implementation. *J Biomech.* 2001;34(7):967-73.
251. Chaudhari AM, Hearn BK, Andriacchi TP. Sport-dependent variations in arm position during single-limb landing influence knee loading: Implications for anterior cruciate ligament injury. *Am J Sports Med.* 2005;33(6):824-30.
252. Fedie R, Carlstedt K, Willson JD, Kernozek TW. Effect of attending to a ball during a side-cut maneuver on lower extremity biomechanics in male and female athletes. *Sports Biomech.* 2010;9(3):165-77.
253. Jindrich DL, Besier TF, Lloyd DG. A hypothesis for the function of braking forces during running turns. *J Biomech.* 2006;39(9):1611-20.
254. Spiteri T, Cochrane JL, Hart NH, Haff GG, Nimphius S. Effect of strength on plant foot kinetics and kinematics during a change of direction task. *Eur J Sport Sci.* 2013;13(6):646-52.
255. Nimphius S, McGuigan MR, Newton RU. Relationship between strength, power, speed and change of direction performance of female softball players. *J Strength Cond Res.* 2010;24(4):885-985.
256. Markolf KL, Wascher DC, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part II: The effect of section of the posterolateral structures. *J Bone Joint Surg Am.* 1993;75(3):387-94.
257. Pollard CD, Sigward SM, Powers CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clin J Sport Med.* 2007;17(1):38-42.
258. Shultz SJ, Schmitz RJ, Benjaminse A, Chaudhari AM, Collins M, Padua DA. ACL Research Retreat VI: An update on ACL injury risk and prevention, March 22-24, 2012, Greensboro, NC. *J Athl Train.* 2012;47(5):591-603.
259. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38(10):1968-78.
260. Waldén M, Häggglund M, Ekstrand J. High risk of new knee injury in elite footballers with previous anterior cruciate ligament injury. *Br J Sports Med.* 2006;40(2):158-62.
261. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train.* 2008;43(4):396-408.
262. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidences of knee injury in female athletes: A prospective study. *Am J Sports Med.* 1999;27(6):699-706.
263. Myer GD, Paterno MV, Ford KR, Hewett TE. Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. *J Strength Cond Res.* 2008;22(3):987-1014.
264. Emery CA, Roy T-O, Whittaker JL, Nettel-Aguirre A, Van Mechelen W. Neuromuscular training injury prevention strategies in youth sport: A systematic review and meta-analysis. *Br J Sports Med.* 2015;49(13):865-70.
265. Khayambashi K, Ghoddosi N, Straub RK, Powers CM. Hip muscle strength predicts noncontact anterior cruciate ligament injury in male and female athletes: A prospective study. *Am J Sports Med.* 2016:[in press].

266. Powers CM. The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *J Orthop Sports Phys Ther.* 2010;40(2):42-51.
267. Pánics G, Tállay A, Pavlik A, Berkes I. Effect of proprioception training on knee joint position sense in female team handball players. 42. 2008;42(6):472-6.
268. Mendiguchia J, Edouard P, Samozino P, Brughelli M, Cross MR, Ross A, et al. Field monitoring of sprinting power-force-velocity profile before, during and after hamstring injury: Two case reports. *J Sports Sci.* 2016;34(6):535-41.
269. Fulton J, Wright K, Kelly M, Zebrosky B, Zanis M, Drvol C, et al. Injury risk is altered by previous injury: A systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther.* 2014;9(5):583-95.
270. Opar DA, Serpell BG. Is there a potential relationship between prior hamstring strain injury and increased risk for future anterior cruciate ligament injury? *Arch Phys Med Rehabil.* 2014;95(2):401-5.
271. Chumanov ES, Schache AG, Heiderscheit BC, Thelen BJ. Hamstring are most susceptible to injury during the late swing phase of sprinting. *Br J Sports Med.* 2012;46(2):90.
272. Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves single-leg stability in young female athletes. *J Orthop Sports Phys Ther.* 2004;34(6):305-16.
273. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform.* 2005;1(1):50-7.
274. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2013;41(7):1549-58.
275. Alii LK. Sample size and subject to item ratio in principal components analysis and exploratory factor analysis. *J Biomet Biostat.* 2010;1(2):1-6.
276. Pyne DB, Gardner AS, Sheehan K, Hopkins WG. Fitness testing and career progression in AFL football. *J Sci Med Sport.* 2005;8(3):321-32.
277. Jones PA, Herrington LC, Graham-Smith P. Technique determinants of knee joint loads during cutting in female soccer players. *Hum Movement Sci.* 2015;42(1):203-11.
278. Sigward SM, Powers CM. Loading characteristics of females exhibiting excessive valgus moments during cutting. *Clin Biomech.* 2007;22(7):827-33.
279. Dalleau G, Belli A, Bourdin M, Lacour J-R. The spring-mass model and the energy cost of treadmill running. *Eur J Appl Physiol.* 1998;77(3):257-63.
280. Ball KA. Kinematic comparison of the preferred and non-preferred foot punt kick. *J Sports Sci.* 2011;29(14):1545-52.
281. Brown SR, Hume PA, Brughelli M, Besier TF. Clinical determinants of individual knee joint loads experienced while sidestepping: An exploratory study with male rugby athletes. *Am J Sports Med.* 2016:[in preparation].
282. Bahr R. Why screening tests to predict injury do not work—and probably never will...: A critical review. *Br J Sports Med.* 2016:[in press].
283. Fox AS, Bonacci J, McLean SG, Spittle M, Saunders N. A systematic evaluation of field-based screening methods for the assessment of anterior cruciate ligament (ACL) injury risk. *Sports Med.* 2016;46(5):715-35.
284. Kritz M. Development, reliability and effectiveness of the Movement Competency Screen (MCS): Auckland University of Technology; 2012.
285. O'Connor FG, Deuster PA, Davis J, Pappas CG, Knapik JJ. Functional Movement Screening: Predicting injuries in officer candidates. *Med Sci Sports Exerc.* 2011;43(12):2224-30.
286. Askling CM, Nilsson J, Thorstensson A. A new hamstring test to complement the common clinical examination before return to sport after injury. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(12):1798-803.
287. Mendiguchia J, Alentorn-Geli E, Brughelli M. Hamstring strain injuries: are we heading in the right direction? *Br J Sports Med.* 2012 February 1, 2012;46(2):81-5.

288. Hides JA, Brown CT, Penfold L, Stanton WR. Screening the lumbopelvic muscles for a relationship to injury of the quadriceps, hamstrings, and adductor muscles among elite Australian Football League players. *J Orthop Sports Phys Ther.* 2011;41(10):767-75.
289. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: Criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther.* 2006;36(6):385-402.
290. Proske U, Morgan DL, Brockett CL, Percival P. Identifying athletes at risk of hamstring strains and how to protect them. *Clin Exp Pharmacol Physiol.* 2004;31(8):546-50.
291. Croisier J-L. Muscular imbalance and acute lower extremity muscle injuries in sport. *Int Sportmed J.* 2004;5(3):169-76.
292. Pappas E, Carpes FP. Lower extremity kinematic asymmetry in male and female athletes performing jump-landing tasks. *J Sci Med Sport.* 2012;15(1):87-92.
293. Verrall GM, Kalairajah Y, Slavotinek JP, Spriggins AJ. Assessment of player performance following return to sport after hamstring muscle strain injury. *J Sci Med Sport.* 2006;9(1-2):87-90.
294. Brown SR, Morin J-B. A targeted strength training programme and its effect on performance and injury risk: A case study in sprinting 21st annual Congress of the European College of Sport Science. Vienna, AUT; 2016.
295. Brown SR, Hume PA, Lorimer AV, Brughelli M, Besier TF. An individualised approach to assess the sidestep manoeuvre in rugby union athletes: Are we missing individual asymmetries by focusing on group means? *Am J Sports Med.* 2016:[in review].
296. Fuller CW, Bahr R, Dick RW, Meeuwisse WH. A framework for recording recurrences, reinjuries, and exacerbations in injury surveillance. *Clin J Sport Med.* 2007;17(3):197-200.
297. Podlog L, Eklund RC. Assisting injured athletes with the return to sport transition. *Clin J Sport Med.* 2004;14(5):257-9.
298. Brown SR, Brughelli M, Hume PA. Carrying a ball can influence sidestepping mechanics in rugby. 33rd International Conference on Biomechanics in Sports. Poitiers, FRA; 2015.
299. Austin D, Gabbett T, Jenkins D. Repeated high-intensity exercise in professional rugby union. *J Sports Sci.* 2011;29(10):1105-12.
300. Gabbett TJ. Incidence of injury in junior and senior rugby league players. *Sports Med.* 2004;34(12):849-59.
301. Gabbett TJ, Kelly J, Pezet T. Relationship between physical fitness and playing ability in rugby league players. *J Strength Cond Res.* 2007;21(4):1126-33.
302. Newman MA, Tarpenning KM, Marino FE. Relationships between isokinetic knee strength, single-sprint performance, and repeated-sprint ability in football players. *J Strength Cond Res.* 2004;18(4):867-72.
303. Montgomery MM, Shultz SJ. Isometric knee-extension and knee-flexion torque production during early follicular and postovulatory phases in recreationally active women. *J Athl Train.* 2010;45(6):586-93.
304. Li RCT, Wu Y, Maffulli N, Chan KM, Chan JLC. Eccentric and concentric isokinetic knee flexion and extension: A reliability study using the Cybex 6000 dynamometer. *Br J Sports Med.* 1996;30(2):156-60.
305. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods.* 2002;7(1):105-25.
306. Cronin JB, Hansen KT. Strength and power predictors of sports speed. *J Strength Cond Res.* 2005;19(2):349-57.
307. Gabbett TJ. Sprinting patterns of national rugby league competition. *J Strength Cond Res.* 2012;26(1):121-30.
308. Alexander D, Kennedy M, Kennedy J. Injuries in rugby league football. *Med J Aust.* 1979 10;2(7):341-2.
309. Carling C, Le Gall F, Orhant E. A four-season prospective study of muscle strain recurrences in a professional rugby club. *Res Sports Med: Int J.* 2011;19(2):92-102.

310. Clanton TO, Coupe KJ. Hamstring strains in athletes: Diagnosis and treatment. *J Am Acad Orthop Surg*. 1998;6(4):237-48.
311. Ahmad CS, Redler LH, Ciccotti MG, Maffulli N, Longo UG, Bradley J. Evaluation and management of hamstring injuries. *Am J Sports Med*. 2013;41(12):2933-47.
312. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, Thelen DG. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation, and injury prevention. *J Orthop Sports Phys Ther*. 2010;40(2):67-81.
313. Sherry MA, Best TM, Silder A, Thelen DG, Heiderscheit BC. Hamstring Strains: Basic Science and Clinical Research Applications for Preventing the Recurrent Injury. *Strength Cond J*. 2011;33(3):56-71.
314. Sherry M, group UHSMP. Rehabilitation guidelines for patellar tendon and quadriceps tendon repair. [http://www.uwhealth.org/files/uwhealth/docs/pdf6/sm\\_pat\\_tendon\\_quad.pdf](http://www.uwhealth.org/files/uwhealth/docs/pdf6/sm_pat_tendon_quad.pdf): UW Health Sports Rehabilitation; 2011.
315. Croisier J-L. Factors Associated with Recurrent Hamstring Injuries. *Sports Med*. 2004;34(10):681-95.
316. Bennell K, Wajswelner H, Lew P, Schall-Riauour A, Leslie S, Plant D, et al. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *Br J Sports Med*. 1998;32(4):309-14.

**Section 4:**  
**Appendices**

## Appendix I. Additional Research Outputs Since Starting the Doctor of Philosophy.

### Publications:

**Brown SR**, Wang H, Dickin DC, Weiss KJ. The relationship between leg preference and knee mechanics during sidestepping in collegiate female footballers. *Sports Biomech.* 2014;13:351-361.

Sheerin K, **Brown SR**. So is he ready to play? The science of return to play status. *Sports Physiother NZ.* 2014;5:12-3.

Cronin JB, Brughelli M, Gamble P, **Brown SR**, McKenzie C. Acute kinematic and kinetic augmentation in horizontal jump performance using haltere type handheld loading. *J Strength Cond Res.* 2014;28:1559-64.

Winwood PW, Cronin JB, **Brown SR**, Keogh JWL. A biomechanical analysis of the farmers walk, and comparison with the deadlift and unloaded walk. *Int J Sports Sci Coaching.* 2014; 9:1127-1143.

Helms ER, Zinn C, Rowlands DS, **Brown SR**. A systematic review of dietary protein during caloric restriction in resistance trained lean athletes. A case for higher intakes. *Int J Sport Nutr Exerc Metab.* 2014;14:127-38.

**Brown SR**, Hopkins WG. The 33rd International Conference on Biomechanics in Sports. *Sportsci.* 2015;19:55-59.

Cross MR, Brughelli M, **Brown SR**, Samozino P, Gill ND, Cronin JB, Morin J-B. Mechanical properties of sprinting in elite rugby union and rugby league. *Int J Sports Physiol Perform.* 2015;10:695-702.

McKenzie C, Brughelli M, Whatman C, **Brown SR**. The influence of optimal handheld load on the technical ability to apply ground reaction forces. *Int J Sports Med.* 2015;37:318-23.

Winwood PW, Cronin JB, **Brown SR**, Keogh JWL. A biomechanical analysis of the heavy sprint-style sled pull and comparison with the back squat. *Int J Sports Sci Coaching.* 2015;10:851-868.

- Winwood PW, Cronin JB, **Brown SR**, Keogh JWL. A biomechanical analysis of the strongman log lift and comparison with weightlifting's clean and jerk. *Int J Sports Sci Coaching*. 2015;10:869-886.
- Morin J-B, Petrakos, G, Jiménez-Reyes P, **Brown SR**, Samozino P, Cross MR. Very-heavy sled training for improving horizontal force output in soccer players. *Int J Sports Physiol Perform*. [In press].
- Hume PA, Theadom A, Lewis GN, Quarrie KL, **Brown SR**, Hill R, Marshall SW. A comparison of cognitive function in former rugby union players compared with former non-contact-sport players and the impact of concussion history. *Sports Med*. 2016. [In press].
- Lewis GN, Hume PA, Stavric V, **Brown SR**, Taylor D. NZ Rugby Health study: Motor cortex excitability in retired elite and community level rugby players. *NZ Med J*. [In press].
- Carvalho AF, **Brown SR**, Abade EA. Evaluating injury risk in professional football: muscular strength and asymmetries. *J Hum Kinet*. 2016;51:19-26.
- McKenzie C, Brughelli M, Whatman C, **Brown SR**. Handheld loading to enhance horizontal jump performance in female netball players. *J Aust Strength Cond*. 2016. [In press].
- Helms ER, Storey A, Cross MR, **Brown SR**, Lenetsky S, Ramsay H, Dillen C, Zourdos MC. RPE and velocity relationships for the back squat, bench press, and deadlift in powerlifters. *J Strength Cond Res*. 2016. [In press].
- Lopes J, **Brown SR**. Your monthly app review: My Sprint. *Sports Physiother NZ*. 2016;1:8-9.
- Wang HE, **Brown SR**. The effects of total ankle replacement on ankle joint mechanics during walking. *J Sport Health Sci*. 2016. [In press].

#### **Submitted Manuscripts:**

- Brown SR**, Feldman ER, Cross MR, Helms ER, Marrier B, Samozino P, Morin J-B. The potential for a targeted strength training programme to decrease asymmetry and



increase performance: A proof-of-concept in sprinting. *Int J Sports Physiol Perform.* [In review].

Cross MR, Brughelli M, Samozino P, **Brown SR**, Morin J-B. Optimal loading for maximizing power during over-ground sled resisted sprinting. *Int J Sports Physiol Perform.* [In review].

Glassbrook DJ, Helms ER, **Brown SR**, Storey AG. A review of biomechanical and muscle activity differences between the high-bar and low-bar back-squat. *J Strength Cond Res.* [In review].

Glassbrook DJ, **Brown SR**, Helms ER, Duncan S, Storey AG. The high-bar and low-bar back-squats: A biomechanical analysis. *J Strength Cond Res.* [In review].

Weiss KJ, Wang H, **Brown SR**, Dickin DC. The relationship between leg preference and knee mechanics during unplanned sidestepping in collegiate female athletes. *Sports Biomech.* 2016. [In review].

Bridgeman LA, Weiss KJ, **Brown SR**. Lower-extremity isokinetic strength profiling of professional basketball athletes. *Isokinet Exerc Sci.* 2016. [In review].

#### Conference Presentations:

**Brown SR**, Griffiths PC, Cronin JB, Brughelli M. Lower body isokinetic strength profiling in professional rugby league and rugby union. Bay of Plenty Polytechnic Sports Research Symposium. 2013, Tauranga, NZL.

**Brown SR**, Brughelli M, Hume PA, King D, Gill N, Craighead H, Kara S. Multi-disciplinary perspectives on use of lower-extremity injury assessments for a rugby player's return-to-play. New Zealand Sports Medicine and Science Conference. 2013, Wellington, NZL.

**Brown SR**, Brughelli M. Determining return-to-sport status with a multi-component assessment strategy: A case study in rugby. Bay of Plenty Polytechnic Sports Research Symposium. 2014, Tauranga, NZL.

- Brown SR**, Brughelli M. Assessment strategies for individualised injury prevention in sport. New Zealand Sports Medicine and Australasian College of Sports Physicians Conference. 2015, Wellington, NZL.
- Brown SR**, Cross MR. Sprint kinetics and kinematics on a non-motorised treadmill are unique to position in rugby athletes. European College of Sport Science. 2015; Malmö, SWE.
- Brown SR**, Brughelli M, Hume PA. Carrying a ball can influence sidestepping mechanics in rugby. International Society of Biomechanics in Sports. 2015; Poitiers, FRA.
- Brown SR**. Knee and hip strength profiles characterise functional needs in rugby athletes. International Society of Biomechanics. 2015; Glasgow, GBR.
- Weiss KJ, **Brown SR**. The effect of limb preference on knee mechanics during a fatigued unanticipated sidestepping manoeuvre. International Society of Biomechanics in Sports. 2015; Poitiers, FRA.
- Weiss KJ, **Brown SR**. The effect of limb preference on knee mechanics during unanticipated sidestepping. International Society of Biomechanics. 2015; Glasgow, GBR.
- Brown SR**, Morin JB. A targeted strength training programme and its effect on performance and injury risk: A case study in sprinting. European College of Sport Science. 2016; Vienna, AUT.
- Brown SR**, Simperingham K, Morin JB. The effects of ball carrying on sprint mechanics: An insight into the technical demands of rugby. International Society of Biomechanics in Sports. 2016; Tsukuba, JPN.
- Anyadike-Danes K, **Brown SR**. The effect of concussion history on positional balance ability in rugby union athletes. International Society of Biomechanics in Sports. 2016; Tsukuba, JPN.

## Appendix II. Ethics Approval for Chapters 3 – 9 and Appendices VI – IX.



AUTEC  
SECRETARIAT

To: Matt Brughelli  
Cc: Scott Brown, Patria Hume  
From: Kate O'Connor, Executive Secretary, AUTEC  
Date: 12 March 2014  
Subject: Ethics Application: **13/378 Does leg symmetry matter in strength, balance and sidestepping measures for male rugby players?**

Dear Matt

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

I have approved the minor amendments to your ethics application allowing changes to the test protocol.

I remind you that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 17 December 2016;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 17 December 2016 or on completion of the project.

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

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

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


All the very best with your research,

Kate O'Connor

Executive Secretary

Auckland University of Technology Ethics Committee

### Appendix III. Participant Consent Form.

<p><b>Consent Form</b></p> <p>For use when laboratory or field testing is involved.</p>	 <p><b>AUT</b> UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU</p>
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*Project title:* Does leg symmetry matter in strength, balance and sidestepping measures for male rugby players?

*Project Supervisor:* Dr Matt Brughelli

*Researcher:* **Scott Brown**

- ☐ I have read and understood the information provided about this research project in the Information Sheet dated 17<sup>th</sup> December 2013.
- ☐ I have had an opportunity to ask questions and to have them answered.
- ☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ☐ I am not suffering from any current injury or illness that may impair my ability to perform the required tasks nor am I outside the limits of the required age range of 18 to 35 years.
- ☐ I agree to answer questions and provide physical effort to the best of my ability throughout testing.
- ☐ I agree to take part in this research.
- ☐ I wish to receive a copy of the report from the research (please tick one): Yes ☐ No ☐

Participant's signature:.....

Participant's name:.....

Participant's Contact Details (if appropriate):

.....

.....

.....


Date: .....

**Approved by the Auckland University of Technology Ethics Committee on 17/12/2013**

**AUTEC Reference number 13/378.**

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

## Appendix IV. Participant Information Sheet.

<h3>Participant Information Sheet</h3>	 <p><b>AUT</b> UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU</p>
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Date Information Sheet Produced:

17<sup>th</sup> December 2013

Project Title

Does leg symmetry matter in strength, balance and sidestepping measures for male rugby players?

An Invitation

Hi, my name is Scott Brown and I am a PhD student at AUT University. On behalf of my supervisors Dr Matt Brughelli, Prof. Patria Hume and Prof. Thor Besier, I would like to personally invite you to assist us in our project that aims to determine the difference between legs in strength, balance and sidestepping in male rugby players.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of this research?

This research aims to determine the difference between legs in strength, balance and sidestepping in male rugby players. The results of this research could help to inform future research on lower-extremity injury risk, and are intended for publication. The results will contribute to part of my PhD thesis and will also be submitted to peer-reviewed journals for publication. Your individual identity will not be disclosed in any of these publications.

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

I have contacted your coaching staff as associates of mine to see if they would allow you to participate in this research on your own will. Since they have allowed this, I was able to verbally present to you and your coaching staff the nature of the study, the time and activities required to be involved with the study, potential benefits of the study, and a contact email if you were interested. Since you have contacted me showing interest, you have identified yourself as a potential participant in this research. You have been asked to participate in this research as you fit our research criterion being a male rugby player between the ages of 18 and 35 years without a current major lower-extremity injury.

What will happen in this research?

Once you have decided to participate in the study you will be asked to visit our exercise laboratory for a 3-hour testing session. This testing session will include three 1-hour tests administered by me, with aid from my research assistants. An outline of the testing session will proceed as follows.

You will arrive at AUT-Millennium campus SPRINZ testing facility where you will have your height and body weight measured. You will be given a complete verbal familiarisation of the testing procedures and equipment followed by a general self-selected lower-extremity dynamic warm-up. You

will be asked to perform (1) static and dynamic balance testing to assess your overall joint stability and balance by standing on a force plate with one leg during a series of five balance tasks containing eyes open and eyes closed tasks; (2) isokinetic concentric strength tests by providing five maximal efforts for extension and flexion actions at  $60^{\circ}\cdot s^{-1}$  within an anatomical  $90^{\circ}$  range-of-motion on each leg for the knee and the hip; and (3) five successful  $45^{\circ}$  sidestepping manoeuvres on each leg consisting of a 10 metre sprint at a speed of  $7\text{ m}\cdot s^{-1}$ . Testing order will be randomly determined and you will be given a 45 second rest between each practice and test trial, a two-minute rest between side-to-side testing and a five minute rest between positions/tests to ensure adequate rest between trials.

If you wish to continue your participation, you will be invited to return to our testing facilities for a second testing session seven days later at the same time of day. This session will follow the same procedures as the first testing session to determine the reliability and validity of the test variables.

What are the discomforts and risks?

You will be asked to perform some sub-maximal (moderate intensity) and maximal (very heavy intensity) exercise during the data collection and therefore during the latter are likely to experience discomfort for a short period of time towards the concluding minutes of these maximal assessments. The intensity of the exercise will be similar to what is felt in match-play situations.

How will these discomforts and risks be alleviated?

Being an experienced athlete who regularly competes and is familiar with training at high intensities, the exercise trials will be similar to what you have experienced within a typical week to week training and competition program. If you are experiencing discomfort at any stage you are encouraged to inform the researcher with you at the time in order that they can best address the problem. If you have any questions regarding and risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

You may benefit from this study as you will be given a personalised athletic assessment of your symmetry variables (strength, balance and sidestepping). This information can be used to provide further insight into your personalised training recommendations. We as researchers will also benefit as this is a novel, applied research study. New knowledge for researchers and practitioners will be gained looking into the importance of symmetry in rugby players. The wider sporting community will be educated as to the effects of symmetry on injury prevention and performance and if effective this could lead to a change in athletic screening and prescription for athletes in NZ.

The results of this research are intended for publication and will contribute to part of my PhD thesis and will also be submitted to peer-reviewed journals for publication.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

To protect your privacy, your name will be coded on all materials used for data collection, analysis, reports and publications. During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. However, your name will remain coded and anonymous. Your privacy and anonymity will be of primary concern when handling the data.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research officer in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus for ten years.

Following the ten-year storage period all hard copies of data will be destroyed (shredded) and electronic data will be wiped.

What are the costs of participating in this research?

The first testing session will take approximately three hours. If you decide to participate in the second testing session, another three-hour block will be required seven days later at the same time of day. You will receive a \$20 petrol voucher as koha for travel reimbursement to testing sessions.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within two weeks whether you would be available to take part in the study or not. After consideration you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to me, Scott Brown.

Will I receive feedback on the results of this research?

Yes, upon completion to the study a written report will be sent to you detailing the results in graphical form as well as specific recommendations for yourself based on your test results. It is your choice whether you share this information with your coach or other people.

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

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Dr Matt Brughelli, matt.brughelli@aut.ac.nz, 09 921 9999 ext 7025.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEK, Kate O'Connor, ethics@aut.ac.nz, 09 921 9999 ext 6038.

Whom do I contact for further information about this research?

***Researcher Contact Details:***

Scott R. Brown, scott.brown@aut.ac.nz, 09 921 9999 ext 5182.


***Project Supervisor Contact Details:***

Dr Matt Brughelli, Sport Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Faculty of Health and Environmental Sciences, AUT University, Private Bag 92006, Auckland 1020, matt.brughelli@aut.ac.nz, 09 921 9999 ext 7025.

**Approved by the Auckland University of Technology Ethics Committee on 17/12/2013,  
AUTEK Reference number 13/378.**

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

## Appendix V. Recording Protocol Form.

<b>Recording</b>  <b>Protocol for Test</b>	
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Surname: \_\_\_\_\_ First name: \_\_\_\_\_ Middle initial: \_\_\_\_\_

Date of birth (DD/MM/YY): \_\_\_\_\_ Age: \_\_\_\_\_

Contact email for results report: \_\_\_\_\_

**What is your ethnic origin?** (Please tick all that apply)

- |   |   |  |
|---|---|--|
| <input type="checkbox"/> NZ European / Pakeha | <input type="checkbox"/> Fijian                 | <input type="checkbox"/> Other Asian (e.g. Philippine, Japanese) |
| <input type="checkbox"/> NZ Maori             | <input type="checkbox"/> Other Pacific          | <input type="checkbox"/> British / European                      |
| <input type="checkbox"/> Samoan               | <input type="checkbox"/> Other (Please specify) | <input type="checkbox"/> Australian                              |
| <input type="checkbox"/> Cook Island Maori    | <input type="checkbox"/> Chinese                | <input type="checkbox"/> South African                           |
| <input type="checkbox"/> Tongan               | <input type="checkbox"/> Korean                 |  |
| <input type="checkbox"/> Niuean               | <input type="checkbox"/> Indian                 |  |

**At what age did you first play rugby?**

- |                                      |                                |   |
|--------------------------------------|--------------------------------|---|
| <input type="checkbox"/> Less than 6 | <input type="checkbox"/> 10-11 | <input type="checkbox"/> 16-17            |
| <input type="checkbox"/> 6-7         | <input type="checkbox"/> 12-13 | <input type="checkbox"/> 18-19            |
| <input type="checkbox"/> 8-9         | <input type="checkbox"/> 14-15 | <input type="checkbox"/> 20 years or more |

**How many total years of rugby experience do you have?** \_\_\_\_\_**What is the highest level of rugby you have played** (please tick one) **and please write in which years you played at each level?** (e.g. 1995-1999 & 2001) (If you never played at one level please leave blank)

- |   |  |
|---|--|
| <input type="checkbox"/> Social Club _____                        | <input type="checkbox"/> Provincial (e.g. ITM Cup, NPC) _____        |
| <input type="checkbox"/> Club Senior Reserve / Second grade _____ | <input type="checkbox"/> Elite National (e.g. Super Rugby) _____     |
| <input type="checkbox"/> Club Senior A / Premier _____            | <input type="checkbox"/> Elite International (e.g. All Blacks) _____ |

**What position have you played most often during your rugby career?**

- |   |  |                                    |
|---|--|------------------------------------|
| <input type="checkbox"/> L. head prop   | <input type="checkbox"/> Blindside flank | <input type="checkbox"/> Centre    |
| <input type="checkbox"/> T. head prop   | <input type="checkbox"/> No. 8           | <input type="checkbox"/> Wing      |
| <input type="checkbox"/> Hooker         | <input type="checkbox"/> Half-back       | <input type="checkbox"/> Full-back |
| <input type="checkbox"/> Lock           | <input type="checkbox"/> 1st 5/8         |                                    |
| <input type="checkbox"/> Openside flank | <input type="checkbox"/> 2nd 5/8         |                                    |



**How many games total have you played whilst playing rugby?** (spent any time on the field during the game)

- ☐ 1-50                                      ☐ 101-150                                      ☐ more than 200  
☐ 51-100                                      ☐ 151-200

**Participant information** (these are measured by the researchers)

Participant ID: \_\_\_\_\_ Body-height: \_\_\_\_\_ m                      Body-mass: \_\_\_\_\_ kg  
 Preferred kicking leg: \_\_\_\_\_ Preferred sidestepping leg: \_\_\_\_\_

**Participant tracking** (these are measured by the researchers)

**Session one date** (DD/MM/YY): \_\_\_\_\_

Time in: \_\_\_\_\_ Total time: \_\_\_\_\_ min                      Shorts size: \_\_\_\_\_  
 Time out: \_\_\_\_\_ Shirt size: \_\_\_\_\_                      Shoe size: \_\_\_\_\_ US

**Session two date** (DD/MM/YY; if applicable): \_\_\_\_\_

Time in: \_\_\_\_\_ Total time: \_\_\_\_\_ min                      Shorts size: \_\_\_\_\_  
 Time out: \_\_\_\_\_ Shirt size: \_\_\_\_\_                      Shoe size: \_\_\_\_\_ US

**Participant testing** (these are measured by the researchers)

	Left leg (sidestep right)		Right leg (sidestep left)	
	Ball	Without	Ball	Without
Trial 01				
Trial 02				
Trial 03				
Trial 04				
Trial 05				
Trial 06				
Trial 07				
Trial 08				
Trial 09				
Trial 10				
Trial 11				
Trial 12				
Trial 13				
Trial 14				
Trial 15				

Notes:

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Approved by the Auckland University of Technology Ethics Committee on *17/12/2013*  
 AUTEK Reference number *13/378*.

## Appendix VI. Conference Presentation: Sprint Kinetics and Kinematics on a Non-Motorised Treadmill are Unique to Position in Rugby Athletes.

This appendix comprises the following presentation at *European College of Sports Science 2015* which is in support of Chapter 4.

### Reference:

Brown SR, Cross MR. Sprint kinetics and kinematics on a non-motorised treadmill are unique to position in rugby athletes. 20th annual Congress of the European College of Sport Science. 2015:329.

### Author contribution:

Brown SR, 95%; Cross MR, 5%.

### Overview

Unique positional characteristics are an accepted part of rugby union. Ruling structures indirectly govern athletes to specific actions that result in distinct mechanical stresses specific to position. While variables such as horizontal force ( $F_H$ ) have been highlighted as fundamental to sprint performance in rugby [231], kinetics and kinematics specific to position have not been investigated. We assessed rugby athletes on a non-motorised treadmill (NMT) to illuminate if position-specific sprint profiles exist. Thirty male academy rugby athletes, separated into forwards and backs ( $n = 15 / 15$ ), performed maximal 6s sprints on a NMT. Comparison of kinetic and kinematic variables were made between positions during initial acceleration (steps 1 – 2), acceleration (steps 3 – 12) and maximal velocity (steps 13 – 22) phases using effect sizes (ES). Backs produced higher absolute and relative  $F_H$  at initial acceleration (ES = 1.07 and ES = 1.6 respectively) but lower absolute  $F_H$  at acceleration (ES = -0.78) and maximal velocity (ES = -1.0) compared to forwards. Backs displayed faster split times at 2m (ES = -1.03), 5m (ES = -0.82), 10m (ES = -0.63) and 15m (ES = -0.50) but achieved a lower peak velocity (ES = -0.54) compared to forwards. During NMT sprinting, backs generated greater levels of  $F_H$  during initial acceleration, resulting in faster short-distance split times, whereas forwards produced greater levels of  $F_H$  during acceleration and maximum velocity. While backs typically reach greater peak velocities during over-ground sprinting [231], forwards displayed higher peak velocities on the NMT; seeming contradictory to moderate correlations between NMT and over-ground sprinting [238].

Given forwards are heavier and possess greater posterior-chain strength [9], the superior levels of absolute force and peak velocities exhibited by this position supports the notion that NMT sprinting favours these characteristics. The high intrinsic resistance of the NMT, requiring greater levels of  $F_H$ , reinforces the contention that the lighter and weaker backs were disadvantaged in maintaining faster split times with increasing distance and reaching peak velocity. The relationship between over-ground and NMT sprint performance may be weakened in sporting codes featuring position-subsets with differing mechanical profiles. Practitioners wishing to profile and compare sprint mechanics using NMTs are advised to separate athletes by position.

## Appendix VII. Conference Presentation: Carrying a Ball can Influence Sidestepping Mechanics in Rugby.

This appendix comprises the following presentation at *International Society of Biomechanics in Sport 2015* which is in support of Chapter 7.

### Reference:

Brown SR, Brughelli M, Hume PA. Carrying a ball can influence sidestepping mechanics in rugby. 33rd International Conference on Biomechanics in Sports. Poitiers, FRA; 2015.

### Author contribution:

Brown SR, 90%; Brughelli M, 5%; Hume PA, 5%.

### Overview

**Introduction:** Rugby union is the most played contact sport in the world with over seven million participants spanning 120 countries [1]. Rugby includes an assortment of physically demanding activities including running, sprinting, kicking, passing, colliding, tackling and scoring; all are required during the course of an 80-minute match [177]. Rugby athletes are often plagued with lower-extremity musculoskeletal injuries, specifically hamstring and anterior cruciate ligament (ACL) injury [75]. The majority of ACL injury rehabilitation claims are classified as non-contact and are seen frequently during sidestepping [75].

Previous research examining sidestepping has primarily focused on females, footballers or a combination of the two [75]. With 78% (4.5 million) of all rugby athletes being male [1], there is limited research that has examined male rugby athletes and accurately replicated the tasks seen in match play. While sidestepping has been examined in Australian Rules footballers, the velocities at which the task was performed may potentially be lower than match velocities [75], calling into question the applicability of findings. Several authors have examined the influence of ball-handling [251], passing [252] and dribbling [153] during sidestepping and have discovered substantial alterations in lower-extremity mechanics. There is no published study that has examined the effects of carrying a ball during sidestepping in rugby; ball retention being a major component of success in rugby [1].

**Methods:** Eighteen male academy (high performance development) rugby athletes (age  $20 \pm 3$  y, body-height  $1.9 \pm 0.1$  m, body-mass  $100 \pm 14$  kg) performed maximal effort  $45^\circ$  sidestepping tasks without and with a rugby ball.

**Data collection:** The planned sidestepping task [178] consisted of athletes accelerating with maximum effort for 10-m before performing an offensively-initiated evasive manoeuvre, using their preferred kicking leg, at a 45° angle and then reaccelerating out to complete the task. Following a warm-up, static calibration and range of motion trials were captured at 200 Hz with a nine-camera three-dimensional motion capture system (T10S, Vicon Motion System Ltd., Oxford, UK) and a synchronised embedded force platform (Type 9287C, Kistler Instrumente AG, Winterthur, CH) collected at 1000 Hz. Athletes completed a minimum of eight trials without and with a ball given in a random order. A successful trial consisted of athletes reaching a velocity of  $\geq 6 \text{ m}\cdot\text{s}^{-1}$ , striking the force platform completely with the sidestepping leg and executing the task as quickly as possible to closely simulate the requirements of a match situation.

**Data processing:** Athlete-specific joint-centre locations were calculated from the range-of-motion trials using a custom-made MATLAB programme (R2014b, The MathWork, Inc., Natick, MA, US). Three-dimensional motion and ground reaction force data were filtered with a fourth-order Butterworth low-pass filter using a cut-off frequency of 16 Hz in Visual 3D (4.91.0, C-Motion, Inc., Germantown, MD, US). Knee power data were normalised by body-mass ( $\text{W}\cdot\text{kg}^{-1}$ ) and time data were normalised to stance phase (%; from initial contact to final contact) to facilitate comparison between all athletes. Knee angle and hip data were examined during initial contact, weight acceptance, peak push-off and final push-off phases while knee power and knee velocity were examined at peak braking and peak propulsive phases using another custom-made MATLAB programme [178].

**Results:** Performance variable effects of sidestepping with a ball compared to without a ball were: approach velocity ( $6.6 \pm 0.7 \text{ m}\cdot\text{s}^{-1}$  and  $6.6 \pm 0.4 \text{ m}\cdot\text{s}^{-1}$ ; ES = 0.13) was unclear, stance time ( $0.19 \pm 0.02 \text{ ms}$  and  $0.19 \pm 0.03 \text{ ms}$ ; ES = 0.013) was likely trivial, depart velocity ( $6.1 \pm 0.4 \text{ m}\cdot\text{s}^{-1}$  and  $6.2 \pm 0.5 \text{ m}\cdot\text{s}^{-1}$ ; ES = -0.20) was possibly trivial and the angle ( $16 \pm 2^\circ$  and  $16 \pm 3^\circ$ ; ES = 0.092) was likely trivial. Knee flexion angle showed a possibly trivial decrease (ES = -0.16) at initial contact, knee adduction angle showed a possibly trivial increase at initial contact, a likely small increase at weight acceptance, a possibly trivial increase at peak push-off (ES = 0.19, 0.38 and 0.17 respectively) and hip adduction angle showed a possibly small increase at peak push-off (ES = 0.27) when sidestepping with a ball compared to without a ball; all other variables showed unclear or trivial inferences (Table A). Sidestepping with a ball showed peak knee power as unclear and peak knee velocity with a possibly trivial decrease (ES = 0.032 and ES = -0.14 respectively) during the braking phase and possibly trivial decreases (ES = -0.20 and -0.16 respectively) during the propulsive phase compared to without a ball (Figure A).

**Discussion:** Studies [153, 251, 252] including a ball during sidestepping have noted kinematic increases in knee flexion, knee abduction and hip adduction angles; the current study can only partially support these findings. Knee flexion angle for example, while carrying a ball, was slightly smaller at initial contact and then remained consistent throughout the remaining phases of sidestepping. Knee adduction angle was slightly larger while carrying a ball at all phases of sidestepping; with an unclear inference at final push-off. Unlike Chan et al. [153] who found that dribbling a ball increased knee abduction angle at weight acceptance in female basketball athletes, we found an increased knee adduction angle at initial contact, weight acceptance and peak push-off when sidestepping with a ball which is more in line with findings [252] while attending to a ball in male and female basketball athletes. Hip adduction angle was larger at all phases while carrying a ball in this study and showed a clear and possibly small increase during peak push-off, which is comparable to findings of larger hip adduction angles [153, 252]. Our findings of larger knee and hip adduction angles may be the result of substantially faster velocities while entering ( $\sim 6.6 \text{ m}\cdot\text{s}^{-1}$ ) and exiting ( $\sim 6.2 \text{ m}\cdot\text{s}^{-1}$ ) the manoeuvre. In addition, male rugby athletes may present different (unique) sidestepping mechanics as the requirements of the sport differ considerably from those found in male and female basketball athletes.

Table A. Sidestepping kinematics without and with a ball.

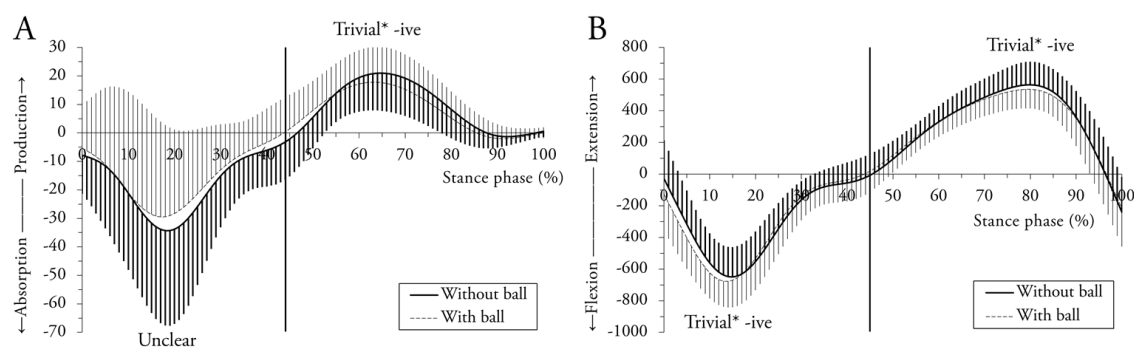
Joint angles: Sidestepping phase:	Without ball (Deg)	With ball (Deg)	With – without ball sidestepping		
			<i>p</i> -value	Mean change; 90% CL	ES: Qualitative inference
Knee flexion (+) / extension (–)					
Initial contact	27 ± 8	26 ± 7	0.091	-1.4; ±1.3	-0.16: Trivial* -ive
Weight acceptance	39 ± 7	39 ± 6	0.732	0.29; ±1.41	0.041: Trivial**
Peak push-off	52 ± 5	52 ± 6	0.919	-0.086; ±1.457	-0.016: Unclear
Final contact	22 ± 7	22 ± 6	0.877	-0.15; ±1.69	-0.023: Unclear
Knee adduction (+) / abduction (–)					
Initial contact	9 ± 5	10 ± 4	0.199	1.1; ±1.5	0.19: Trivial* +ive
Weight acceptance	13 ± 5	15 ± 4	0.023	2.2; ±1.5	0.38: Small** +ive
Peak push-off	18 ± 7	19 ± 6	0.207	1.3; ±1.7	0.17: Trivial* +ive
Final contact	11 ± 5	11 ± 4	0.821	0.16; ±1.24	0.039: Unclear
Hip adduction (+) / abduction (–)					
Initial contact	5 ± 8	6 ± 6	0.179	1.04; ±1.28	0.13: Trivial**
Weight acceptance	6 ± 8	7 ± 7	0.191	0.94; ±1.20	0.12: Trivial**
Peak push-off	10 ± 8	12 ± 7	0.031	2.2; ±1.6	0.27: Small* +ive
Final contact	11 ± 7	11 ± 5	0.561	0.33; ±0.97	0.055: Trivial***

Footnote: Knee and hip joint kinematics during sidestepping without and with a ball and inferences for change of the means. Values are means ± standard deviation; mean change; ±confidence limits (CL) (90%); ES, effect size; (+) and (–) , positive and negative values associated with the corresponding angle; +ive and -ive, substantial positive and negative change with ball relative to without ball sidestepping; trivial and small inference: 25-74%, possibly (\*); 75-94%, likely (\*\*).

The results for knee power and knee flexion velocities were unclear or trivial mechanistically and are most likely due to large confidence limits. While further work is needed in this area to clarify our findings, it is interesting that smaller peaks were observed in knee joint power while the knee velocity peaks were similar when sidestepping with a ball during the braking and propulsive phases when compared without a ball. During these phases, the ACL and other soft tissue structures in the lower-extremity have the potential to experience a greater amount of loading over a longer period as a result of increased tension development [178]. If sidestepping without a ball elicits greater energy absorption and production peaks, the ACL may experience greater tensile loading; results of which may present incorrect or misleading information that are unrepresentative of those found during match play. Furthermore, when compared to female footballers performing sidestepping on the preferred leg without a ball, the male rugby athletes in this study elicited substantially larger power absorption ( $-34$  vs  $-23$   $\text{W}\cdot\text{kg}^{-1}$ ; 33%), power production ( $20$  vs  $12$   $\text{W}\cdot\text{kg}^{-1}$ ; 42%), knee flexion velocity ( $-708$  vs  $-499$   $\text{deg}\cdot\text{s}^{-1}$ ; 30%) and knee extension velocity ( $587$  vs  $530$   $\text{deg}\cdot\text{s}^{-1}$ ; 10%) [178]. Based on this simple observation, it would seem essential that male and female athletes should not be placed into the same data pool for lower-extremity analyses.

While purely speculative at this time, the altered mechanics of sidestepping with a ball compared to without a ball as observed in this study may be due, in part, to the athletes' ingrained protection of the ball to maintain possession. In order to acquire a similar centre-of-mass position without the use of the arms (e.g. while carrying a ball) and obtain the same performance objective, an athlete may be required to reorient the trunk and / or the lower-extremities. As this topic was not the focus of the current study, further investigation is required to accept or reject this contention.





**Figure A.** Graphical representations of (A) knee power ( $\text{W}\cdot\text{kg}^{-1}$ ) and (B) knee velocity ( $\text{deg}\cdot\text{s}^{-1}$ ) without and with a ball during the stance phase of sidestepping; error bars, equivalent to one standard deviation; vertical line, indicates the division of the braking and propulsive phases; -ive, substantial negative change with ball relative to without ball sidestepping; trivial inference: 25-74%, possibly (\*) [298].

**Conclusion:** Sidestepping with a ball resulted in 15% greater knee adduction angle during weight acceptance and 18% greater hip adduction angle during peak push-off than without a ball; implicating that sidestepping with a ball alters lower-extremity mechanics relevant to ACL injury risk. It is suggested that future biomechanical evaluations of athletes require the inclusion of the implement / ball specific to the sport in order to ensure accurate interpretation of movement patterns.

## Appendix VIII. Conference Presentation: Knee and Hip Strength Profiles Characterise Functional Needs in Rugby Athletes.

This appendix comprises the following presentation at *International Society of Biomechanics 2015* which is in support of Chapter 3.

### Reference:

Brown SR. Knee and hip strength profiles characterise functional needs in rugby athletes 25th Congress of the International Society of Biomechanics. Glasgow, GBR; 2015.

### Author contribution:

Brown SR, 100%.

### Overview

**Introduction and objectives:** Rugby union is an intermittent high-intensity contact sport requiring maximum strength and power performances, interspersed with low-intensity efforts [177]. Rugby forwards utilise strength for success in contact situations such as front-on tackling, rucks, mauls and scrums; whereas backs utilise power for success in high-speed side-on tackling and contact evasion [168]. Unique force-producing attributes are developed in specific joints and angles between the two positions for efficiency. Lower-extremity strength assessment techniques should shift their importance to multi-joint assessments in conjunction with the angles of peak torque for a complete representation of an athlete's lower-extremity strength [170]. Bilateral single-joint or unilateral multi-joint strength deficits may increase risk of lower-extremity injury; especially when unique positional attributes can further accelerate strength differences [98]. We assessed rugby athletes through multi-joint and multi-speed isokinetic actions to illuminate any position specific strength profiles.

**Methods:** Twenty-nine male academy (development-level) rugby athletes (age  $22 \pm 4$  y, body-height  $1.9 \pm 0.1$  m, body-mass  $97 \pm 11$  kg), separated into forwards ( $n = 15$ ) and backs ( $n = 14$ ), performed bilateral isokinetic strength assessments at the knee and hip with concentric ( $60^\circ \cdot s^{-1}$  and  $180^\circ \cdot s^{-1}$ ) actions and at the knee with eccentric ( $60^\circ \cdot s^{-1}$ ) actions. Fourth-order polynomial curve fitting was used to identify peak torque and angle of peak torque. Hamstrings-to-quadriceps (H:Q) ratios and knee flexion-to-hip extension (KF:HE) ratios were calculated.

**Results:** Backs were smaller in stature (MDiff =  $-0.032$  m; ES =  $-0.45$ ) and lighter in body-mass (MDiff =  $-13$  kg; ES =  $-1.3$ ) compared to forwards. Strength comparisons at the knee showed small decreases in strength of the backs compared to forwards during concentric knee

extension and flexion at  $60^{\circ}\cdot s^{-1}$  (MDiff = -19 N·m; ES = -0.37 and MDiff = -11 N·m; ES = -0.48 respectively) and small to moderate decreases at  $180^{\circ}\cdot s^{-1}$  (MDiff = -23 N·m; ES = -0.59 and MDiff = -15 N·m; ES = -0.85). Eccentric peak extension and flexion torques showed unclear and small decreases in strength of backs compared to forwards (MDiff = 1.07 N·m; ES = 0.018 and MDiff = -10.7 N·m; ES = -0.30). Compared to forwards, backs showed moderate decreases in peak concentric flexion angles at  $60^{\circ}\cdot s^{-1}$  and  $180^{\circ}\cdot s^{-1}$  (MDiff =  $-10^{\circ}$ ; ES = -1.004 and MDiff =  $-3.3^{\circ}$ ; ES = -0.65) and moderate to small changes in peak eccentric extension and flexion at  $60^{\circ}\cdot s^{-1}$  (MDiff =  $-5.7^{\circ}$ ; ES = -0.78 and MDiff =  $4.4^{\circ}$ ; ES = 0.58). At the hip, strength comparisons between forwards and backs showed unclear to small decreases in strength during hip extension and flexion at  $60^{\circ}\cdot s^{-1}$  (MDiff = -10 N·m; ES = -0.12 and MDiff = -11 N·m; ES = -0.33) with differences between the groups unclear at  $180^{\circ}\cdot s^{-1}$  (MDiff = 4.2 N·m; ES = 0.046 and MDiff = -5.0 N·m; ES = -0.16). Backs showed a small increase in angle of peak torque during  $60^{\circ}\cdot s^{-1}$  hip extension (MDiff =  $1.1^{\circ}$ ; ES = 0.29) and a large decrease during hip flexion (MDiff =  $-2.7^{\circ}$ ; ES = -1.2) compared to forwards.

**Conclusion:** It was not surprising that forwards had greater peak torque values at the knee and hip compared to backs considering the conceptual positional requirements of each group [168]. Strength differences between forwards and backs were similar to those reported for professional rugby athletes [177]; with the exception of an overall decrease in strength, likely a result of the age, competition level and strength training history. Backs possessed more desirable angles of peak torque during extension and flexion actions (i.e. larger extension and smaller flexion angles) and speeds given the types of movement patterns they use in match play. Adequate strength at long muscle lengths are more desirable in sports with sprinting bouts as hamstring injuries are suggested to occur near full knee extension [114]. Forwards and backs showed substantially smaller H:Q ratios (0.54 vs 0.67 forwards; 0.53 vs 0.64 backs) and KF:HE ratios (0.39 vs 0.58 forwards; 0.37 vs 0.61 backs) compared to professional rugby athletes [177]; most likely resulting from overactive quadriceps and / or weak hamstrings. Meaningful strength differences were present in academy rugby forwards and backs at the knee and hip which became more substantial during faster assessment speeds. While rugby forwards had superior lower-extremity strength compared to backs, their associated angle of peak torque occurred at inferior degrees; potentially lending way to lower-extremity injury. Bilateral single-joint and unilateral multi-joint lower-extremity strength assessments can

facilitate more informed recommendations on whether athletes would be more advantaged to perform specific movements aimed to improve strength at longer muscle lengths.

## **Appendix IX. Conference Presentation: A Targeted Strength Training Programme and its Effect on Performance and Injury Risk: A Case Study in Sprinting.**

This appendix comprises the following presentation at *European College of Sports Science 2016* which is in support of Chapter 9.

### **Reference:**

Brown SR, Morin JB. A targeted strength training programme and its effect on performance and injury risk: A case study in sprinting 21<sup>st</sup> annual Congress of the European College of Sport Science. 2016.

### **Author contribution:**

Brown SR, 95%; Morin JB, 5%.

### **Overview**

Athletic performance and injury risk are key components within sports science; and while they may appear unlike, they are in fact inherently coupled. A maximal sprint effort on a non-motorised treadmill (NMT) for example, can provide both performance (i.e. power) and injury risk (i.e. asymmetry) variables within the same trial [242]. However, this link is seen less often in practice due to the overwhelming demands of performance. Recent observations show that hip extension strength is related to sprint horizontal force ( $F_H$ ) and thus performance [227], and that targeted strength training can decrease lower-extremity asymmetry [98]. We therefore assessed an athlete on a NMT to illuminate any sprint asymmetry and then prescribed a targeted strength training programme aimed at altering the deficiencies. One male athlete performed four 6-s sprints on a NMT once per week for two 6-week blocks. The sprint testing consisted of an initial “unloaded” sprint to profile symmetry and three subsequent sprints with randomised electronic-brake loads to profile performance. A general training regime with no additional sprint training was programmed during weeks 1-6, and then targeted hip extension exercises based on the asymmetries found were added for weeks 7-12. Pre to post training, the athlete maintained maximal velocity (8.4 to 8.3 m·s<sup>-1</sup>; -0.26%) and improved relative maximal  $F_H$  (8.3 to 10 N·kg<sup>-1</sup>; 15%) and power (18 to 20 W·kg<sup>-1</sup>; 13%). The athlete also increased  $F_H$  in his “weak” leg (2.7 to 3.1 N·kg<sup>-1</sup>; 15%) thereby decreasing his original  $F_H$  asymmetry (52 to 45%; 13%). Greater outcomes were found in weeks 10-12 compared to weeks 7-9. We examined both global

force production and individual contribution from each leg during a maximal sprint and found encouraging alterations in performance and injury risk variables as a result of targeted hip extension exercises. These changes are very likely the result of the exercise prescription to increase  $F_H$  (via hip extension) in the “weak” leg, thus elevating global  $F_H$  and subsequently performance while simultaneously reducing the  $F_H$  asymmetry between the legs [227]. These pilot findings may have strong implications for individualised programming to both increase sprint performance and decrease injury risk.

## Appendix X. Ethical Approval from AUTECH for Appendices XI – XIV.



**AUTECH  
SECRETARIAT**

To: Patria Hume  
 From: Madeline Banda, Executive Secretary, AUTECH  
 Date: 17 June 2013  
 Subject: Ethics Application: **12/332 Sports Performance research institute New Zealand (SPRINZ) Clinics database**

Dear Patria

Thank you for providing evidence as requested, which satisfies the points raised by the AUT University Ethics Committee (AUTECH).

Your ethics application has been approved for three years until 17 June 2016.

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

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 17 June 2016;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 17 June 2016 or on completion of the project.

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

AUTECH grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

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

All the very best with your research,

Madeline Banda

Executive Secretary

**Auckland University of Technology Ethics Committee**

## **Appendix XI. Conference Presentation: Multi-Disciplinary Perspectives on the Use of Lower-Extremity Injury Assessments for a Rugby Player's Return-to-Play.**

This appendix comprises the following presentation at *Sports Medicine New Zealand 2013* which is in support of Chapters 3, 4 and 9.

### **Reference:**

Brown SR, Brughelli M, Hume PA, King D, Gill N, Craighead H, Kara, S. Multi-disciplinary perspectives on the use of lower-extremity injury assessments for a rugby player's return-to-play. *NZ J Sports Med.* 2014;41(1):30.

### **Author contribution:**

Brown SR, 80%; Brughelli M, 5%; Hume PA, 5%; King D, 2.5%; Gill N, 2.5%; Craighead H, 2.5%; Kara S, 2.5%.

### **Overview**

Intra and inter-limb imbalances can affect injury risk and athletic performance in rugby [177]. Dynamometry and force plate instrumented treadmills are two methods for assessing an athlete's return-to-play status [114]. Interpretation of these data by health practitioners is important to the health and longevity of the athlete. Intra and inter-limb imbalances can affect injury risk and athletic performance in rugby. Dynamometry and force plate instrumented treadmills are two methods for assessing an athlete's return-to-play status. Interpretation of these data by health practitioners is important to the health and longevity of the athlete. A professional male rugby league athlete (28 y, 1.78 m, 98 kg) was tested pre and 10-weeks post-rehabilitation of a patellar tendon rupture. Isokinetic concentric knee and hip extensor and flexor strength on each leg at  $60^{\circ}\cdot\text{s}^{-1}$  was completed using a Humac Norm dynamometer and standard protocols [177]. Bilateral sprint kinetics for five maximal effort sprints was completed on a Woodway self-motorised instrumented treadmill. Peak torque, angle of peak torque, peak horizontal force and peak vertical force were compared pre and post-rehabilitation against normative data from 14 un-injured rugby league athletes of the same position and similar characteristics. Pre to post testing: peak torque increased in the injured leg during knee extension (47%), knee flexion (47%) and hip extension (49%); peak torque leg asymmetry decreased 22%; angle of peak torque increased in the injured leg during hip extension (27%) and hip flexion (67%) reducing asymmetries by 50%; sprinting horizontal force increased (injured: 50%, non-injured: 19%); sprinting vertical force



decreased (injured: 3%, non-injured: 5%); horizontal and vertical peak force leg asymmetries decreased 18% and 13% respectively. The return-to-play decision made by the athlete's supporting health team and coaching staff was based primarily on the sizable asymmetry decreases and return to normative ranges for knee and hip strength measures. Sports injury and performance biomechanist Patria Hume: "To enable return to sport at the elite level, baseline values are needed to determine return-to-play levels, as well as quality normative databases for athlete types". Sports medic Doug King: "I use baseline values a lot and judge athletes' return-to-sport activities based around these values. I perform regular baseline assessments to ensure athletes can equal or better these values throughout the season". Strength and conditioning coach Nic Gill: "The use of objective data to assess the quality of rehabilitation and to track progress back to 'normal function' is valuable for all rugby code athletes". Sports team physiotherapist Hamish Craighead: "Concise programs that provide targeted exercises give medical, training staff and the athlete the opportunity to approach their rehabilitation with confidence". Sports team doctor Stephen Kara: "Reliable, valid and sensitive assessments ensure we have minimised the risk of recurrence prior to returning the athlete to play". Lower-extremity assessments are useful for an athlete's career and a team's investment. It is recommended that coaching staff support athletic baseline and post-injury assessments for improved performance and to enable quality information on which to base return-to-play decisions.

## **Appendix XII. Conference Presentation: Assessment Strategies for Individualised Injury Prevention in Sport.**

This appendix comprises the following presentation at *Sports Medicine New Zealand 2014* which is in support of Chapters 3, 4 and 9.

### **Reference:**

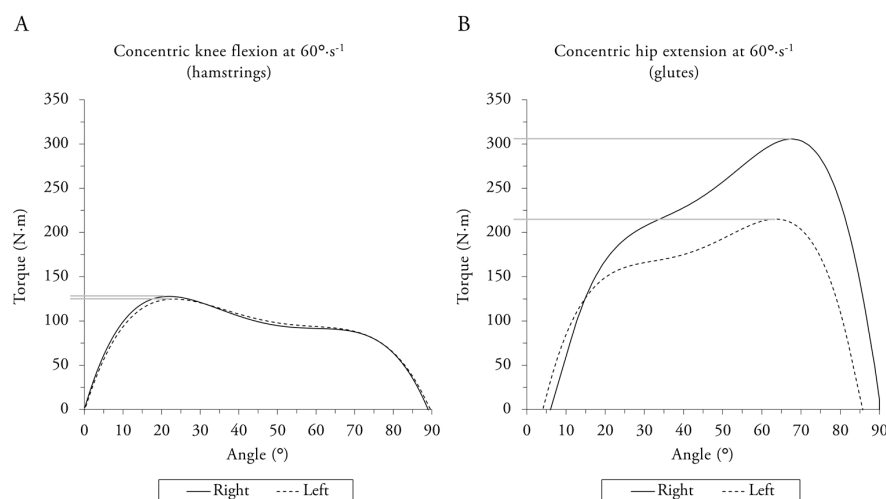
Brown SR, Brughelli M. Assessment strategies for individualised injury prevention in sport. *NZ J Sports Med.* 2014;41(2):78-9.

### **Author contribution:**

Brown SR, 95%; Brughelli M, 5%.

### **Overview**

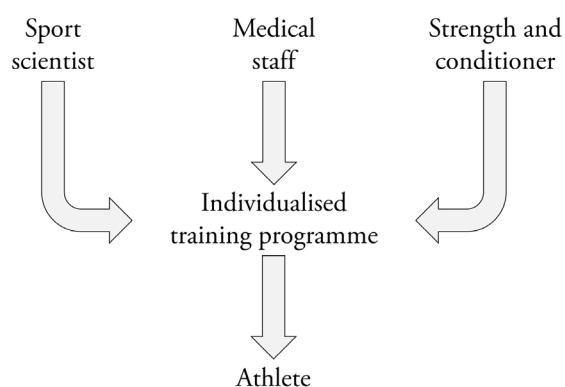
Injury prevention programmes are effective at decreasing injuries in sport by modifying variables such as knee flexion and knee valgus angles during landing tasks [94]. The majority of injury prevention programmes include components of running, active stretching, strength (concentric & eccentric), balance, plyometric and sport-specific drills; however, the key components to make a successful programme are unknown. Failure to understand the key variables is attributed to 1) a reductionist view supporting a linear and unidirectional cause-effect model with single-component assessments to predict injury; and 2) a generalised “catch-all” approach to injury prevention throughout the sport season. While single-component assessment strategies (i.e. isokinetic peak torque values during knee extension / flexion) may financially match the needs of a sporting team, they isolate individual joints and / or movements and can potentially miss “the big picture” (Figure B). Multi-component assessment strategies, on the other hand, (i.e. isokinetic peak torque and angles of peak torque values of the knee and hip during extension / flexion and / or non-motorised treadmill sprint kinetics) increase equipment, time and cost but allow for a holistic view of the strengths and weaknesses of the athlete [98]. Information gained from the assessments can then be used to further guide programming recommendations.



**Figure B.** An example of a typical graph examining side-to-side asymmetries during concentric isokinetic A.) knee flexion with no apparent difference in peak torque (2%); and B.) hip extension with an obvious difference in peak torque (42%) [170].

Generalised programming, designed for large team sports such as American football, may appear to be the best option, requiring minimal personnel and sectioning athletes into similar sub-groups while training. Generalised programming may overlook individual deficiencies, however, when compared to the progress of the majority. Individualised programming is custom-made to target an athlete's weakness; aimed at decreasing injury risk that may result from a deficiency and improving performance to the level of the position / team. Similar to the multi-component assessment strategy, individualised programming requires additional personnel, time and knowledge.

Injury prevention cannot be individualised without first identifying clinical and functional deficits for each athlete. Thus multiple and independent assessments are required that involve reliable, objective and quantitative results during various movements. Assessment data (profiling) will then begin to illustrate guidelines during the interpretation process [177]. Several researchers [98, 112, 172] have shown positive results from individual programming in sports such as Australian football league, football and rugby league. Knowledge in this area however, is limited; requiring further research into multi-component assessments and individualised programming on a large scale. Communication and collaboration between sports scientist, medical staff and strength and conditioners are required to ensure the most effective steps are taken in the injury prevention process (Figure C).



**Figure C. An example of a collaboration to create an individualised training programme for an athlete [170].**

Our jobs as sport scientists, physiotherapists or medical staff are not easy as we must continue to collect as much information as possible whilst considering important factors like time and cost. We must keep in mind that an athlete's career (short- and long-term) is often in our hands and should be our most important concern, regardless of the process. We therefore propose that all injury prevention "screening" include multi-component assessments to enhance our understanding of the athlete. This information should then be used to guide individualised injury prevention programming.

### **Appendix XIII. Publication: Lower-Extremity Isokinetic Strength Profiling in Professional Rugby League and Rugby Union.**

This appendix comprises the following publication in *International Journal of Sports Physiology and Performance* which is in support of Chapter 3.

#### **Reference:**

Brown SR, Brughelli M, Griffiths PC, Cronin JB. Lower-extremity isokinetic strength profiling in professional rugby league and rugby union. *Int J Sports Physiol Perform.* 2014;9(2):358-61.

#### **Author contribution:**

Brown SR, 85%; Brughelli M, 5%; Griffiths PC, 5%; Cronin JB, 5%.

#### **Overview**

While several studies have documented isokinetic knee strength in junior and senior rugby league athletes, investigations of isokinetic knee and hip strength in professional rugby union athletes are limited. The purpose of this study was to provide lower-extremity strength profiles and compare isokinetic knee and hip strength of professional rugby league and rugby union athletes. Thirty-two professional rugby league and twenty-five professional rugby union athletes participated in this cross sectional analysis. Isokinetic dynamometry was used to evaluate peak torque and strength ratios of the preferred and non-preferred leg during seated knee extension / flexion and supine hip extension / flexion actions at  $60^{\circ}\cdot s^{-1}$ . Forwards from both codes were taller, heavier and had a higher body mass index compared to the backs of each code. Rugby union forwards produced significantly ( $P < 0.05$ ) greater peak torque during knee flexion in the preferred and non-preferred leg (ES = 1.81 and 2.02) compared to rugby league forwards. Rugby league backs produced significantly greater hip extension peak torque in the preferred and non-preferred leg (ES = 0.83 and 0.77) compared to rugby union backs. There were no significant differences in hamstring to quadriceps ratios between code, position or leg. Rugby union forwards and backs produced significantly greater knee flexion to hip extension ratios in the preferred and non-preferred leg (ES = 1.49 to 2.26) compared to rugby union athletes. It seems that the joint torque profiles of athletes from rugby league and union codes differs, which may be attributed to the different demands of each code.

## Introduction

While rugby league and rugby union contain similar fundamental skills such as tackling, passing, catching etc., they differ in their technical [168] and physical demands [299]. Rugby league forwards and backs generally play and train, on defence and offence, at mid to high-speeds in an upright position [168]. Rugby union forwards are generally involved in strength dominated and relatively low speed action such as front-on tackling, rucking and mauling whereas rugby union backs are involved in high-speed side-on tackling and contact evasion [168, 300]. It is therefore logical to assume that these differences in demands at specific joints and joint angles would lead to unique force producing attributes between codes and positions.

Profiling lower-extremity strength and power of rugby league [301] and rugby union [168] athletes is of interest to strength and conditioning coaches for injury prevention and performance purposes. To our knowledge, only one study [302] has compared strength profiles between rugby codes using isokinetic testing. Unfortunately, no profiling of hip strength has been reported. There is a need for strength profiling of elite athletes of both codes and positions at the knee and hip, as this will aid in understanding how the requirements and characteristics of athletes of both codes differ as well as guiding specific conditioning practices to better effect.

## Methods

### *Athletes*

Thirty-two professional male rugby league (mean  $\pm$  SD: age =  $23 \pm 3$  y, body-height =  $1.84 \pm 0.06$  m, body-mass =  $101 \pm 11$  kg) and rugby union (mean  $\pm$  SD: age =  $25 \pm 3$  y, body-height =  $1.86 \pm 0.07$  m, body-mass =  $103 \pm 12$  kg) athletes volunteered as participants for this research (Table B). All athletes were currently under the supervision of their respective teams' strength and conditioning coaching staff. All procedures used in this study were approved by the Auckland University of Technology Ethics Committee (12/332).

Table B. Athlete characteristics used in Appendix XII.

	Rugby League			Rugby Union		
	Total ( <i>n</i> = 32)	Forwards ( <i>n</i> = 18)	Backs ( <i>n</i> = 14)	Total ( <i>n</i> = 25)	Forwards ( <i>n</i> = 14)	Backs ( <i>n</i> = 11)
Age (y)	23 ± 3	23 ± 3	23 ± 3	25 ± 3*	25 ± 3	24 ± 3
Body-height (m)	1.84 ± 0.06	1.86 ± 0.05‡	1.81 ± 0.05	1.86 ± 0.07	1.89 ± 0.06‡	1.82 ± 0.04
Body-mass (kg)	101 ± 11	106 ± 10‡	96 ± 9	103 ± 12	111 ± 8‡‡	93 ± 7
Body-mass index (kg·m <sup>-2</sup> )	30 ± 2	30 ± 2	29 ± 2	30 ± 3	31 ± 3‡	28 ± 2
Rugby experience (y)	13 ± 6	12 ± 6	15 ± 5	16 ± 5*	16 ± 5*	17 ± 5
Professional rugby experience (y)	4 ± 4	4 ± 4	4 ± 4	6 ± 4	6 ± 4	5 ± 3
Preferred leg	R = 31, L = 1	R = 17, L = 1	R = 14, L = 0	R = 24, L = 1	R = 14, L = 0	R = 10, L = 1

Footnote: R, right; L, left. \*Significantly different between rugby league and rugby union,  $P \leq .05$ . ‡Significantly different between forwards and backs,  $P \leq .05$ .

‡‡Significantly different between forwards and backs,  $P \leq .001$ . Values are means ± standard deviation.

## *Design*

This cross sectional analysis comprised isokinetic testing to determine hip and knee strength of the athletes. Each athlete completed the testing in one session (~2 hr) and each code completed the testing over the course of three days; where testing occurred at the same time of day. Testing for both codes took place during their respective off-season following a rest day (~24 hr) and prior to training on that day.

## *Methodology*

Following the warm-up, athletes were secured to a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA) to assess isokinetic concentric knee and hip extensor and flexor strength on each leg at 100 Hz. The dynamometer was set up in two separate positions using a standardized protocol for knee and hip actions [303]. In both positions, gravity adjustments were made by determining the combined effects of leg mass and the passive muscle tension using the HUMAC software. The leg that the athlete preferred to kick the ball was defined as the preferred leg [66].

Each leg was tested at a fixed angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$  for five extension and five flexion actions [304]. Familiarisation required three movements at an individually perceived 50, 70 and 90% of maximum exertion at each position. Where athletes did not understand or did not perform the movement properly, further instruction was verbally given or additional familiarisation trials were given as needed. Investigators provided strong verbal encouragement during each trial to maximise the athletes' effort across trials [303]. Athletes were given appropriate rest between trials (>2 minutes) in order to prevent the effects of fatigue.

A custom made LabVIEW program (Version 11.0, National Instruments Corp., Austin, TX, USA) was used to fit the torque-angle curves with a 4<sup>th</sup> order polynomial to identify peak torque using the average of the last four repetitions for the final value. Hamstring to quadriceps ratios (H / Q ratio) were calculated by dividing the peak flexion torque by the peak extension torque of the same leg using Excel (2010, Microsoft, Redmond, WA, USA). Similarly, knee flexion to hip extension ratios (knee flexion / hip extension ratio) were calculated by dividing the peak knee flexion torque by the peak hip extension torque of the same leg.



### ***Statistical analysis***

Statistical analysis was performed in SPSS (Version 19.0 for Windows, SPSS Inc., Chicago, IL, USA) using a two-tailed heteroscedastic Student t-test to compare athlete characteristics and a one-way Analysis of Variance (ANOVA) to compare forwards and backs (rugby league versus rugby union). A post-hoc Fisher's Least Significant Difference (LSD) Test was used to determine any specific differences between groups indicated by the ANOVA. Two-tailed paired Student t-tests were used to determine differences in variables between preferred and non-preferred legs. An alpha level of 0.05 was used for all statistical procedures. Effect size for each significant finding was calculated using Excel software [305].

### **Results**

Athlete characteristics were compared between codes age and experience. When compared within code, rugby league forwards were significantly taller (+3%;  $P = 0.039$ ) and heavier (+10%;  $P = 0.0104$ ) compared to rugby league backs. Similarly, rugby union forwards were taller (+4%;  $P = 0.0053$ ), heavier (+20%;  $P < 0.001$ ) and had a greater BMI (+12%;  $P = 0.0021$ ) compared to rugby union backs.

During isokinetic strength testing, rugby union forwards produced significantly greater peak knee flexion torque in the preferred (+44 N·m;  $ES = 1.81$ ,  $P < 0.001$ ) and non-preferred (+35 N·m;  $ES = 2.02$ ,  $P < 0.001$ ) legs compared to rugby league forwards (Table C). Rugby union forwards also produced greater (+35 N·m;  $ES = 0.71$ ,  $P = 0.047$ ) peak torques than rugby league forwards during knee extension in the preferred leg. Rugby league backs demonstrated greater peak hip extension torque in the preferred (+ 71 N·m;  $ES = 0.83$ ,  $P = 0.019$ ) and non-preferred (+58 N·m;  $ES = 0.77$ ,  $P = 0.001$ ) legs compared to rugby union backs. When peak torques were further analysed as knee flexion / hip extension ratios, rugby union ratios for forwards and backs in the preferred ( $ES = 1.49$ ,  $P < 0.001$  and  $ES = 1.72$ ,  $P < 0.001$  respectively) and non-preferred ( $ES = 2.26$ ,  $P < 0.001$  and  $ES = 1.62$ ,  $P < 0.001$  respectively) legs were greater as compared to rugby league athletes.

Table C. Knee and hip strength in rugby union and rugby league.

	Rugby League		Rugby Union	
	Forwards	Backs	Forwards	Backs
Knee peak torque (N·m)	246 ± 52	223 ± 55	281 ± 45*	244 ± 29
Preferred extension	243 ± 64	240 ± 74	268 ± 44	247 ± 38
Non-preferred extension	140 ± 21	135 ± 34	184 ± 27‡**	157 ± 27
Preferred flexion	133 ± 26	136 ± 31	180 ± 20‡**	156 ± 27
Non-preferred flexion				
Hip peak torque (N·m)	355 ± 59	353 ± 91*	328 ± 62	282 ± 81
Preferred extension	345 ± 59	317 ± 81*	319 ± 39‡	260 ± 68
Non-preferred extension	148 ± 19	145 ± 33	157 ± 36	140 ± 30
Preferred flexion	147 ± 28	142 ± 31	148 ± 26	138 ± 36
Non-preferred flexion				
Hamstring:quadriceps ratio				
Preferred	0.59 ± 0.14	0.62 ± 0.14	0.66 ± 0.09	0.64 ± 0.10
Non-preferred	0.59 ± 0.25	0.59 ± 0.11	0.68 ± 0.10	0.64 ± 0.08
Knee-flexion:hip-extension ratio				
Preferred	0.40 ± 0.05	0.39 ± 0.06	0.59 ± 0.18**	0.59 ± 0.15**
Non-preferred	0.39 ± 0.08	0.43 ± 0.05	0.57 ± 0.08**	0.63 ± 0.17**

Footnote: Knee and hip peak torque, hamstring:quadricep ratios, and knee-flexion:hip-extension ratios of rugby league versus rugby union and forwards versus backs, evaluated at an angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$ , Mean ± SD. \*Significantly different between rugby league and rugby union,  $P \leq .05$ . †Significantly different between rugby league and rugby union,  $P \leq .001$ . ‡Significantly different between forwards and backs,  $P \leq .05$ .

## Discussion

Professional rugby union forwards produced significantly greater peak torque during knee flexion in both preferred and non-preferred legs in comparison with professional rugby league forwards and rugby union backs. Thus the main knee joint strength difference between the codes and between positions occurred during knee flexion. It could be speculated that the superior strength of rugby union forwards was due to their code and position-specific training and / or demands. Tackling, scrummaging, rucking, mauling and pick-and-goes, common activities associated with the demands of rugby union forward play, are all activities requiring great lower limb strength and power while the hip and knee joints are held in flexed positions.

It is interesting to note that the rugby union athletes in the current study had H:Q ratios of  $0.64 - 0.68$ , whereas professional rugby league athletes from this ( $0.59 - 0.62$ ) and previous ( $0.53 - 0.58$ ) studies [306] were less. It seems that rugby league athletes have weaker hamstrings. This is the first study to include isokinetic hip assessment with typical knee flexion / extension assessments for professional rugby athletes. Rugby league athletes produced greater peak torque ( $26 - 71 \text{ N}\cdot\text{m}$ ) during hip extension than rugby union athletes in both preferred and non-preferred legs, however, this difference was only significant between the backs ( $ES = 0.83$  and  $ES = 0.77$  respectively). These differences may be partially explained by the technique demands of rugby league: minimal scrummaging; tackles made primarily to the upper-half or the body; reception and running with the ball generally from upright positions; and, sprint efforts commonly preceded with backwards running [307]. The net effect is an athlete who trains and plays in a more upright position and therefore uses their hip extensors as the main producers of force, work and power.

The main lower limb strength differences between rugby codes were localised to the posterior chain. As such, the ratio between hip extension and knee flexion is of interest. If the posterior-chain is not operating correctly, performance could be compromised. The rugby league forwards and backs in the current study had knee flexion / hip extension ratios ( $\sim 0.40$ ) in both preferred and non-preferred legs, which was significantly less ( $\sim 0.60$ ) than the rugby union athletes ( $ES = 1.49 - 2.26$ ). The optimum ratio of hip extension / knee flexion peak torque is currently unknown.

It should be noted that isokinetic assessments typically have poor relationships with athletic performance, such as sprinting and jumping [302, 306]. The differences found between

codes and positions in the present study, would likely also be found in other unilateral assessments of sport-specific strength, speed and power. Additionally, the data referenced in this research should be acknowledged as 'normative' and not necessarily 'ideal'. Future research comparing rugby league and rugby union athletes is warranted.

### **Conclusion**

Important lower limb strength differences at the hip and knee exist between rugby league and rugby union athletes; specifically, rugby union athletes tend to have weaker hip extensors, while rugby league tend to have weaker knee flexors. Intra-limb and bilateral limb imbalances can directly affect athletic performance; especially in sports that involve sprinting, changing direction and kicking like rugby league and rugby union [234, 299]. This study offers a direct comparison of muscular strength at the knee and hip between professional rugby union and rugby league athletes.

## **Appendix XIV. Publication: Determining Return-to-Sport Status with a Multi-Component Assessment Strategy: A Case Study in Rugby.**

This appendix comprises the following publication in *Physical Therapy in Sport* which is in support of Chapters 3, 4 and 9.

### **Reference:**

Brown SR, Brughelli M. Determining return-to-sport status with a multi-component assessment strategy: A case study in rugby. *Phys Ther Sport*. 2014;15(3):211-5.

### **Author contribution:**

Brown SR, 95%; Brughelli M, 5%.

### **Overview**

The effectiveness of rehabilitation programmes are often distorted by the athlete's desire to return and can result in injury recurrence. Athletic assessments allow for objective and reliable measurements to track rehabilitation progress. This case study used a multi-component assessment strategy to assess a rugby athlete's lower-extremity strength and symmetry as a primary determinate of their return-to-sport status. A professional rugby league athlete was assessed for lower-extremity isokinetic strength and sprint kinetics pre- and 10-weeks post-rehabilitation programme following two consecutive knee injuries involving surgical intervention. Pre-testing analysis showed clinical and functional strength deficits in the injured leg as high as 34% compared to the non-injured leg. Pre- to post-testing showed: increases in peak torque (49%) and decreased asymmetries by 50%; unilateral horizontal force increased (injured: 50%, non-injured: 19%) during sprinting; force production asymmetries decreased up to 18%. The rugby athlete showed clinical and functional strength deficiencies return to normal ranges following a rehabilitation programme. A return-to-sport decision was made by the athlete's supporting health team based on the sizeable asymmetry decreases and return-to-normative ranges for knee and hip strength and sprint kinetics. The athlete returned to the 2013 National Rugby League season without any major injuries.

## Background

Injury rates in professional rugby league are among the highest in elite team sports with rates most commonly reported between 195.5 to 277.78 injuries per 1000 hours [24, 308]. The largest percentage of all injuries in rugby league occur at the lower-limb; most commonly including soft-tissue injuries at the knee such as anterior cruciate ligament sprains and bi-articulate hamstring muscle strains [24]. Since these injuries can be severe and debilitating, rehabilitation programmes have been established to return an athlete to sport as quickly as possible while obtaining the desired effects of the programme. Unfortunately, inadequate rehabilitation programmes can result in clinical and functional deficits lasting several years following the initial injury, and thus prolong the risk of re-injury [289, 309]. Instability, muscle imbalances and functional deficits can directly affect re-injury risk and athletic performance; especially in sports that involve sprinting, changing direction and kicking like rugby. It should be noted that re-injury has been defined as an injury to the same site over a short period of time (i.e. < 2 months [309]), or to an original site in the lower-extremities over a prolonged period [113]. To gain better insight into tracking rehabilitation progress, athletic assessments have become a staple in modern sport at the elite level and are frequently used for assessing injury / re-injury risk and for tracking athletic performance [113, 177, 310].

In the past, indistinguishable similarities in muscular properties between injured and non-injured muscles made early detection of risk-factors in healthy athletes a daunting task [290]. In recent time however, an increase in knowledge of the hamstring injury has allowed for more effective assessments to recognise and properly treat injured athletes [311]. Assessment tools such as dynamometry and force plate instrumented treadmills are commonly used to detect adaptations of strength and power in athletes. While not as impactful on their own as they are when combined, a multi-component assessment strategy can illuminate a clear depiction of an athlete's return-to-sport status [114]. The proper analysis and interpretation of these assessments are therefore vital to the health of the athlete and the longevity of their career. Although several authors [114, 289, 312, 313] have commented on the value of a multi-component approach, including reliable and objective assessments (i.e. laboratory and functional assessments), few have been implemented in the literature. This case study sought to use a multi-component assessment strategy to assess an athlete's lower-extremity strength

and symmetry pre- and post-rehabilitation as a primary determinate of their return-to-sport status.

### **Case description**

A 28-year-old male professional rugby league athlete (body-height = 1.8 m, body-mass = 98 kg) presented for a complete athlete assessment package. The athlete played on the starting side for a National Rugby League team for the previous eleven years and five years on an international representative team for New Zealand.

The athlete's past two-year medical history included two major injuries to the left leg (non-preferred leg; preferred stance or support leg while kicking) and an assortment of minor injuries to the right leg (preferred kicking leg). The first major injury consisted of a 2011 season-ending anterior cruciate ligament rupture in the left knee requiring surgery and accounted for 27 weeks away from competitive play and 25 missed games; 88 weeks (1 year and 8 months) prior to our assessment. The anterior cruciate ligament surgery consisted of a contralateral (right) patellar tendon graft immediately following the injury. The second major injury consisted of a 2012 season-ending patellar tendon rupture in the left knee requiring surgery accounting for 16 weeks away from competitive play and 14 missed games; 29 weeks (< 7 months) prior to our assessment. All minor soft-tissue injuries occurred in 2012 before the patellar tendon rupture and included a lateral femoral condyle contusion to the left knee missing two games, a lateral ligament sprain to the right ankle missing one game and a biceps femoris strain on the right leg missing one game. All injuries occurred during match play and were a mix between contact / non-contact and first-half / second-half injuries.

A rehabilitation programme using general guidelines [314] was given by the supporting team's medical staff following the most recent surgery on the patellar tendon. This rehabilitation programme consisted of five phases wherein the main goals of each phase were: (I) 5-14 days, control pain and inflammation and work up to 30° passive range of motion; (II) 2-6 weeks, control pain and inflammation, continue passive range of motion and begin weight-bearing activities; (III) 6-12 weeks, control pain and inflammation, progress mobility and strength to full active range of motion; (IV) 12-16 weeks, complete weight-bearing and progress strength, begin neuromuscular strength and gait re-training; and (V) 16-24 weeks, begin jogging / running and sport specific activities. After progressing the athlete through a

rehabilitation programme, wherein he had returned to light practicing conditions, the athlete was assessed to determine his return-to-sport status.

Upon initial completion of the testing it was discovered that the athlete did not fall within 10% of the upper or lower normative range for sport or position established by our group [177] nor did he pass the required criteria in order to return-to-sport based on previous literature [114]. As such, it was recommended to the team to proceed with an additional programme aimed at increasing unilateral muscular strength and reducing asymmetries between limbs [172]. All aspects of the research were thoroughly explained to the athlete and team staff and written informed consent was obtained prior to commencement as part of the contractual arrangements with the New Zealand Warriors. All procedures used in this case study were reviewed by the Auckland University of Technology Ethics Committee and received full ethical approval for human participant research (12/332).

### *Laboratory testing protocol*

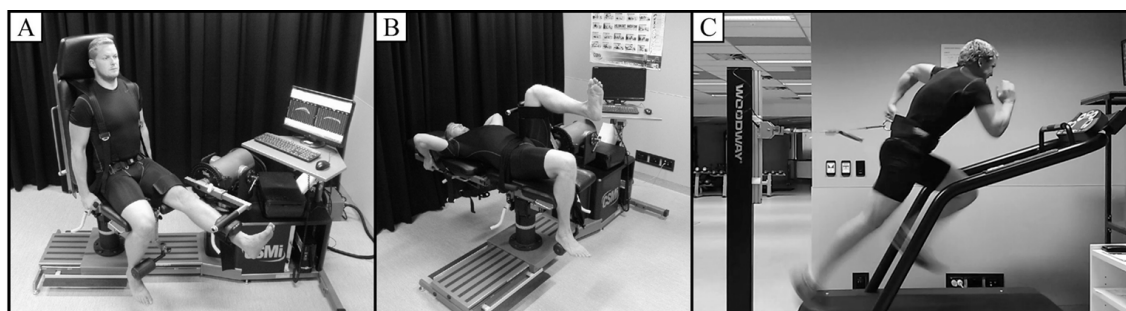
This case study comprised isokinetic testing to determine hip and knee strength and symmetry, and sprint kinetic testing to determine unilateral functional strength and symmetry. Testing was performed pre- and 10-weeks post-rehabilitation programme following a regeneration phase aimed to increase single-joint and functional strength, and reduce strength deficits and asymmetries [114, 312]. Rehabilitation and testing took place during the athlete's off-season / pre-season and testing sessions followed a 24-hour rest day and preceded training on that day. Testing sessions lasted approximately two hours and occurred at the same time of day (~9:00 AM).

Testing sessions were performed by the same researcher and followed an identical protocol as described in detail elsewhere [177, 243]. In short, the athlete was secured to a Humac Norm dynamometer (Lumex, Ronkonkoma, NY, USA) to assess isokinetic concentric knee (Figure D-A) and hip (Figure D-B) extensor and flexor strength on each leg at 100 Hz. The athlete was either set in an upright seated position for testing at the knee or in a supine position for the hip where gravity and limb mass adjustments were made accordingly. The "zero angle" was set at full leg extension during knee actions, and full hip extension during hip actions. A familiarisation process was instructed to the athlete to perform three trials of the movement at a self-perceived 50, 70 and 100% of maximum effort. Testing followed with five extension and five flexion actions at a fixed velocity of  $60^{\circ}\cdot\text{s}^{-1}$ . Strong verbal



encouragement was provided through all tests and appropriate rest was given between trials and limbs.

Subsequent to isokinetic testing, the athlete was tested on a non-motorised instrumented treadmill (Woodway Force 2.0, Woodway USA, Inc., Waukesha, WI, USA) to assess bilateral sprint kinetics (Figure D-C). As previously described [243], force instruments were calibrated and zeroed. A horizontal strain-gauge was attached to the athlete's waist via a non-elastic tether. Starting in a sprinter's stance with the right foot back, the athlete was asked to build up in speed over a four second period to a maximum velocity and then to maintain that velocity for an additional five seconds. Real-time sprint performance was shown to the athlete and strong verbal encouragement was provided to increase the likelihood of maximal effort. Ten steps were analysed during the maximum velocity phase.



**Figure D.** Isokinetic knee (A) and hip (B) strength testing and non-motorised treadmill sprint testing (C) [98].

### *Outcome measures*

Data were processed using a custom LabVIEW programme (Version 11.0, National Instruments Corp., Austin, TX, USA) to fit the torque-angle curves with a 4<sup>th</sup> order polynomial to identify peak torque and angle of peak torque using the average of the last four repetitions for the final value. Another custom LabVIEW programme was used to assess the ten steps during maximum velocity sprinting. The ten steps were separated by left and right legs based on counting the first recorded step as the right leg and then counting forward. Peak horizontal and vertical forces were extracted and independently averaged. Data were analysed using Excel (2010, Microsoft, Redmond, WA, USA) where asymmetries as percentages were calculated during pre- and post-testing by subtracting the injured leg from the non-injured leg, then dividing the product by the non-injured leg and multiplying by 100 (Equation 2). Percent change (pre- to post-testing) was determined by subtracting the

post- by the pre-value, then dividing the product by the pre value and multiplying by 100. All final data were compared with a normalised data-base of 14 professional rugby league athletes of the same position (backs) and similar characteristics (age =  $23 \pm 3$  y, body-height =  $1.8 \pm 0.1$  m, body-mass =  $96 \pm 9$  kg) from previous work by this group [177].

### Outcomes

Noticeable deficits in peak torque were seen during the pre-testing examination (Table D). The injured leg showed 59 N·m less torque than the non-injured leg during knee extension, 22 N·m less during knee flexion and 57 N·m less during hip extension. These deficits translate to asymmetrical differences as large as 34% between legs during the same muscle action. Post-testing deficits decreased substantially with the injured leg showing only 27 N·m less torque than the non-injured leg during knee extension, 4 N·m more during knee flexion and 28 N·m less during hip extension. Hip flexion torques remained very similar at pre-training (3 N·m less in the injured leg) and post-training (2 N·m less in the injured leg).

Peak torque increased between pre and post testing in both legs for all testing actions at the knee and hip. The most substantial increases came from the injured leg during knee extension (54 N·m; 47%), knee flexion (44 N·m; 47%) and hip extension (101 N·m; 49%). Peak torque leg asymmetries decreased in the knee and hip by 22% and 13% respectively. Angle of peak torque increased between pre and post in the injured leg during hip extension ( $14^\circ$ ; 27%) and hip flexion ( $8^\circ$ ; 67%). Asymmetries in the angle of peak torque were reduced in the knee and hip by as much as 17% and 50% respectively.

Similar noticeable deficits in peak force during sprinting were also seen during pre-testing (Table E). The injured leg showed 112 N less force than the non-injured leg in the horizontal direction and 259 N less in the vertical direction. Again, deficits decreased post-testing with the injured leg showing only 55 N less force than the non-injured leg in the horizontal direction and 185 N less force in the vertical direction. Horizontal force production during sprinting increased from pre to post-testing (injured: 126 N; 50%, non-injured: 69 N; 19%) whereas vertical force production decreased (injured: 72 N; 3%, non-injured: 146 N; 5%). Horizontal and vertical force asymmetries between legs decreased from pre to post by 18% and 2% respectively.

Table D. Knee and hip strength pre- and post-rehabilitation programme.

		Peak torque (N·m)			Angle of peak torque (Deg)		
		Normative	Pre	Post	Normative	Pre	Post
Knee							
Injured	Extension	234 ± 35	116	170	66 ± 44	71	67
Non-injured	Extension		175	197		71	68
	Asymmetry (%)		-34	-14		0	-1
Injured	Flexion	139 ± 17	94	138	28 ± 4	26	23
Non-injured	Flexion		116	134		23	24
	Asymmetry (%)		-19	3		13	-4
Hip							
Injured	Extension	322 ± 60	208	309	69 ± 3	51	65
Non-injured	Extension		265	337		66	63
	Asymmetry (%)		-22	-8		-23	3
Injured	Flexion	142 ± 15	124	141	23 ± 2	12	20
Non-injured	Flexion		127	143		24	20
	Asymmetry (%)		-2	-1		-50	0

Footnote: Knee and hip peak torque pre- and post-rehabilitation programme compared against normative values, evaluated at an angular velocity of 60°·s<sup>-1</sup>. Normative values are means ± standard deviation. Injured, left leg (non-preferred leg; preferred stance or support leg while kicking); Non-injured, right leg (preferred leg; preferred kicking leg).

## Discussion

A professional rugby league team requested a biomechanical analysis of lower-extremity strength and symmetry in order to determine return-to-sport status following a severe knee injury requiring surgery. Succeeding the initial examination, a second rehabilitation programme was recommended to the team's staff with an emphasis placed on increasing unilateral muscular strength and reducing limb asymmetries. Although the details of the rehabilitation programmes are not the focus of this study, we can speak to the effectiveness of programme; as seen by our assessments. Traditional return-to-sport models typically encompass a three- to four-phase programme comprised of unreliable and subjective means [114, 289]. Progression between these phases can often be jaded by an athlete's perceived health and often lead to injury recurrence [293]. As described in the 'Function Phase' framework [114, 312, 313], post-rehabilitation assessments are necessary to determine if an athlete has passed the functional criteria required to safely return-to-sport. Three of the five tests recommended in this framework, including 9 dependent variables, were conducted to gather reliable and objective information. These quantitative assessments showed clear improvements between pre- and post-testing on the second rehabilitation programme.

**Table E. Sprint kinetics pre- and post-rehabilitation programme.**

	Normative	Pre	Post
Horizontal force (N)			
Injured	342 ± 76	252	378
Non-injured		364	433
Asymmetry (%)		-31	-13
Vertical force (N)			
Injured	2,468 ± 236	2,670	2,598
Non-injured		2,929	2,783
Asymmetry (%)		-9	-7

Footnote: Horizontal and vertical force production pre- and post-rehabilitation programme compared against normative values, evaluated at maximum sprinting velocity. Normative values are means ± standard deviation. Injured, left leg (non-preferred kicking leg); Non-injured, right leg (preferred kicking leg).

Muscle weakness during concentric and / or eccentric actions is a risk factor for lower-extremity injury [315]. As such, isokinetic testing during preseason is a crucial benchmark for comparison should the athlete suffer an injury during the season. Evaluations at the knee and hip allow for greater insight into the functional status and efficiency of the major bi-articulate muscles of the lower-extremities [177]. The professional rugby league athlete in this study showed major strength deficiencies up to 71% below the lower normative range

return closely to normal ranges following the second rehabilitation programme. While peak knee extension in the injured and non-injured leg following the second rehabilitation programme were still 18% and 1% below the lower normative range respectively, major strength increases indicated promising results and all other peak torque variables fell within the normal range. These increases in strength were also accompanied by normalisation of the associated angles of peak torque. Underdeveloped knee extensors following an injury to the knee can limit the rehabilitative progress and eventually increase the risk of re-injury; additionally, proper co-contraction of the quadriceps and hamstrings at appropriate muscle lengths (i.e. optimum angles of peak torque) is imperative in providing dynamic stabilisation in the knee joint [289].

Most importantly, the lower-extremity asymmetries seen pre-rehabilitation (up to 34%) in this study did not pass any of the standard criteria [114, 289] for return-to-sport while the majority of post values did. While a 14% asymmetry remained in knee extension following our assessment, the athlete demonstrated positive results (20% decrease in asymmetry pre-to post-test) in only 10-weeks of rehabilitation that was speculated to continue to improve. Isokinetic assessments, when used in isolation as a screening tool, are somewhat limiting in predicting the likelihood of injury; even when knee and hip dynamometry are examined together [316]. Lower-extremity muscular strength can only shed light into the potential functional stability of an athlete and not necessarily to the transfer of that ability to a practical setting. To complete the picture, additional measurements are required to then analyse this transfer in a more applied and practical situation such as sprinting.

Proper multi-joint movement following an injury is a key factor in an athlete's return-to-sport. As several lower-extremity injuries occur during multiple phases of sprinting [114], it seems pertinent to examine force production (i.e. magnitude and direction) during sprinting. During sprinting, clear deficits in horizontal force production were seen during pre-testing followed by marked increases after the programme post-testing. These findings in horizontal deficits are in agreement to those found in injured Australian rules footballers [97]. Speculation as to why force deficits might be seen during sprinting is attributed to alterations in the proximal to distal transfer of power between joints wherein the posterior muscles aid in translation of the centre-of-mass through stance phase [114]. An injured leg might therefore be unable to produce such efficient movements; these inefficiencies were apparent

in our assessments. This theory, in conjunction to the slight decrease in body mass (98 kg pre- to 96 kg post-testing), may also explain the minor decrease found in vertical force production pre- to post-rehabilitation programme.

In following the recommendations of a return-to-sport algorithm [114] used by our staff, this case study only conducted 3 / 5 of the functional phase tests. It was presumed that the injury in this study did not affect the rotational components of the trunk and while a global assessment of performance can be beneficial, these means may overlook localised deficiencies [289]. Additionally, despite the fact that ultrasound imaging is fairly inexpensive, the process is operator dependant and unable to image bone whilst magnetic resonance imaging is relatively expensive and difficult to use. So while further testing could have been implemented, it was thought that the tests performed were the most suitable for this particular injury, the athlete's and staff's time and the team's finances. As a result, clear improvements were detected by our chosen assessments. After a full analysis, a return-to-sport decision was made by the athlete's supporting health team and coaching staff based primarily on the sizable asymmetry decreases and return-to-normative ranges for knee and hip strength measures and sprint kinetics.

Following this return-to-sport decision, the athlete partook in the 2013 New South Wales Rugby League for nine games and eventually returned to the 2013 National Rugby League and participated in three games. While there were recurrent minor irritations noted in the left knee, no major injuries were recorded throughout the season. The athlete is currently involved in preseason training in anticipation for the 2014 National Rugby League season.

### **Practical implications**

Objective and quantitative assessments are useful for an athlete's career and a team's investment. A multi-component assessment strategy consisting of dynamometry and sprint kinetics is recommended for a more complete picture of an athlete's strength and symmetry. Baseline values are needed at all levels of performance to determine return-to-sport standards and quality normative databases for all athlete types. It is recommended that coaching staff should support athletic baseline and post-injury assessments to enable quality information on which to base return-to-sport decisions.

**The End**