University of Bedfordshire

THE RELATIONSHIP BETWEEN STIFFNESS, ASYMMETRIES AND CHANGE OF DIRECTION SPEED

Sean Maloney

THE RELATIONSHIP BETWEEN STIFFNESS, ASYMMETRIES AND CHANGE OF DIRECTION SPEED

SEAN MALONEY

PhD

2016

UNIVERSITY OF BEDFORDSHIRE

THE RELATIONSHIP BETWEEN STIFFNESS, ASYMMETRIES AND

CHANGE OF DIRECTION SPEED

by

SEAN MALONEY

A thesis submitted to the University of Bedfordshire, in fulfilment of the

requirements for the degree of Doctor of Philosophy

February 2016

THE RELATIONSHIP BETWEEN STIFFNESS, ASYMMETRIES AND CHANGE OF DIRECTION SPEED

SEAN MALONEY

ABSTRACT

Change of direction speed (CODS) is an important determinant of performance in many sports. Greater stiffness of the lower limb should be beneficial to CODS, but this had not been well investigated. The purpose of this thesis was to establish the relationship between vertical stiffness, vertical stiffness asymmetries and CODS, with a view to augmenting CODS performance.

The pilot study and studies 1-2 sought to determine the most reliable and ecologically valid method to assess stiffness in athletes required to perform changes of direction. The pilot study reported that the use of ultrasonography to determine Achilles tendon stiffness did not demonstrate appropriate reliability for inclusion in subsequent studies. Coefficients of variation (CVs) in excess of 27% were reported during an isometric plantar flexion task. Study 1 reported that CVs for vertical stiffness were lower when assessed during unilateral drop jumping (~7%) than during bilateral drop jumping (~12%) or bilateral hopping (~14%). Study 2 reported that the expression of vertical stiffness ($P = 0.033$) and vertical stiffness symmetry angle ($P = 0.006$) was significantly different across three performance tasks: unilateral drop jumping, bilateral drop jumping and bilateral hopping. Asymmetry percentages between compliant and stiff limbs were 5.6% ($P < 0.001$; d: 0.22), 23.3% ($P = 0.001$; $d = 0.86$) and 12.4% ($P = 0.001$; $d = 0.39$), respectively. Given the findings of studies 1 and 2, this thesis demonstrated the reliability and validity of a novel method by which to assess vertical stiffness - the unilateral drop jump. This task was used in subsequent studies to measure vertical stiffness.

Study 3 sought to determine if vertical stiffness and vertical stiffness asymmetries influenced CODS performance determined during a 90° cutting task. Multiple regression analyses reported that mean vertical stiffness and asymmetry in jump height explained 63% ($r^2 = 0.63$; $P = 0.001$) of CODS performance. Study 3 was the first investigation to demonstrate the importance of vertical stiffness to CODS performance.

Study 4 sought to determine if acute exercise interventions designed to augment vertical stiffness would improve CODS. Unilateral and bilateral 'stiffness' interventions were evaluated against a control condition. CODS performances following the unilateral intervention were significantly faster than control (1.7%; $P = 0.011$; $d = -1.08$), but not significantly faster than the bilateral intervention (1.0% faster; $P = 0.14$; $d = -0.59$). Versus control, vertical stiffness was 14% greater ($P = 0.049$; $d = 0.39$) following the unilateral intervention. Study 4 demonstrated that a novel unilateral 'stiffness' intervention improved vertical stiffness and CODS performance. This highlights that the potential applicability of unilateral stiffness interventions in the pre-performance preparation of athletes.

Acknowledgements

I dedicate this thesis to my mother, Deborah and to the memory of father, John. Thank you for your love and support.

Thank you to my supervisors, Iain Fletcher and Joanna Richards, for their guidance and support throughout the last three years. Your contributions have been invaluable in the production of this thesis. Thank you also to Andrew Mitchell for stepping in to support us through the final leg of our journey.

Lastly, thank you to Warwick Riley and his team of lab technicians at the University of Bedfordshire. Your tireless efforts in supporting the projects of students and staff should never be underestimated.

Contents

List of Tables

List of Figures

<u>Abbreviations</u>

CODS = change of direction speed

vGRF = vertical ground reaction force

COM = centre of mass

SEM = standard error of measurement

CV = coefficient of variation

ICC = intra-class correlation coefficient

90% CI = 90% confidence intervals

ANOVA = analysis of variance

θSYM = symmetry angle

MVC = maximal voluntary contraction

EMG = electromyography

Operational Definitions

To aid the clarity, the following terminology and their operational definitions will be used throughout the entirety of the thesis:

- **Stiffness**

A general term used to describe the notion of a displacement of the human body, or parts thereof, in response to the application of forces or moments (Serpell et al., 2012).

- **Vertical stiffness**

Specifically describes the vertical displacement of the centre of mass in response to vertical ground reaction force during a task performed in the sagittal plane (Latash & Zatsiorsky, 1993).

- **Leg stiffness**

Specifically describes the displacement of the leg spring in response to force in any plane or direction (McMahon & Cheng, 1990).

- **Joint stiffness**

Specifically describes the angular displacement of a joint in response to the moment at the joint (Farley et al., 1998).

- **Asymmetry**

A general term used to describe a functional imbalance between limbs (Zifchock et al., 2008).

- **Asymmetry percentage**

Specifically describes the difference between two sides using the larger value as a reference value (Vagenas & Hoshizaki, 1991).

- **Symmetry index**

Specifically describes the difference between two sides using the sum of larger and smaller sides as a reference value (Robinson et al., 1987).

- **Symmetry angle**

Specifically describes the difference between two sides using a vector of symmetry as a reference point (Zifchock et al., 2008).

- **Change of direction speed**

The speed at which an individual can perform a pre-planned movement, or sequence or movements, involving changes of direction (Brughelli et al., 2008).

Chapter 1 - Introduction

1.1 Change of direction speed

Change of direction speed (CODS) underpins performance in a wide range of sports. Young et al. (2002) reported that reactive strength, a quality closely linked to stiffness, may be the strongest physical predictor of CODS. Theoretically, greater stiffness should facilitate a more rapid release of elastic energy under circumstances where minimal tissue, segmental or body displacement is desired, such as during a change of direction (Bret et al., 2002). To this author's knowledge, only Pruyn, Watsford, and Murphy (2014) have examined the effect of stiffness on CODS; Pruyn et al. (2014) reported that medial gastrocnemius stiffness, but not vertical stiffness, was related to CODS performance in elite netball players.

Inter-limb asymmetries in CODS between dominant and non-dominant limbs have been reported in a number of investigations (Young et al., 2002; Henry et al., 2013; Hart et al., 2014a), and is hypothesised to be a consequence of greater reactive strength in the dominant limb (Young et al., 2002; Henry et al., 2013). Whilst it may seem reasonable to hypothesise that asymmetries would be detrimental to overall CODS performance given the body of evidence introduced in Section 1.3, such propositions need to be examined directly.

Pre-conditioning interventions have been independently shown to improve CODS (Maloney et al., 2014b) and to increase vertical stiffness (Barnes et al., 2015). It is hypothesised that increased stiffness may contribute to such performance enhancements (Maloney et al., 2014b) but this has not been examined directly. Moreover, the acute effects of a plyometric intervention on parameters of stiffness has not been determined.

1.2 Stiffness

Stiffness describes the deformation of an object in response to a given force and is a concept which can be used to characterise human movement (Latash & Zatsiorsky, 1993; Butler et al., 2003; Pearson & McMahon, 2012). Stiffness can be modelled with increasing levels of determinism, for example, the summative stiffness of the entire lower limb down to the stiffness of a single collagen fibre. Typically, research has sought to use measures of summative lower limb stiffness (Hobara et al., 2008; 2010), individual joint stiffness (Kuitunen et al., 2011) or tendon stiffness (Kubo et al., 2007) to examine relationships with athletic performance.

Greater vertical stiffness has been reported in sprint-trained versus endurance-trained runners (Hobara et al., 2008) and in endurance-trained runners versus untrained controls (Hobara et al., 2010). Within a single sport, athletes exhibiting greater stiffness of the gastrocnemius and soleus may perform better in CODS, jump and short sprint tests (Pruyn et al., 2014). As increased stiffness would appear beneficial to short-duration maximal performance measures, interventions designed to augment stiffness may be hypothesised to improve CODS.

It has been demonstrated that stiffness can be modified in response to both acute (Comyns et al., 2007; Moir et al., 2011) and chronic (Pearson & McMahon, 2012) resistance exercise interventions. The results of any assessment can therefore directly inform the training process of athletes.

1.3 Asymmetry

Quantification of asymmetry is useful if seeking to determine the magnitude of a functional imbalance within the body. Asymmetry in force/power qualities has been linked to impaired performance in several investigations (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015) and asymmetry in vertical stiffness specifically has been linked to increased injury incidence in Australian Rules footballers (Pruyn et al., 2012).

Research has commonly used the symmetry index to characterise asymmetries, however, the symmetry angle devised by Zifchock et al. (2008) may provide a more suitable alternative. In addition to reporting a clear direction of asymmetry, the symmetry angle provides a standard scale for interpretation and reduces the likelihood of artificially inflated values.

The expression of asymmetry is highly task dependant. For example, Flanagan and Harrison (2007) reported that no asymmetries were demonstrated during cyclic, repeated sledge hops but a significant asymmetry in reactive strength index during acyclic hops. Also, Benjanuvatra et al. (2013) observed that inter-limb impulse asymmetries observed during bilateral jumping were not necessarily indicative of the asymmetries observed during unilateral jumping. These studies highlight the importance of selecting the most appropriate test by which to assess stiffness asymmetries. To date, the literature has not examined the effects of stiffness asymmetries or explored how CODS may be affected.

1.4 Thesis aims

This thesis will seek to:

1. Determine the most reliable and ecologically valid method to assess vertical stiffness in athletes required to perform changes of direction.

2. Determine if vertical stiffness and vertical stiffness asymmetries influence CODS.

3. Determine if acute 'stiffness' interventions can positively influence CODS and if augmentations are linked to the modulation of vertical stiffness and vertical stiffness asymmetries.

1.5 Thesis rationale

- CODS is an important determinant of performance in many sports.

- Greater stiffness is likely to be beneficial to CODS but this relationship has not been well explored.

- Asymmetries in force-related properties have been linked to impaired performance in a variety of tasks but not considered CODS.

- Stiffness asymmetries have been linked to increased injury incidence but the relationship with performance is yet to be explored.

- Pre-conditioning interventions have been shown to augment CODS but not considered the reasons for these enhancements.

- Resistance exercise interventions have been shown to acutely augment stiffness but plyometric interventions have not been similarly evaluated.

1.6 Intended impact

Studies 1 and 2 will determine the most reliable and ecologically valid method to assess vertical stiffness. This will provide athletes, coaches and applied practitioners with the most appropriate assessment tool for vertical stiffness. Study 3 will determine if vertical stiffness and/or vertical stiffness asymmetries influence CODS. Were these factors found to influence CODS, this would carry two important consequences. Firstly, this would highlight the importance of testing for these variables. Secondly, this would influence how interventions to improve CODS may be devised and structured. Study 4 will determine if acute 'stiffness' interventions positively influence CODS. Were these interventions found to be effective, this would influence the performance preparation strategies of athletes.

1.7 Organisation of the project
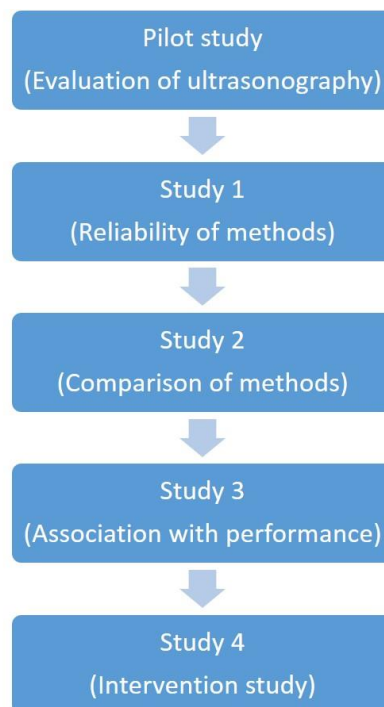
Figure 1.1 - A flow diagram representing the organisation of the project.

Chapter 2 - Literature Review

2.1 An introduction to stiffness

Stiffness is a physical concept that describes the deformation of an object in response to a given force (Latash & Zatsiorsky, 1993; Butler et al., 2003; Pearson & McMahon, 2012). It is based on the Hookean premise that the force required to deform a material is related to a proportionality constant and the distance the material is deformed (Latash & Zatsiorsky, 1993; Butler et al., 2003) (Equation 2.1); it is this proportionality constant that represents the stiffness of the object.

Equation 2.1: $F = kx$ (Latash & Zatsiorsky, 1993; Butler et al., 2003)

Where F = force, k = the proportionality constant and x = the distance the material is deformed.

In order to calculate the proportionality constant, Equation 2.1 can be rearranged to form Equation 2.2 (Latash & Zatsiorsky, 1993).

Equation 2.2: $k = \Delta F / \Delta x$ (Latash & Zatsiorsky, 1993)

Where k = the proportionality constant, ΔF = change in force and Δx = change in length.

Therefore, theoretically, stiffness can be modelled where both a length change and force output change can be approximated.

2.2 The spring-mass model

In regards to human movement, stiffness describes the ability of the body, or individual joints within the body, to resist displacement in response to the application of ground reaction force or individual joint moments (Serpell et al.,

6

2012). The stiffness of the body is commonly approximated using a spring-mass model (Blickhan, 1989; McMahon & Cheng, 1990; Farley et al., 1991; Seyfarth et al., 2000; Kuitunen et al., 2002; Butler et al., 2003; Cavagna, 2006; Hobara et al., 2007). In this model, the lower limb is represented as a simple 'leg-spring' supporting the mass of the body (Butler et al., 2003). The spring-mass model can be applied as shown in Figure 2.1a to tasks such as hopping (Hobara et al., 2007) or vertical jumping (Arampatzis et al., 2001b), and as shown in Figure 2.1b to tasks such as walking/running gait (Cavagna, 2006) or horizontal jumping (Seyfarth et al., 2000), to provide a global approximation of leg-spring stiffness.
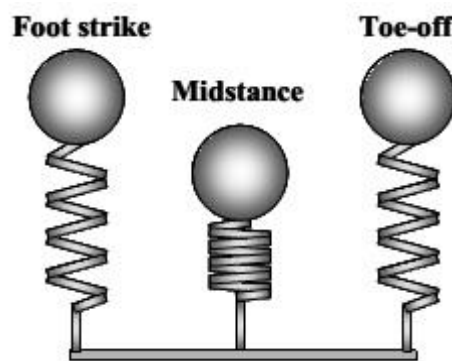
Figure 2.1a - A representation of the spring mass-model applied to hopping and vertical jumping.
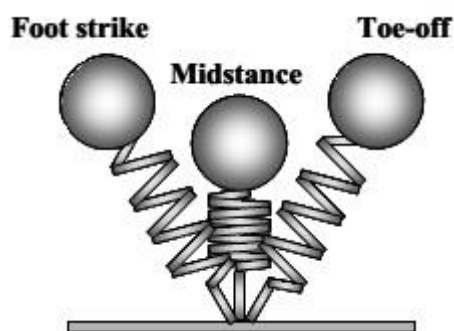
Figure 2.1b - A representation of the spring-mass model applied to walking/running gait and horizontal jumping.

In a physical context, an ideal spring has the mass of the system concentrated at the end of the spring whilst the spring itself is massless, moves solely in one

direction and has a stiffness that is independent of how the force is applied (Butler et al., 2003). The notion of applying a simple spring-mass, or leg-spring, model to describe the mechanical properties of the human body is therefore flawed given the complex interaction of many individual components and numerous degrees of freedom (Latash & Zatsiorsky, 1993). However, as noted by Blickhan (1989), the spring-mass model does not imply that hopping and running is just 'elastic bounding' and states that "even in the case of actively supplied forces, a bouncing system behaves similarly to a spring-mass system" (Blickhan 1989, p. 1227). It is general features of the spring-mass model, most notably the conservation of momentum during instances of ground contact, that make the model successful in describing mechanical features of human movement (Blickhan, 1989); such features are not dependent on the assumption of a linear, massless leg-spring (Blickhan, 1989).

Whilst the leg-spring may not represent a true physical spring (Morin et al., 2005; Morin et al., 2006), the ability to approximate deformation of the lower limb in response to force is of important practical relevance to athletes and coaches. Lower limb stiffness, as approximated using simple spring-mass modelling, has been widely demonstrated to influence athletic performance (Pearson & McMahon, 2012) and will be discussed in greater detail in Section 2.4.

2.3 Modelling stiffness in human movement

Stiffness can be modelled at various physiologic levels, contextualised in Figure 2.2.
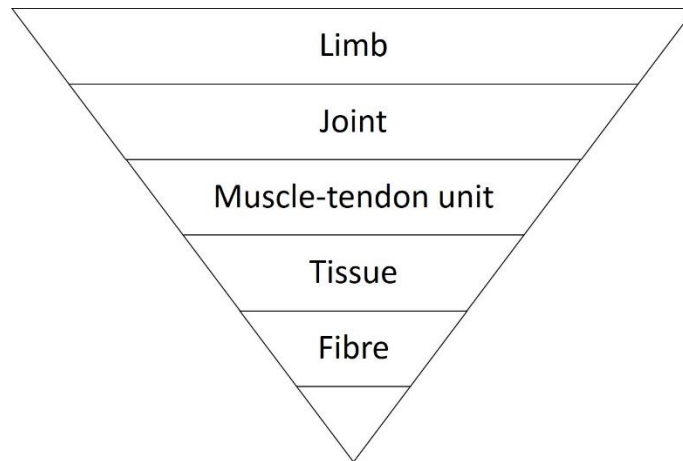
Figure 2.2 - An inverted pyramid representing the different physiologic levels at which parameters of stiffness may be determined.

Limb stiffness, at the top of the inverted pyramid, is a summative representation of all the underlying layers. For example, the stiffness of individual collagen fibres within the Achilles tendon, at the bottom of the pyramid, will influence leg-spring stiffness at the top of the pyramid. Whilst it is possible to approximate stiffness at each level of the pyramid, two key factors should be considered. Firstly, whilst a deterministic approach can elucidate important information pertaining to the summative limb stiffness, it is critical that the complex interaction of these various components is considered (Chow & Knudson, 2011). During human movement *in vivo* the lower limb is required to function as an integrated unit (Butler et al., 2003; Pearson & McMahon, 2012). Secondly, it is important to consider the practicality of the methodology required to assess a given stiffness. Typically, the more reductionist the approach, the greater the monetary cost, prerequisite skill level of the investigator and time taken for the assessment. For example, the determination of Achilles tendon stiffness *in vivo* requires the integration of force dynamometry, electromyography and motion capture analysis (Pearson & McMahon, 2012) and may be contraindicated within athletic training centres.

2.3.1 Vertical stiffness

Vertical stiffness is a representative measure of the summative musculoskeletal stiffness of the lower limb, approximating how the leg-spring deforms in response to force during a vertical movement task such as a hop or a vertical jump (Butler et al., 2003). Specifically, vertical stiffness considers the extent to which the body's centre of mass is displaced in response to vertical ground reaction force (McMahon & Cheng, 1990), as shown in Equation 2.3, and is based on the Hookean premise of the lower limb functioning as a simple leg-spring.

Equation 2.3: $Kvert = Fmax/\Delta y$ (Latash & Zatsiorsky, 1993)

Where K_{vert} = vertical stiffness, F_{max} = maximum vertical force and Δy = maximum vertical displacement of the centre of mass.

Relative to other approximations of stiffness, vertical stiffness is a quick and easy method by which to assess the viscoelastic properties of the lower limb (Butler et al., 2003). Ground reaction forces can be obtained using a force plate, a tool becoming increasingly common within the athletic training environment, and centre of mass displacement can be determined from the force trace using principles of inverse mechanics (Cavagna, 1975).

Vertical stiffness is most commonly assessed during the performance of a bilateral 'hopping' task (Joseph et al., 2013; Hobara et al., 2014). As well as offering the most simple spring-mass model with which to assess vertical stiffness (Farley et al., 1991), bilateral hopping is established to be more efficient in energetic consumption in comparison to other types of gait (Cavagna et al., 1964). Hopping should therefore provide a strong representation of musculoskeletal stiffness given the limited requirement for subsequent active force generation after the initiation of the hopping sequence (Farley et al., 1991). During hopping tasks, individuals are

required to perform a number of repeated bilateral hops on a force plate whilst vertical ground reaction force is recorded. Centre of mass displacement is then calculated from the force trace using principles of inverse dynamics. The centre of mass displacement is deemed representative of how much the leg-spring deforms in response to the ground reaction force (Butler et al., 2003). Vertical stiffness is subsequently calculated as the ratio of peak ground reaction force to peak centre of mass displacement as outlined in Equation 2.3 (Joseph et al., 2013; Hobara et al., 2014).

One potential issue with hopping tasks is that they are typically performed at set hopping frequencies and are inherently submaximal in nature (Joseph et al., 2013; Hobara et al., 2014). As such, bilateral hopping tasks may demonstrate greater correspondence to sub-maximal cyclic performances, such as endurance running, rather than short-term maximal performances, such as jumping. Whilst vertical stiffness may be determined during a squat jump or countermovement jump (i.e. Witmer et al., 2010), these tasks do not incur impact forces and do not represent how the leg-spring is typically loaded during sporting activities. Tasks such as running and changes of direction are dependent upon a flight phase and an initial impact during ground contact. For this reason, it may be desirable to assess vertical leg stiffness during a drop jump. The drop jump is an acyclic action performed with the intent to maximise jump height whilst minimising ground contact time (Marshall & Moran, 2013). It may therefore carry greater ecological validity as an assessment tool for vertical stiffness when compared to hopping tasks and be more representative of single maximal jumping effort (Flanagan & Harrison, 2007). Whilst vertical stiffness has been modelled during drop jumping by Arampatzis et al. (2001b), this task has not been used to examine relationships with performance or to examine inter-group differences in the same way as bilateral hopping tasks.

2.3.2 Leg stiffness

Whilst vertical stiffness does aim to approximate stiffness of the leg, the terms vertical stiffness and leg stiffness should not be used interchangeably. Leg stiffness is a separate measure which examines the extent to which the leg-spring compresses in response to ground reaction forces as opposed to assessing the displacement of the body's centre of mass (McMahon & Cheng, 1990), as shown in Equation 2.4. The change in leg length is calculated using greater number of factors in comparison to vertical stiffness. This method accounts for resting leg length, ground contact time and horizontal velocity in addition to vertical ground reaction force and calculated centre of mass displacement (McMahon & Cheng, 1990). The detailed equation for leg stiffness is presented in Appendix A2.

Equation 2.4: $Kleg = Fmax/\Delta L$ (McMahon & Cheng, 1990)

Where K_{leg} = leg stiffness, F_{max} = maximum vertical force and ΔL = change in leg length.

If seeking to describe stiffness using a simple spring-mass model, the calculation of leg stiffness may be preferable to vertical stiffness during performance tasks in which the lower limb contacts the ground in a non-vertical position such as during running gait or a change of direction. During tasks such as hops or vertical jumps, which are performed strictly in the vertical direction, leg stiffness and vertical stiffness formulae should provide the same value as the change in leg length is a function of the angle at which the leg-spring contacts the ground (McMahon & Cheng, 1990; Butler et al., 2003).

2.3.3 Joint stiffness

Given that calculations of vertical stiffness and leg stiffness are based on the premise that the lower limbs function as a global spring-mass system (Butler et al.,

2003), they do not take into consideration the various joints that contribute to summative stiffness (Pearson & McMahon, 2012). In order to elucidate the potential determinants of vertical stiffness properties, it is important to consider the respective contribution of the stiffness of individual joints.

Two-dimensional computer simulation models created by Farley et al. (1998) and Farley and Morgenroth (1999) demonstrated that vertical stiffness during bilateral hopping was modulated as a consequence of changes in ankle stiffness and were relatively unaffected by changes in knee stiffness. Farley et al. (1998) collected data reporting significant increases in ankle stiffness (173%; $P = 0.023$), but not knee stiffness ($P = 0.18$), between stiff and compliant surfaces. In the subsequent simulation model, a 175% increase in ankle stiffness resulted in a 170% increase in vertical stiffness whereas a 200% increase in knee stiffness increased vertical stiffness by just 8% (Farley et al., 1998).

This proposition has been subsequently supported in hopping investigations by Kuitunen et al. (2011) and Kim et al. (2013), and in drop jumping by Arampatzis et al. (2001). Kuitunen et al. (2011) reported strong correlations between vertical stiffness and ankle stiffness ($r = 0.72\text{-}0.92$; $P = 0.05\text{-}0.01$), but not knee stiffness, in eight 'physically active' males. Kim et al. (2013) demonstrated that modulation of ankle stiffness had the highest correlation to hopping frequency ($r^2 = 0.83$; $P < 0.01$) in a 'well-trained' mixed-sex cohort (males: 7, females: 4). In a population of fifteen decathletes, Arampatzis et al. (2001) reported that vertical and ankle stiffness both increased in a linear manner with shorter ground contact times, whilst knee stiffness did not. However, Arampatzis et al. (2001) did not specifically examine the vertical versus ankle stiffness relationship.

In contrast, Hobara et al. (2009) reported that knee stiffness, but not ankle stiffness, explained variance in vertical stiffness during maximal bilateral hopping in ten 'well-trained' male athletes. Multiple regression analysis accounted for 84% ($P = 0.003$) of the variance in vertical stiffness with a significant correlation reported for knee stiffness ($r = 0.64$; $P = 0.03$) but not ankle stiffness ($r = 0.37$; $P = 0.17$). Whilst Kuitunen et al. (2011) demonstrated that knee stiffness did not influence global stiffness, the investigators reported that knee stiffness modulated mechanical output and overall performance; knee stiffness significantly correlated to take-off velocity during bilateral hopping ($r = 0.56$; $P < 0.001$) and was increased in response to greater hopping intensities. Horita et al. (2002) also highlight the role of the knee in determining performance, correlating knee moment ($r = 0.84$; $P < 0.01$), although not knee stiffness ($r = 0.42$), to take-off velocity in drop jumping in nine 'healthy' males.

The contributions of ankle and knee stiffness are of particular importance if seeking to ascertain the determinants of global stiffness measures. On balance of the evidence, it appears that ankle stiffness is more closely related to the modulation of vertical stiffness but that knee stiffness is linked to mechanical output and overall performance. It may be reasonable to suggest that knee stiffness becomes more important as the intensity of the task increases, during a drop jump for instance, as performers will attempt to utilise the stronger knee extensors (Alexander & Ker, 1990) to a greater extent. However, such analyses have not been well considered outside of hopping and running gaits, and require further investigation. In addition, the potential contribution of respective joints to asymmetries in vertical stiffness (to be discussed in Section 2.8) has not been explored.

2.3.4 Muscle-tendon unit stiffness

It is perhaps best to consider lower limb and joint stiffness as a product of musculotendinous stiffness (Pearson & McMahon, 2012) as acute or chronic training adaptations will seek to induce specific adaptations within the muscle-tendon unit in order to modulate stiffness. As the ankle may be the most pertinent joint to consider during hopping (Kuitunen et al., 2011; Kim et al., 2013), drop jumping (Arampatzis et al., 2001b) and changes of direction (Pruyn et al., 2014), the Achilles tendon - medial gastrocnemius complex may be the most pertinent muscle-tendon unit to consider.

Following the principle outlined in Equation 2.2, stiffness of the Achilles tendon - medial gastrocnemius muscle-tendon unit can be calculated by using ultrasonography to track displacement of the tendon-aponeurosis complex during contraction whilst synchronistically monitoring force output of the talocrural joint (Magnusson et al., 2001). Muscle-tendon unit stiffness may be determined passively, utilising tasks such as passive lengthening (Muraoka et al., 2002) or free oscillation (Walshe & Wilson, 1997) of the joint. However, it is more important to determine how the tendon stiffens in an active, quasi-isometric fashion as this is how it is required to function *in vivo* (Fukashiro et al., 2006; Magnusson et al., 2008). Whilst Achilles tendon-medial gastrocnemius stiffness may be calculated during global performance tasks such as jumping (Arampatzis et al., 2001b) and gait (Fukunaga et al., 2001), the most common task utilised is an isometric plantar flexion (Magnusson et al., 2001). Chapter 3 will consider the calculation of gastrocnemius muscle-tendon unit stiffness in greater detail.

2.4 Stiffness and athletic performance

The ability to generate greater stiffness is likely to be beneficial to activities where the ability to produce and express a given impulse more quickly would be beneficial to performance. For example, greater vertical stiffness has been linked to greater running velocity (Bret et al., 2002), hopping height (Kuitunen et al., 2011) and take-off velocity during jumping (Arampatzis et al., 2001b). A stiffer leg-spring should facilitate a more rapid release of elastic energy under circumstances were minimal joint or centre of mass displacement is desired, such as during a drop jump or change of direction (Bret et al., 2002).

Hopping tasks have been shown to differentiate between certain athletic groups. Hobara et al. (2008) demonstrated that power-trained (sprint-trained for >9 years) athletes exhibit greater vertical stiffness (> 15% based upon graphical data) than endurance-trained (distance running trained for > 7 years) athletes. Similarly, endurance-trained (club-level 5 or 10 km runners) athletes have been shown to exhibit greater vertical stiffness (> 25% based upon graphical data) than untrained individuals (Hobara et al., 2010). Harrison et al. (2004) employed countermovement and drop jumps performed on a sledge apparatus (a custom built chair sliding on a fixed track on an inclination of 30° to the horizontal) as opposed to hopping. Harrison et al. (2004) reported greater vertical stiffness in sprinters (100 m personal best: 10.45 - 11.20 s) versus endurance runners (national league 1500 m - 10,000 m runners) in both countermovement (~75% based upon graphical data) and drop jumps (73%). However, it is important to consider the limitations of the sledge apparatus. The vector at which the force is applied to the leg-spring is not representative of typical locomotion. This is likely to reduce the reaction forces experienced by the leg-spring and increase the associated contact times.

The relationship between stiffness and performance appears to hold true within homogenous athletic populations. Bourdin et al. (2010) reported that vertical stiffness, determined during 'maximal' bilateral hopping, correlated (r = 0.66; P = 0.001) with season's best performances in thirty-eight national male throwers (discus, hammer and shot). Pruyn et al. (2014) split a cohort of female Netball athletes (training experience: 15 ± 3 years) into high-stiffness (202 ± 30 $N.m^{-1}.kg^{-1}$) and low-stiffness (150 ± 14 $N.m^{-1}.kg^{-1}$) groups following a unilateral hopping test performed at 2.2 Hz. Whilst inter-group differences were not significant, performances in a number of speed and power tests (10 m sprint, squat jump, drop jump, etc.) were superior in the 'high stiffness' group and were reported with 'moderate-to-large' effect sizes (d > 0.7).

Taken together, it would appear that individuals with greater stiffness are likely to perform better in short-duration maximal activities such as jumps, throws and sprints. For this reason, the quantification of vertical stiffness would appear of clinical relevance to athletes, coaches and applied practitioners. The role of stiffness in specific relation to change of direction speed (CODS) will be examined in Section 2.11.

2.5 Quantifying asymmetry

Using a single discrete measure to describe the difference between two sides is useful if seeking to characterise a functional imbalance for a given parameter (Zifchock et al., 2008), for instance, a difference in vertical stiffness between the left and right limbs. To calculate an index of asymmetry, the difference between the two sides is typically divided by a reference value and then expressed as a percentage thereof (Zifchock et al., 2008).

How indices of asymmetry are reported in the literature is highly inconsistent. For this reason, it is important to understand not only the terminology used by investigators in the presentation of results, but also the equations from which asymmetries are derived. Indeed, a number of investigations from the same research group (Sato & Heise, 2012; Bailey et al., 2013; Bazyler et al., 2014; Bailey et al., 2015) report using the symmetry index (Equation 2.6a), citing Shorter et al. (2008), although do not employ the correct formula as was cited in the manuscript of Shorter et al. (2008). Instead, these investigations determine asymmetry using Equation 2.7 (Page 19).

At its most simple an index of asymmetry can be quantified as a percentage using the dominant or maximal side as the reference value (Equation 2.5). Whilst termed as the 'index of asymmetry' in some investigations (Vagenas & Hoshizaki, 1991; Benjanuvatra et al., 2013), this method will be termed an asymmetry percentage for the remainder of this thesis to avoid confusion with alternative equations.

Equation 2.5: $ASYM\% = \frac{Max - Min}{Max} * 100$ (Vagenas & Hoshizaki, 1991)

Where *ASYM%* = asymmetry percentage, *Max* = larger side value, *Min* = smaller side value.

A simple asymmetry percentage provides an effective means of communicating to the athlete, coach or applied practitioner. For example, "knee extensor strength of the left limb is 14% less than the right limb." However, in the literature asymmetries are typically reported using different formulae.

The symmetry index (Equation 2.6a) was first used by Robinson et al. (1987) to quantify gait asymmetries in individuals with back pain, although subsequent investigations have used the 'symmetry index' in both healthy (Shorter et al., 2008;

Gouwanda & Senanayake, 2011) and athletic (Bell et al., 2014; Hart et al., 2014b) populations.

Equation 2.6a: $SI\% = \frac{2(Max - Min)}{Max + Min} * 100$ (Robinson et al., 1987)

Where *SI%* = symmetry index, *Max* = larger side value, *Min* = smaller side value.

The formula for the symmetry index can also be reported as shown in Equation 2.6b (Becker et al., 1995), both formulae providing the same resulting value. This thesis will not differentiate between the specific variations of the equation used, terming the results of either solely as the symmetry index.

Equation 2.6b: $SI\% = \frac{Max - Min}{0.5\,(Max + Min)} * 100$ (Becker et al., 1995)

Where *SI%* = symmetry index, *Max* = larger side value, *Min* = smaller side value.

Another index of asymmetry (Equation 2.7), has been used in a wide number of investigations by a single research group (Sato & Heise, 2012; Bailey et al., 2013; Bazyler et al., 2014; Bailey et al., 2015), incorrectly citing this formula as the symmetry index. As this formula represents differences as a percentage of both values without further transformation, any asymmetry calculated will be halved in comparison to the symmetry index. However, the application of this equation would not influence the statistical differences calculated in these investigations. For this reason, this thesis will term this as the deflated symmetry index.

Equation 2.7: $DSI\% = \frac{Max - Min}{Max + Min} * 100$ (Sato & Heise, 2012)

Where *DSI%* = inflated symmetry index, *Max* = larger side value, *Min* = smaller side value.

The symmetry angle (Equation 2.8) was proposed by Zifchock et al. (2008) as an alternative to the symmetry index. The symmetry angle formula employs left and right side values, expressing them as a vector, and it can therefore highlight a direction of asymmetry (negative values indicate a greater left side value whilst positive values indicate a greater right side value) (Zifchock et al., 2008). The symmetry index also treats positive and negative values as equal and opposite in magnitude (Zifchock et al., 2008).

$$\text{Equation 2.8: } SYM\alpha\% = \frac{(45° - \arctan(\frac{X\,\text{left}}{X\,\text{right}}))}{90°} * 100$$

(Zifchock et al., 2008)

Where SYMα% = symmetry angle, X left = left side value, X right side value.

The symmetry angle is able to identify inter-limb differences in a similar manner to other asymmetry indices, such as the symmetry index (Robinson et al., 1987), but because of the standardised reference point, provides a standard scale for interpretation and reduces the likelihood of artificially inflated values (Zifchock et al., 2008).

Table 2.1 - An example of how four equations for the quantification of asymmetry provide different asymmetry scores.

Athlete	Vertical ground reaction force (N)		Asymmetry percentage	Symmetry index	Deflated symmetry index	Symmetry angle
	Left Limb	Right Limb				
1	1430	1674	14.54%	15.72%	7.86%	4.48%
2	1989	1642	17.45%	19.11%	9.56%	-5.46%

Given that asymmetry values may vary greatly dependant on how the data has been analysed, it is important that the equation used to quantify asymmetry is

clearly reported by investigators. Whilst the symmetry index is the most widely used formula to assess asymmetry (Shorter et al., 2008; Gouwanda & Senanayake, 2011; Bell et al., 2014; Hart et al., 2014b) - highlighted in Section 2.7 - this thesis will use the symmetry angle as the primary formula to determine and quantify asymmetry due to its ability to demonstrate a lateral dominance with a standardised scale of interpretation. This thesis will also use the asymmetry percentage as an adjunct to the symmetry angle in order to aid the reporting and dissemination of research findings to applied practitioners.

2.6 Expression of asymmetries

The expression of asymmetry is highly specific. For example, Flanagan and Harrison (2007) compared asymmetries of eight individuals (five male, three female) from various sporting backgrounds (disciplines included basketball, Gaelic games, weightlifting, athletics, recreational running, soccer, and golf); the investigators stated that participants were of varying activity profiles to allow for a generalised application of the experimental findings. To assess asymmetries, participants performed unilateral drop jumps and repeated drop jumps on a sledge apparatus - described in Section 2.4. The investigators reported that no asymmetries were apparent during the cyclic, repeated jumps, however, significant asymmetry in reactive strength index was evident during the acyclic drop jump task. Reactive strength is a quality which may be closely linked to stiffness. Ground contact time is the denominator in the reactive strength index calculation (Newton & Dugan, 2002) and shorter ground contact times during drop jumping are associated with greater vertical stiffness (Arampatzis et al., 2001b). However, given that reactive strength is also dependent upon flight time (or jump height),

changes in this index may not necessarily correspond to changes in contact time. Inferences based upon reactive strength index must therefore be interpreted with a note of caution. When presented as a symmetry angle, average differences in reactive strength index between limbs were -1.1% for drop jumping and 0.4% for repeated drop jumping (Flanagan & Harrison, 2007). Whilst the observations of Flanagan and Harrison (2007) demonstrate that the type of performance task chosen to assess stiffness carries the potential to modulate how asymmetries may be expressed, further research is necessary to elucidate this effect. Moreover, it must be established if these findings may be replicated *in vivo* as the loading experienced by the leg-spring during sledge hopping is not representative of how the leg-spring is loaded during human movement.

As cyclic, submaximal versus acyclic, maximal performance tasks may differently express asymmetries, so too may bilateral versus unilateral performance tasks. Benjanuvatra et al. (2013) compared impulses of the left and right limbs during bilateral and unilateral countermovement jumping in 58 physically active, but not highly trained, individuals. The investigators noted that all participants were required to have inter-leg length differences of ≤ 2% to remove this as a potential confounding variable which may contribute to asymmetry (Perttunen et al., 2004). Benjanuvatra et al. (2013) reported that the asymmetries presented in the bilateral jump did not correspond to asymmetries in the unilateral jump. For example, 18 participants expressed left-side dominance during the unilateral task but only six of these individuals expressed similar left-side dominance in the bilateral task. In total, only 46% of the participants demonstrated the same asymmetry/symmetry profile across the two jumps. Whilst the correlation between impulse asymmetries in unilateral versus bilateral jumping was significant, although weak, in females (n = 30; r = 0.45, P < 0.05) this relationship was not significant in males (n = 28; r =

0.06, $P = 0.76$). Also, it is important to note that these correlations do not assess agreements, only relationships (Bland & Altman, 1986). Significant correlations could therefore exist in the presence of limited agreement between the relative limb-dominance between the two jumps.

Benjanuvatra et al. (2013) concluded that asymmetry in bilateral tasks is driven by neural factors as opposed to mechanical factors, a proposition supported by an earlier investigation conducted by Simon and Ferris (2008). Simon and Ferris (2008) examined inter-limb differences in the isometric force production of ten healthy, non-athletic participants performing a bilateral leg press at various contraction intensities (20, 40 and 60% of maximum). At all contraction intensities, participants produced significantly less force when normalised to their unilateral maximum voluntary contraction force (20%: $P = 0.047$, 40%: $P = 0.001$, 60%: $P < 0.001$). In addition, a significant inter-limb difference in force was observed during a bilateral (symmetry angle: 7%; $P < 0.001$), but not unilateral (symmetry angle: 1%; $P = 0.38$), maximal isometric contraction. As unilateral jumping tasks rely on the extension forces generated from a single limb, such tasks would appear to be a more suitable choice if seeking to quantify mechanical parameters of the limb such as vertical stiffness. However, such propositions are yet to have been evaluated by the literature and further research is required to explore this assertion.

Data presented by Bailey et al. (2015) would appear to suggest that asymmetries in rate of force development may be greater than asymmetries in peak force in 129 collegiate athletes, although differences were not examined statistically. Moreover, Bailey et al. (2015) also measured asymmetries in additional jump variables in a smaller sub-set of participants (n = 63). For each variable examined (peak force, peak power, peak velocity, net impulse, time to peak force and rate of force development), the deflated symmetry index value was greater during a

countermovment jump (i.e. a faster movement performed using the stretch-shortening cycle) than during a squat jump (no stretch-shortening cycle) although these differences were not analysed statistically. The largest asymmetries of all (12.8% for males, 17.2% for females; both deflated symmetry indicies) were reported for peak power during a countermovement jump performed with 20 kg. As these interaction effects were also not examined by the investigators, future research would need to explore how asymmetries may be differently expressed dependent on the temporal nature of the variable. For example, the discrepancy between vertical ground reaction force asymmetries and vertical stiffness asymmetries.

2.7 Force-related asymmetries and performance

Several investigations have reported that asymmetries in force-related qualities may be detrimental to athletic performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), as shown in Table 2.2. The literature does not provide a clear rationale as to why asymmetry may be detrimental as a standalone factor. Of the studies shown in Table 2.2, only Hart et al. (2014b) have attempted to explain this relationship. However, Hart et al. (2014b) do not move beyond the idea that the weaker leg is smaller, able to produce less force and may therefore limit performance. It is perhaps likely that where the body has identified a 'weak link' in the chain the neural system will act to inhibit the force production in other areas as a consequence. This contention would appear to fit with the conclusions of Simon and Ferris (2008) and Benjanuvatra et al. (2013), that asymmetry in bilateral tasks is driven by neural factors, but requires further investigation.

The results of the published investigations to date suggest that asymmetries in force qualities are detrimental to athletic performance, although the reasons behind this relationship are as yet unclear. Nonetheless, strength appears to be the most important modulating factor in this relationship (Bazyler et al., 2014). Bazyler et al. (2014) reported greater asymmetry in force production during an isometric squat in a 'weak' group (n = 9; one repetition maximum (1RM) back squat: 137.84 ± 19.10 kg) compared to a 'strong' group (n = 9; 1RM back squat: 167.57 ± 26.44 kg) of recreationally trained males (inclusion criteria: 1RM back squat ≥1.3 x body mass), highlighting a potential role of strength and/or training background in the modulation of asymmetry. This proposition was supported by the finding that whilst both strong and weak groups increased strength following a seven-week training intervention, only the weak group reduced asymmetry (to be discussed in greater detail in Section 2.9).

Table 2.2 - A summary of the investigations examining the association of force related asymmetries and athletic performance tests.

Authors	Population	Determination of asymmetry	Symmetry index	Magnitude of asymmetry	Association with performance
Bailey et al. (2013)	36 collegiate athletes (male)	Peak force in isometric mid-thigh pull	Deflated symmetry index	Group mean: 6.6% (±5.1%)	Asymmetry negatively correlated with squat jump and countermovement jump height (r = -0.39 to -0.52; P < 0.01) and peak power output (r = -0.28 to -0.43; P < 0.05) at 0kg and 20kg loads.
Bell et al. (2014)	167 collegiate athletes (male: = 103, female = 64)	Peak force in countermovement jump	Symmetry index	95% of group: -11.8% - 16.8%	Jump height was not statistically significant across different levels of force (P = 0.37) or power (P = 0.08) asymmetry.
		Peak power in countermovement jump		95% of group: -9.9% - 11.5%	≥10% power asymmetry resulted in decreased jump height of ~0.09 m (d = 0.80)
Hart et al. (2014b)	31 sub-elite Australian Rules footballers (male)	Peak force in isometric squat (hip and knee flexion: 140°)	Symmetry index	Accurate group: -1% (±1%) Inaccurate group: 8% (±1%)	Accurate (n = 15) and Inaccurate (n = 16) groups based on top and bottom in kicking accuracy test. The accurate group exhibited significantly lower asymmetries in peak force (P = 0.002; d = 0.9). Asymmetry negatively correlated with kicking accuracy (r = -0.52; P value not reported)

Table 2.2 (cont)- A summary of the investigations examining the association of force related asymmetries and athletic performance tests.

Bazyler et al. (2014)	18 recreationally trained individuals (male)	Peak force in isometric squat (knee flexion: 120°)	Deflated symmetry index	Strong group: 1.9% (±1.1%) Weak group: 3.9% (±1.8%)	Strong (n = 9) and weak (n = 9) groups based on a median split of peak force output in isometric squat at 120° knee flexion. Asymmetries at 90° (*P* = 0.045) and 120° (*P* = 0.007) larger in the weak group versus strong group. Asymmetry at 120° negatively correlated with peak force output at 120° (*r* = -0.64; *P* = 0.004).
		Peak force in isometric squat (knee flexion: 90°)		Strong group: 2.2% (±1.7%) Weak group: 4.6% (±4.3%)	
Bailey et al. (2015)	129 collegiate athletes (male: = 64, female = 65)	Peak force in isometric mid-thigh pull	Deflated symmetry index	Strong group: 4.7% (±0.1%) Weak group: 9.4% (±0.1%)	Strong (n = 13) and weak (n = 13) groups based on top and bottom 10% performers in mid-thigh pull force output. The stronger group exhibited significantly lower asymmetries in peak force (*P* = 0.03; *d* = 0.82) and rate of force development (*P* = 0.02; *d* = 0.90).
		Rate of force development in isometric mid-thigh pull		Strong group: 5.5% (±0.5%) Weak group: 12.9% (±0.7%)	

Whilst sex would also appear to influence asymmetries and performance (Bailey et al., 2015), this is perhaps an indirect effect of greater strength levels in male participants. Bailey et al. (2015) measured asymmetries in additional jump variables (peak force, peak power, peak velocity, net impulse, time to peak force and rate of force development) in a smaller sub-set of participants (n = 63). Asymmetries in the majority of the variables examined were greater in females than in males, however, this trend was not observed in the larger sample (n = 129) when athletes were split based on isometric strength. It is therefore likely that the sex-related differences observed were more related to differences in strength as opposed to sex itself.

Taken together, it is apparent that asymmetries are lower in stronger (versus weaker) athletes and that measures of force-related variables (i.e. performance measures) are also greater in stronger athletes. Research has not examined whether this relationship is still observed in non-athletic populations and should be considered in furture investigations. Were a modulating effect of strength to be similarly reported in a 'weak' participant population it would be important to determine whether the magnitude of this effect would remain the same.

2.8 Stiffness asymmetries

Literature investigating inter-limb asymmetries in stiffness measures is limited. It has been proposed that stiffness asymmetries may be detrimental to athletic performance given a likely imbalance in the application of force (Wilson et al., 1994), however, this hypothesis has not been well explored. Bachman et al. (1999), Heise and Bachman (2000) and Divert et al. (2005) all observed no significant vertical or leg stiffness asymmetries during running, although the cyclic,

submaximal limb action and bilateral nature of locomotion may be expected to encourage symmetry. When the results of Bachman et al. (1999) are presented as a symmetry angle, average differences in vertical stiffness between the left and right limbs were -3.8% and -2.7% at running speeds of 3.5 m.s^{-1} and 5.3 m.s^{-1}, respectively. Similarly, Hobara et al. (2013) did not report significant vertical stiffness asymmetries between non-dominant and dominant limbs during unilateral hopping; symmetry angles of -4.4%, 1.0% and -2.7% were observed at hopping frequencies of 1.5 Hz, 2.2 Hz and 3 Hz, respectively.

Whilst the relationship between vertical stiffness asymmetry and performance has not been well investigated, the potential impact of stiffness asymmetry on the incidence of injury has been considered. Watsford et al. (2010) reported that pre-season asymmetries in vertical stiffness between Australian Rules football players that went on to sustain (asymmetry percentage: 7.3 ± 6.1%) or not sustain (7.4 ± 5.7%) hamstring injuries were not significantly different ($P = 0.95$). However, Watsford et al. (2010) did demonstrate that vertical stiffness of the affected limb in the injured group was significantly greater than the unaffected limb (5%; $P = 0.02$); no between-limb differences were observed in the non-injured group ($P = 0.58$). A subsequent investigation from the same research group (Pruyn et al., 2012) found that mean vertical stiffness asymmetries recorded during the in-season competitive period were higher in Australian Rules footballers that experienced lower body soft tissue injury (asymmetry percentage: 7.5 ± 3.0%) than those that did not (5.5 ± 1.3; $P < 0.05$).

Given the association of force-related asymmetries with the potential for impaired athletic performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015) it may seem reasonable to suggest that stiffness asymmetries would be similarly detrimental to athletic performance, particularly if

the performance task requires high levels of stiffness. This hypothesis must be investigated directly before any conclusions may be drawn. Nonetheless, given a likely association between vertical stiffness asymmetry and increased injury incidence (Watsford et al., 2010; Pruyn et al., 2012), the determination of vertical stiffness asymmetry is certainly of important practical relevance to athletes, coaches and applied practitioners.

2.9 The effect of exercise interventions on asymmetry

Chronic exercise (i.e. training) interventions demonstrate the potential to modulate asymmetry. Bazyler et al. (2014) reported that as lower limb strength increases in response to a training intervention there is a concomitant decrease in asymmetry in weaker individuals (with a larger deflated symmetry index) but not in stronger individuals (with a smaller deflated symmetry index). After the initial identification of strong and weak groups in the investigation conducted by Bazyler et al. (2014), participants completed a seven-week periodised training programme consisting solely of dynamic bilateral back squats. Both strong and weak groups improved 1RM back squat by a similar magnitude (strong: 5.0%, weak: 6.6%; both $P < 0.05$) with no significant difference in the improvements observed between groups. However, reductions in force production symmetry during the isometric squat were only reduced in the weak group (from $4.6 \pm 4.3\%$ to $4.0 \pm 5.1\%$ at 90° knee flexion and from $3.9 \pm 1.8\%$ to $1.9 \pm 1.5\%$ at 120° knee flexion; both $P < 0.05$). The large standard deviations observed in this investigation, in some instances larger than the associated mean values, could highlight a high degree of variability in the asymmetry responses to training. Inter-individual responses to a standardised training programme is a well acknowledged phenomenon - see Mann et al. (2014)

for a review; future research should take into account the inter-individual variability in the training response and would be advised to present data in a manner that allows for individual or sub-group (i.e. 'responders' versus 'non-responders') analysis.

The notion that strength training can reduce asymmetry is also supported by the findings of Impellizzeri et al. (2007), although in a population of seven athletes who had undergone anterior cruciate ligament surgery in the previous 8-12 weeks. The data of Impellizzeri et al. (2007) demonstrate an initial asymmetry angle of 7.3% in force output during a vertical jump test, this was reduced to 0.5% following 7-9 weeks of rehabilitation training. As a trend for improvement in weak but not strong groups was observed by Bazyler et al. (2014), the improvements in force observed by Impellizzeri et al. (2007) were confined to the weak (35% increase; $P = 0.02$) but not strong (6% increase; $P = 0.50$) limb. Whilst these results further highlight the importance of pre-intervention strength levels in modulating asymmetries, the findings are limited by the specific nature of the participant population and require investigation in a healthy population.

Golik-Peric et al. (2011) compared two, four-week resistance training interventions on the isokinetic strength ratios of the knee extensors and knee flexors among 38 male athletes. Participants were selected from a sample of 196 national-level athletes chosen because they exhibited a notable strength asymmetry (inclusion criteria: concentric hamstring to quadriceps ratio of < 0.5). The investigators did not report examining left and right limb strength imbalances statistically, although the presentation of normative data allows for subsequent calculations to be made. A unilateral isokinetic training regimen reduced the asymmetry percentage for both the knee extensors (pre: -1.4%, post: 0.2%) and knee flexors (pre: 1.2%, post: -0.2%). A bilateral half-squat regimen produced a larger reduction in knee flexor

asymmetry angle, although the initial asymmetry was substantially larger (pre: 3.5%, post: 1.0%), and minimal change in knee extensor asymmetry (pre: 2.3%, post: 2.0%). Once more, this lends weight to the argument that reductions in asymmetry are likely to be more pronounced where pre-intervention levels of asymmetry are greater. The findings of Golik-Peric et al. (2011) suggest that unilateral versus bilateral training may differently affect inter-limb asymmetries but the discrepancy in training modalities makes it hard to compare these protocols. In addition, the specific selection of participants with large flexor/extensor asymmetries also limits the potential applicability of these findings.

It should be noted that the previously discussed studies examine the chronic modulation of asymmetries and acute interventions have received very little attention. Indeed, the effects of an acute exercise intervention on asymmetry has been investigated only in a single study. Hodges et al. (2011) sought to determine the effects of a fatiguing back squat protocol (5 sets of 8 repetitions performance at 80% of 1RM) on the expression of vertical ground reaction forces in recreational athletes (n = 17; 8RM back squat: 113 ± 35% body mass), hypothesising that fatigue would exacerbate asymmetries. Part of the investigators' selection criteria was that athletes with likely asymmetry (e.g. clinically diagnosed limb length discrepancy, known injury or highly trained in asymmetric skills) were excluded from participation. The investigators reported that average asymmetry percentages across the five sets were 4.3 ± 2.5% for the first and second repetitions of the set, and 3.6 ± 2.3% for the seventh and eighth. Analysed as a whole group, there was no effect of time on absolute ($P = 0.60$) or peak ($P = 0.23$) vertical ground reaction force asymmetry. However, when the investigators removed 'highly symmetric' participants (defined as an asymmetry percentage of < ± 1.7%, leaving n = 12) asymmetries in absolute ($P = 0.044$), but not peak ($P = 0.27$), vGRF was reduced

from reps 1-2 to 7-8. It is reasonable to suggest therefore, that the effects of acute exercise interventions designed to reduce stiffness asymmetries may be more pronounced in individuals with larger asymmetries, as has been observed in chronic interventions (Impellizzeri et al., 2007; Golik-Peric et al., 2011; Bazyler et al., 2014). Considering both acute and chronic exercise interventions, it is therefore apparent that asymmetries may be reduced following the application of an appropriate stimulus. However, no studies to date have examined how exercise interventions, acute or chronic, may affect stiffness asymmetries.

2.10 Determinants of change of direction speed

The ability to quickly and effectively change direction underpins performance in a wide range of sports. For example, change of direction speed (CODS) has been linked to performance in badminton (Sturgess & Newton, 2008), soccer (Reilly et al., 2000), field hockey (Keogh et al., 2003), rugby league (Meir et al., 2001) and basketball (McGill et al., 2012). Understanding the potential determinants of CODS will provide athletes, coaches and applied practitioners with important information which may better inform the training process.

Young et al. (2002) proposed that the determinants of CODS may be broadly grouped into three categories: 1) leg muscle qualities, 2) technical components, and 3) linear sprinting speed. However, given the lack of a strong relationship between linear sprinting performance and CODS (typically $r = 0.3 - 0.5$; see Brughelli et al. (2008) for a review), it may be more appropriate to categorise potential determinants of CODS as either physical (i.e. 'leg muscle qualities' in the Young et al. (2002) model) or technical in nature. Subsequent models proposed by Sheppard and Young (2006) and Hewit et al. (2013) also categorise

determinants as physical and technical in this fashion, although still highlight the importance of linear sprint speed.

Young et al. (2002) outlined three physical factors which may underpin CODS: strength (allied to maximal force production), power (allied to rate of force development) and reactive strength (allied to stiffness). This thesis acknowledges the contribution of these qualities in the proposition of a modified deterministic model of CODS as shown in Figure 2.3.
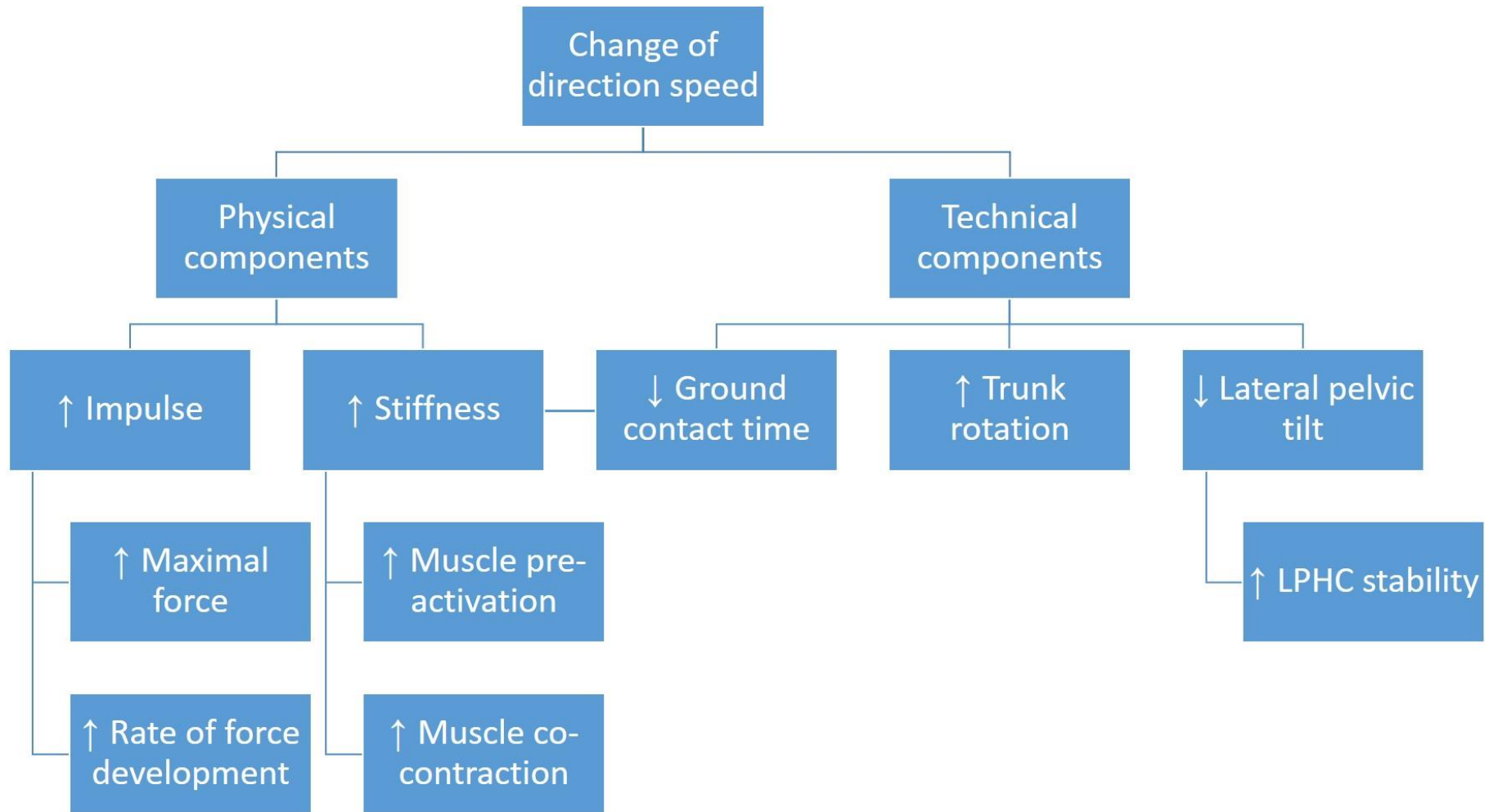
Figure 2.3 - A modified model highlighting the determinants of change of direction speed. Key: LPHC = lumbo-pelvic-hip complex.

2.11 The role of stiffness in change of direction speed

Young et al. (2002) reported that reactive strength index (a function of the flight time or jump height divided by ground contact time recorded during a drop jump (Newton & Dugan, 2002)) was the physical variable which demonstrated the strongest relationship with CODS test time (r = -0.54; P < 0.05). Similar relationships have also been observed by Young et al. (2015) (r = -0.65; P = 0.001) and Delaney et al. (2015) (dominant limb: r = -0.44; P < 0.05, non-dominant limb: r = -0.45; P < 0.05). As ground contact time is the denominator in the reactive strength index calculation, reactive strength is a quality which may be closely linked to stiffness. Arampatzis et al. (2001b) noted that greater vertical stiffness is associated with shorter ground contact times during drop jumping and, as previously stated, greater stiffness of the leg-spring should facilitate a quicker release of elastic energy (Bret et al., 2002). Whilst it has been reported that faster athletes exhibit shorter ground contact times than slower performers in CODS tasks (Sasaki et al., 2011; Marshall et al., 2014; Spiteri et al., 2015), which may be indicative of greater stiffness, the direct relationship between stiffness and CODS has not been well explored.

To the authors' knowledge, only one investigation has sought to directly examine the effect of stiffness on CODS. Pruyn et al. (2014) observed no significant relationship between vertical leg stiffness (determined during a unilateral hopping task) and 5-0-5 CODS test (examining a single 180° change of direction from a 15 m linear acceleration) performance (r = 0.05), although they did report significant relationships between performance and stiffness of the musculature surrounding the ankle (medial gastrocnemius: r = -0.53, soleus: r = -0.47; both P < 0.05). It is important to not only consider the task in which vertical stiffness was assessed by Pruyn et al. (2014) (i.e. cyclic and submaximal) but also the homogeneity of

population sampled. All 18 participants in the investigation were trained netball players (15 ± 3 years of training experience) and exhibited minimal variance in 5-0-5 performance (mean ± SD: 2.72 ± 0.18 sec). The potential relationship between stiffness and CODS would need to be examined in different, and possibly less homogenous, populations before any conclusions may be drawn as the external validity of these findings is limited to a very specific population. Also, given the likely demands to be placed upon the leg-spring during a change of direction (Glaister et al., 2008; Spiteri et al., 2013), it may be more pertinent to determine stiffness within acyclic, high-force activity if seeking to explore the relationship with CODS.

2.12 Asymmetry in change of direction speed

The deterministic models of CODS proposed by Sheppard and Young (2006) and Hewit et al. (2013) include, respectively, 'left-right muscle imbalance' and 'asymmetry' as potential determinants of CODS. Hewit et al. (2013) do not cite any evidence for the inclusion of asymmetry in the model, although the manuscript in which this model was presented did not seek to evaluate this component. Sheppard and Young (2006) cite the investigation conducted by Young et al. (2002) as the primary reason for the inclusion of left-right imbalance within their model; this section will consider the Young et al. (2002) investigation in detail.

Asymmetries in CODS when pushing off the dominant versus non-dominant limb have been reported in several investigations (Young et al., 2002; Henry et al., 2013; Hart et al., 2014a). For example, Hart et al. (2014a) reported that 58 sub-elite Australian Rules footballers demonstrated a typical performance deficit of 5 - 10% between limbs (~0.72 seconds; $P \leq 0.001$) with all players exhibiting a

directional preference; Hart et al. (2014a) recruited players from all positions (forwards, midfielders and backs) to minimise the risk of positional bias. Given the deterministic model proposed by Young et al. (2002) and modified model propsed in Figure 2.3, such asymmetry could be a consequence of an asymmtery in physical qualities. Indeed, Young et al. (2002) noted that athletes who displayed a lateral dominance in CODS performance were likely to have a reactive strength dominance in the limb responsible for the push-off action. The notion of a relationship between asymmetries in physical qualities and lateral dominance is supported by an investigation conducted by Henry et al. (2013). In a population of trained males with a recent involvement (competed within the last 2 years) in Australian Rules football (no mention of playing level), the investigators reported that asymmetries in reactive agility performance (discounting decision making time: 5.6%; $P = 0.04$) mirrored asymmetries in reactive strength index (4.4%; $P = 0.03$), although correlations between these variables were not reported. To date, investigations have not considered whether cognitive or technical factors (e.g. reaction time, foot placement, stride adjustment, etc.) may to contribute CODS asymmetries.

Whether asymmetries in physical qualities, such as vertical stiffness, are detrimental to overall CODS performance has not been investigated. It may seem reasonable to hypothesise that asymmetries in vertical stiffness would be detrimental to overall CODS performance as asymmetries in isometric strength (Bailey et al., 2013; Bazyler et al., 2014; Hart et al., 2014b; Bailey et al., 2015) and vertical jump (Bell et al., 2014) measures have been linked to impaired performance. However, given the lack of empirical evidence pertaining to CODS, stiffness or any combination of these factors, such propositions need to be

examined directly. The exploration of these relationships will therefore form an integral part of this thesis.

2.13 Acute interventions to improve change of direction speed

Acute pre-conditioning interventions incorporating ballistic exercise have been demonstrated to potentiate subsequent short-duration maximal performance (see Maloney et al. (2014a) for a review). The concept of post-activation potentiation is beneficial within a wide range of sports, although it is important to note that these augmentations are transient in nature (up to fifteen minutes (Maloney et al., 2014a)). Whilst this may appear to limit the application of pre-conditioning interventions within intermittent sports (e.g. rugby union or badminton), the creation of a potentiated state in which an athlete may begin their performance is certainly desirable. This may give the athlete an initial advantage in competition and could indeed prove to be the difference between winning and losing (Maloney et al., 2014a). The psychological boost to performance (i.e. increased self-confidence) may last longer than fifteen minutes, however, this idea has not been explored.

Considering ballistic exercise as the pre-conditioning stimulus, plyometric exercises emphasising the development of high levels of musculoskeletal stiffness may carry the greatest benefit to performance (Maloney et al., 2014a). Whilst explanations for the post-activation potentiation effect tend to focus on physiological (such as the phosphorylation of myosin regulatory light chains (Sweeney et al., 1993) and increases in pennation angle (Mahlfeld et al., 2004)) and neural (such as the recruitment of higher order motor units (Gullich & Schmidtbleicher, 1996)) factors, it is also important to consider the potential role of acute modulations in stiffness. Comyns et al. (2007) reported an increase in vertical

stiffness of 10.9% ($P < 0.05$) in twelve elite rugby union players (1RM back squat: 192 ± 35 kg) following a set of three repetitions of the back squat with a 93% 1RM load. Squat loads of 65% and 80% 1RM did not significantly influence stiffness, suggesting that subjecting the leg-spring to sufficiently high compressive loading may be a pre-requisite for the acute modulation of vertical stiffness. Whilst the increase in vertical stiffness was associated with a 7.8% ($P < 0.05$) reduction in ground contact time during a single leg drop jump performed on a sledge apparatus (described in Section 2.4), despite the discrepancy in the vector of force application, flight time during the drop jump (i.e. performance) was reduced by 3.4% ($P < 0.01$). Similarly, Moir et al. (2011) noted an increase in vertical stiffness of 16% (d: 0.52; $P = 0.013$) following high-load (three repetitions at 90% 1RM) but not high-volume (twelve repetitions at 37% 1RM) back squats in eleven female collegiate volleyball players. Also in agreement with the findings of Comyns et al. (2007), the augmentation in stiffness did not improve vertical jump performance by Moir et al. (2011), although no negative effect was reported in this instance.

The lack of association between increased vertical stiffness and a beneficial performance impact in the aforementioned investigations is a likely consequence of the performance tasks utilised. The mean ground contact time (pre-intervention) of the sledge drop jump reported by Comyns et al. (2007) was 0.44 seconds and Moir et al. (2011) employed a standing countermovement jump. As the stretch-shortening cycles associated with these movements would be towards the slower end of the stretch-shorting cycle speed continuum - for example, Schmidtbleicher (1992) defined a slow stretch-shortening cycle as anything greater than 0.25 seconds - the performance of these tasks would be expected to be determined more by the production of force (active force) than by the redistribution of force (passive) (Komi, 2003). Arampatzis et al. (2001b) propose an inverted-U

relationship between leg-spring stiffness and power output during the propulsive phase of jumping. Theoretically, increases in vertical stiffness should enhance power output up until an 'optimal' value is reached and increases beyond this point, as may have been experienced by the participants in the investigations of Comyns et al. (2007) and Moir et al. (2011), would impair power output. Acute augmentations in stiffness are likely to carry greater benefit to faster (versus slower) stretch-shortening cycle activities, for example, Pruyn et al. (2014) report correlations between lateral gastrocnemius stiffness with bilateral drop jumping (r = 0.66; P < 0.05) but not squat jumping (r = 0.34). Whilst the ground contact time during changes of direction are likely to exceed the 250 ms threshold proposed by Schmidtbleicher (1992) - ground contact times of between 250 and 500 ms, dependent on the cutting angle, would be expected (DeWeese & Nimphius, 2016) - shorter ground contact times have been correlated (r = 0.48 - 0.65) to improved CODS on an inter-individual basis (Sasaki et al., 2011; Marshall et al., 2014). Whether the acute reduction of ground contact time would improve CODS has not been investigated and will be explored by this thesis.

Another potential explanation for the lack of performance enhancement could lie within the short recovery periods between pre-conditioning intervention and performance (four and two minutes respectively) employed by Comyns et al. (2007) and Moir et al. (2011). It has been shown that fatigue is likely to mask any potentiative effect immediately following (i.e. ≤ four minutes) heavy resistance exercise and that recovery periods in excess of eight minutes may be required to observe performance enhancements (Gilbert & Lees, 2005; Kilduff et al., 2007; Kilduff et al., 2008).

Pre-conditioning interventions employing both heavy resistance exercise (Zois et al., 2011) and loaded ballistic exercise (i.e. weight vest loaded warm-up) (Maloney

et al., 2014b; Nava, 2015) have been demonstrated to favourably affect CODS. A warm-up performed with additional resistance has also been demonstrated to acutely augment vertical stiffness by 20% (d: 0.76; 90% confidence intervals: ± 4%) during a plyometric jumping task (Barnes et al., 2015). Given the importance of stiffness in maximising CODS, it is possible that the performance improvements observed following pre-conditioning interventions are related to augmentations in stiffness, however, such propositions must be examined directly. In addition to the exploration of asymmetries in stiffness and CODS, this thesis will investigate how these are modulated by acute exercise interventions.

2.14 Summary

Vertical stiffness and joint stiffness are typically determined during bilateral hopping (Joseph et al., 2013; Hobara et al., 2014), however, this may not provide the greatest correspondence to athletes required to engage in short-duration maximal actions such as changes of direction. As asymmetries may be differently displayed in both cyclic versus acyclic (Flanagan & Harrison, 2007) and bilateral versus unilateral (Simon & Ferris, 2008; Benjanuvatra et al., 2013) performance tasks, the unilateral drop jump may provide the most ecologically valid assessment tool by which to assess parameters of stiffness. The reliability of this method has not been evaluated by the literature.

Asymmetry in force-related (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015) parameters have been associated with impaired athletic performance. Whilst asymmetry in vertical stiffness may be hypothesised to carry similar detriments, this is yet to be examined directly. As vertical stiffness and ankle stiffness are likely to be important determinants of CODS, the possibly deleterious effects of asymmetry in these variables warrant particular consideration.

Ballistic exercise may carry a post-activation potentiation effect resulting in improvements to CODS (Maloney et al., 2014b; Nava, 2015). Whilst this is a possible consequence of acute augmentations in stiffness, this has not been evaluated by the literature. Whether acute exercise interventions can a) modulate stiffness and stiffness asymmetry, and b) if these modulations are then associated with performance, has not been previously investigated.

2.15 Thesis aims and objectives

This thesis will seek to:

1. Determine the most reliable and ecologically valid method to assess vertical stiffness in athletes required to perform changes of direction.

2. Determine if vertical stiffness and vertical stiffness asymmetries influence CODS.

3. Determine if acute 'stiffness' interventions can influence CODS and if augmentations are linked to the modulation of vertical stiffness and vertical stiffness asymmetries.

To address these aims, this thesis will have the following objectives:

1. Determine the reliability and validity of stiffness measures. Specifically:

    a. Determine the reliability of ultrasonography assessments of Achilles tendon stiffness.

    b. Determine the reliability of vertical stiffness during bilateral hopping, bilateral drop jumping and unilateral drop jumping.

    c. Determine how vertical stiffness and vertical stiffness asymmetries are expressed in bilateral hopping, bilateral drop jumping and unilateral drop jumping.

2. Determine whether vertical stiffness and vertical stiffness asymmetries are associated with CODS performance.

3. Determine whether acute unilateral and bilateral 'stiffness' interventions can influence CODS performance beyond a control intervention. Additionally, to determine if changes in CODS performance are linked to changes in stiffness or stiffness asymmetries.

2.16 Thesis hypotheses

This thesis hypothesises that:

1. A unilateral drop jump will be the most appropriate assessment tool to assess stiffness in athletes required to perform changes of direction. Specifically:

    a. Coefficients of variation (CVs) for vertical stiffness obtained during bilateral hopping, bilateral drop jumping and unilateral drop jumping tasks will be less than 10%. This would be in line with reliability figures previously reported for bilateral hopping (McLachlan et al., 2006; Joseph et al., 2013).

    b. Vertical stiffness and vertical stiffness symmetry angles will be significantly different between the three performance tasks.

2. CODS performance will demonstrate:

    a. A significant positive correlation with vertical stiffness.

    b. A significant negative correlation with vertical stiffness symmetry angle.

3. The unilateral 'stiffness' intervention will significantly improve CODS performance versus the bilateral and control interventions. Additionally:

    a. Vertical and ankle stiffness will be significantly greater following the unilateral intervention than following bilateral and control interventions.

    b. Vertical and ankle stiffness asymmetries will be significantly lower following the unilateral intervention than following bilateral and control interventions.

Chapter 3 - Reliability of Stiffness Measures

3.1 Overview

The purpose of chapter 3 was to establish the reliability of measurements by which to assess the stiffness of the lower limb in subsequent investigations.

This chapter will report the results of two investigations:

Pilot study: The reliability of Achilles tendon stiffness derived from isometric dynamometry and ultrasonography

Study 1: The reliability of vertical stiffness during bilateral hopping, bilateral drop jumping and unilateral drop jumping

The pilot study sought to examine the reliability of Achilles tendon stiffness using ultrasonography. Were the reliability of this method found to be acceptable during pilot testing, this would justify the use of these techniques during subsequent investigations within this thesis.

Study 1 sought to examine the reliability of vertical stiffness during bilateral hopping, bilateral drop jumping and unilateral drop jumping. Were appropriate reliability to be demonstrated for these methods this would justify their potential inclusion in subsequent investigations within this thesis.

3.2 Pilot Study - Reliability of Achilles tendon stiffness

3.2.1 Introduction

Tendon is responsible for transferring the forces developed during muscular contraction to the skeletal system and the resultant production of joint motion and/or joint stabilisation (Kvist, 1994). As the mechanical properties of tendon will directly determine how these forces are transferred, the calculation of such parameters is important in the understanding of human movement. In the field of sport and physical activity, the properties of tendon, most notably tendon stiffness, are a determining factor in several measures of both performance and injury risk (Butler et al., 2003; Pearson & McMahon, 2012) - see Section 2.4 for greater detail.

Achilles tendon stiffness can be calculated by using ultrasonography to track displacement of the tendon-aponeurosis complex during contraction whilst synchronistically monitoring force output of the talocrural joint (Magnusson et al., 2001). Achilles tendon stiffness may be determined passively, utilising tasks such as passive lengthening (Muraoka et al., 2002; Morse et al., 2008) or free oscillation (Walshe & Wilson, 1997) of the joint. However, it is more important to determine how the tendon stiffens in an active, quasi-isometric manner as this is how it is required to function *in vivo* (Fukashiro et al., 2006; Magnusson et al., 2008). Whilst Achilles tendon stiffness may be calculated during functional tasks such as jumping (Arampatzis et al., 2001a; 2001b) and gait (Fukunaga et al., 2001), the most common task utilised for assessing Achilles tendon mechanical properties is an isometric maximal voluntary contraction (MVC) of the plantar flexors (Kubo et al., 1999; Magnusson et al., 2001; Maganaris & Paul, 2002; Rosager et al., 2002; Kongsgaard et al., 2011).

Despite the widespread use of ultrasonography to assess tendon properties, the literature has not systematically reviewed the reliability of these techniques and compared the results of different investigations. Reliability values have not been reported in a number of widely cited investigations (Rosager et al., 2002; Arampatzis et al., 2005a; Arampatzis et al., 2005b; Kubo, 2005) and where it has been reported in the literature there is a large degree of variability in the figures reported between investigations (Table 3.1). For example, coefficients of variation (CVs) from 5% (Kubo et al., 2001) to over 15% (Mahieu et al., 2004) have been reported. In addition, only Mahieu et al. (2004) have attempted to examine the reliability of variables across more than two testing sessions, examining the reliability over three sessions. It is important to ensure the reliability of ultrasonography techniques if seeking to use them to monitor changes in tendon properties, such as those that may be induced by exercise interventions.

Table 3.1 - Reliability values for key mechanical variables pertaining to Achilles tendon stiffness during isometric plantar flexion dynamometry and ultrasonography investigations.

Authors	Data Sets n =	Measures n =	Intra-session reliability	Inter-session reliability	Notes
Plantar flexion torque					
Burgess et al. (2009)	15	3	ICC = 0.92		3 minutes rest
Joseph et al. (2012)	10	Not stated	ICC = 0.99 SEM = 3.52 N.m		No data provided for SEM as %, ≥12 weeks between sessions
	10	2		ICC = 0.95 SEM = 7.77 N.m	
Achilles tendon force					
Mahieu et al. (2004)	21	3		ICC = 0.96 CV = 9.2%	Left leg
	21	3		ICC = 0.95 CV = 8.5%	Right leg
Kongsgaard et al. (2011)	10	2		ICC = 0.81 TE = 5.6%	
Houghton et al. (2013)	44	2	ICC = 0.99 CV = 2.1%		
Key: ICC = intra-class correlation coefficient, SEM = standard error of measurement, CV = coefficient of variation, TE = typical error, MG = medial gastrocnemius, AP = aponeurosis, ANOVA = analysis of variance.					

Table 3.1 (cont.) - Reliability values for key mechanical variables pertaining to Achilles tendon stiffness during isometric plantar flexion dynamometry and ultrasonography investigations.

Aponeurosis/tendon displacement					
Muramatsu et al. (2001)	3	2		CV = 8.5% (P1), 5.3% (P2) and 5.7% (P3)	P1 = MTJ of MG, P2 = central X of deep AP, P3 = proximal X of AP
	7	3	CV = 8.8% (P1), 2.5% (P2) and 4.7% (P3)		
Magnusson et al. (2001)	5	2	CV = 11.3%		1 minute between trials
Maganaris and Paul (2002)	6	2	No difference in measurements within or between sessions ($P > 0:05$; two-way ANOVA).		Following 1 familiarisation session
	Not stated	8	CV = 6.4%		2 minutes between trials
Muramatsu et al. (2002)	7	3	CV = 5.5% (P1) and 6.3% (P2)		P0 = Origin of MG, P1 = distal X of superficial AP and P2 = proximal X of superficial AP
	7	2		CV = 6.3% (P0), 14.3% (P1) and 8.3% (P2)	
Mahieu et al. (2004)	21	3		ICC = 0.87 CV = 10.2%	Left leg
	21	3		ICC = 0.78 CV = 13.9%	Right leg
Burgess et al. (2009)	15	3	ICC = 0.95		3 minutes rest
Key: ICC = intra-class correlation coefficient, SEM = standard error of measurement, CV = coefficient of variation, TE = typical error, MG = medial gastrocnemius, AP = aponeurosis, ANOVA = analysis of variance.					

Table 3.1 (cont.) - Reliability values for key mechanical variables pertaining to Achilles tendon stiffness during isometric plantar flexion dynamometry and ultrasonography investigations.

Kongsgaard et al. (2011)	10	2		ICC = 0.85 TE = 11.8%	
Joseph et al. (2012)	10	Not stated	ICC = 0.99 SEM = 0.41 mm		No data provided for SEM as %, ≥12 weeks between sessions
	10	2		ICC = 0.93 SEM = 1.59 mm	
Houghton et al. (2013)	44	2	ICC = 0.81 CV = 5.9%		
Time to max force					
Houghton et al. (2013)	11	2		ICC = 0.78 CV = 6.7%	From pre-exercise to post-exercise
Tendon stiffness					
Kubo et al. (2001)	19	2		ICC = 0.90 CV = 5%	
Kubo et al. (2002)	6	2		ICC = 0.89 CV - 5.6%	
Mahieu et al. (2004)	21	3		ICC = 0.82 CV = 15.8%	Left leg
	21	3		ICC = 0.80 CV = 13.0%	Right leg
Key: ICC = intra-class correlation coefficient, SEM = standard error of measurement, CV = coefficient of variation, TE = typical error, MG = medial gastrocnemius, AP = aponeurosis, ANOVA = analysis of variance.					

Table 3.1 (cont.) - Reliability values for key mechanical variables pertaining to Achilles tendon stiffness during isometric plantar flexion dynamometry and ultrasonography investigations.

Kubo et al. (2007)	24	2	CV = 6%		3 minutes between trials
Kongsgaard et al. (2011)	10	2		ICC = 0.84 TE = 8.8%	
Houghton et al. (2013)	44	2	ICC = 0.90 CV = 12.3%		Low-force stiffness
	44	2	ICC = 0.89 CV = 15.6%		High-force stiffness
Key: ICC = intra-class correlation coefficient, SEM = standard error of measurement, CV = coefficient of variation, TE = typical error, MG = medial gastrocnemius, AP = aponeurosis, ANOVA = analysis of variance.					

Joseph et al. (2013) propose that a CV of ≤ 10% and an intra-class correlation coefficient (ICC) ≥ 0.80 as two appropriate threshold values to assist in determining 'good' reliability. Measurements of plantar flexion torque and Achilles tendon force would therefore appear to demonstrate good levels of inter-session reliability across multiple studies (Table 3.1). However, large discrepancies in the reported values for tendon force are apparent despite the fact that the majority of investigations report using a maximal contraction. Forces of between 300 N (Mahieu et al., 2004) and 5000 N (Houghton et al., 2013) have been reported in the literature with values in the low thousands more common (Magnusson et al., 2001; Rosager et al., 2002; Kongsgaard et al., 2011). The larger values reported by Houghton et al. (2013) in comparison to Mahieu et al. (2004) could partially explain the difference in CV between the two investigations given that the CV is a direct function of the mean.

Variance of tendon-aponeurosis displacement is greater than for force output. For example, the values reported by Kongsgaard et al. (2011) and Mahieu et al. (2004) would sit above the 10% CV threshold identified by Joseph et al. (2013). The lowest reported CVs have been observed by Muramatsu et al. (2001) and Houghton et al. (2013), reporting 5.3% and 5.9% respectively. As with tendon force, large discrepancies exist in tendon-aponeurosis displacement. Typical values range from ~5 mm (Mahieu et al., 2004) to ~15 mm (Rosager et al., 2002; Arampatzis et al., 2005b; Houghton et al., 2013), although Kongsgaard et al. (2011) reported displacement of just ~2 mm.

Given the variance of force and displacement measurements observed in the aforementioned investigations by Kongsgaard et al. (2011) and Mahieu et al. (2004), it is unsurprising that calculations of Achilles tendon stiffness also

demonstrated high variance. The values reported by Kongsgaard et al. (2011) fall just below the 10% CV threshold whereas those of Mahieu et al. (2004) and Houghton et al. (2013) fall above this; in the case of the latter, this despite assessing intra-session reliability and reporting both force and elongation to be reliable measures (< 10% CV). Investigations conducted by Kubo et al. (2001; 2002) have observed lower variance - reporting CVs of 5.0% and 5.6% respectively. Also, there is considerable variance in the reported stiffness of the Achilles tendon in the literature, ranging from as low as ~20 N.mm^{-1} in an investigation by Kubo et al. (2001) to in excess of 400 N.mm^{-1} reported by Houghton et al. (2013).

It is difficult to explain why there is such discrepancy between investigations given the similarity in methodologies. Mahieu et al. (2004) employed the same contraction protocol (ramped five second MVC), probe location (mid-gastrocnemius aponeurosis) and method of stiffness calculation (determined between 50-100% maximal force) as Kubo et al. (2001; 2002). Contraction durations of five seconds were also employed by Kongsgaard et al. (2011) and Houghton et al. (2013). Also in line with Kubo et al. (2001; 2002), Houghton et al. (2013) calculated stiffness between 50-90% of maximal force and participants were tested in the prone position.

However, there are some differences between investigations. Participants in the Mahieu et al. (2004) and Kongsgaard et al. (2011) investigations performed MVCs seated and not prone as in Kubo et al. (2001; 2002), although the ankle joint angle was consistent between studies (0° dorsiflexion) and the hip joint angle is argued not to impact on properties of the Achilles tendon (Joseph et al., 2012). The probe location differed in the set-up of Houghton et al. (2013) and Kongsgaard et al. (2011), these investigations report placing the probe over the distal myotendinous

junction of the gastrocnemius and soleus respectively. Also, Kongsgaard et al. (2011) calculated stiffness between 80-100% of maximal force and Mahieu et al. (2004) prescibed recovery of 30 seconds between MVC as opposed to > 3 minutes in all other studies; it is established that both the rate of strain and any pre-conditioning of the tendon are likely to impact on tendon properties (Theis et al., 2012). These small differences in the methodologies between these investigations make it difficult to accurately assess the reliability of Achilles tendon stiffness measures. It is important for investigators to assess the reliability of the specific methodology which will be employed.

Given the high degree of variability and methodological inconstancies reported in previous investigations, the purpose of the pilot study was to assess the inter-session reliability of Achilles tendon stiffness obtained through MVC dynamometry and ultrasonography. Were the reliability of this method found to be acceptable during single-joint quasi-isometric activity, this would allow exploration of the reliability of these techniques during multi-joint tri-phasic movements such as jumps and changes of direction. However, it was hypothesised that the CV for Achilles tendon stiffness would be in excess of 15%.

3.2.2 Method

3.2.2.1 Experimental overview

The pilot study was a within-participant repeated measures investigation designed to assess the inter-session reliability of Achilles tendon stiffness. On four separate occasions (T_1, T_2, T_3, and T_4), participants performed plantar flexor MVCs against an immovable footplate during which data was acquired to determine the mechanical properties of the medial gastrocnemius muscle-tendon unit using ultrasonography.

3.2.2.2 Participants

Six active ($\geq$ 2.5 hours of physical activity per week) males (age: 23 $\pm$ 2 years; height: 1.74 $\pm$ 0.04 m; body mass: 75.2 $\pm$ 6.9 kg) recruited from a university campus provided informed consent (Appendix A1) to participate in the study. Full ethical approval was granted by the review board of the Institute for Physical Activity Research, University of Bedfordshire (Appendix A1) and all procedures were conducted in accordance with the Declaration of Helsinki. All trials were conducted at the same time of day (between 10:00 and 13:00) to alleviate the effects of circadian rhythms and between seven to fourteen days apart to minimise the risk of the previous testing session carrying any residual effects on tendon stiffness (McLachlan et al., 2006). Participants were instructed to refrain from all forms of training involving the lower limbs during the 24 hour period preceding each testing session.

3.2.2.3 Experimental set-up

Participants were seated on an adjustable chair with hips flexed to 90° (hip flexion: 88.8 $\pm$ 1.4°) and knee fully extended (knee extension: 176.1 $\pm$ 1.2°) (Muramatsu et

al., 2001; Mahieu et al., 2004; Arampatzis et al., 2010; Kongsgaard et al., 2011)
(Figure 3.1).
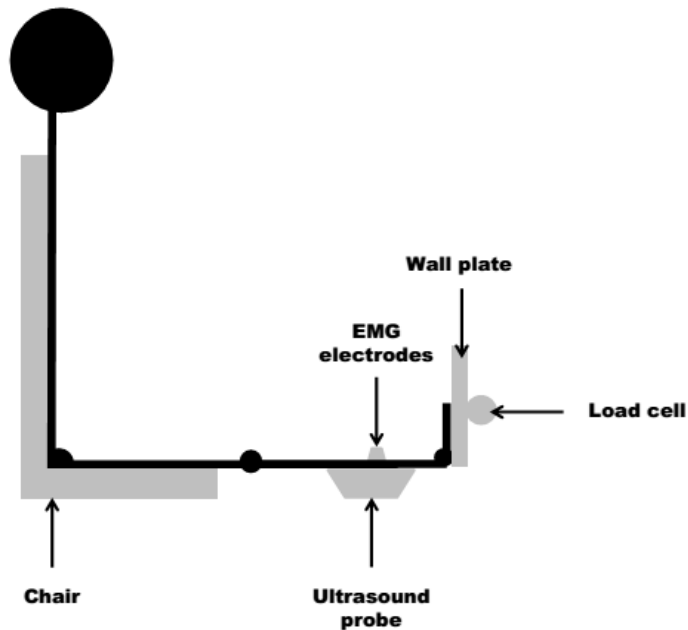
Figure 3.1 - The experimental set-up for the measurement of medial
gastrocnemius aponeurosis displacement during an isometric plantar flexion
performed against an immovable wall plate.

The chair was positioned as close as possible to the wall plate in order to minimise

potential changes in joint angles during the MVCs (Magnusson et al., 2001). The

ankle was placed in an anatomically neutral position, the sole of the foot at 90° to

the tibia (ankle dorsiflexion: $0.9 \pm 0.2°$) (Muramatsu et al., 2001; Arampatzis et al.,

2010; Kongsgaard et al., 2011). Joint angles were measured using a 6" universal

goniometer (Physio Supplies, Spalding, United Kingdom).

3.2.2.4 Measurement of plantar flexion torque

Force output of participants' dominant ankle joint during each of the MVCs was

measured through a load cell (Kistler 9333A; Kistler Instruments, Winterthur,

Switzerland) securely attached to a bolt in the wall and connected to a Powerlab

isolated amplifier (Powerlab AD Instruments 4/25T, AD Instruments, Australia). Limb dominance was self-reported by the participant prior to T_1 and remained consistent for the remaining trials. A 0.3 x 0.6 m hinged wall plate (18 mm medium-density fibreboard) was positioned in front of the dynamometer for participants to press against. Participants performed MVCs unshod and with the sole of the foot resting flat against the wall plate. In an effort to ensure that the sole of the foot remained flat against the wall plate throughout the MVC, participants were instructed to "*keep your heel against the wall plate*".

Participants were instructed to then "*push your toes through the wall plate*" in order to perform an attempted plantar flexion contraction and to exert a maximal force against the wall plate (Magnusson et al., 2001; Burgess et al., 2009; Arampatzis et al., 2010). Participants were instructed to gradually increase force up to a MVC over a period of five seconds (ramping period), hold the MVC for a period of two seconds (MVC period), and then to gradually decrease force back to resting over a period of five seconds (unloading period) (Kubo et al., 2001; Kubo et al., 2002; Maganaris & Paul, 2002; Burgess et al., 2009; Arampatzis et al., 2010). Participants were instructed to monitor real-time on-screen feedback from the dynamometer software (Lab Chart 7, AD Instruments, Australia) which enabled them to see a graph to monitor their force output as well as a timer display to determine the duration of the ramping, MVC and unloading periods (Maganaris & Paul, 2002). Participants were verbally prompted at the beginning of the ramping period to "*start building up force*", at the beginning of the MVC period to "*push as hard as you can - hold for two seconds*", and at the beginning of the unloading period to "*slowly bring it back down*". Participants performed three MVCs prior to sampling (Muramatsu et al., 2001; Burgess et al., 2009; Arampatzis et al., 2010). Two further MVCs were sampled for data collection. A period of 180 seconds of

recovery was prescribed in-between each of these MVCs (Burgess et al., 2009); during this period, participants remained seated in the experimental position with their foot resting against the wall plate.

3.2.2.5 Determination of Achilles tendon force

Achilles tendon force was calculated using Equation 3.1 as outlined by Burgess et al. (2009).

Equation 3.1: $Ftend = \dfrac{P + Pantag}{Tarm}$ (Burgess et al., 2009)

Where F_{tend} = Achilles tendon force, P = observed torque output, P_{antag} = estimated antagonist co-contraction torque, and T_{arm} = tendon moment arm.

Achilles tendon moment arm was defined as the perpendicular distance from the inferior tip of the malleolus (taken to be the centre of rotation of the ankle joint) to the tendon line of action. The length of the moment arm was estimated using the method outlined by Zhao et al. (2009) shown in Equation 3.2.

Equation 3.2: $Tarm = mg - mt$ (Zhao et al., 2009)

Where $Tarm$ = Achilles tendon moment arm, mg = the perpendicular distance between the surface of the skin and the inferior tip of the malleolus and mt = the surface of the skin and the Achilles tendon line of action.

A representation of how the Achilles tendon moment arm was calculated is shown in Figure 3.2. The distance between the surface of the skin and inferior tip of the malleolus (*Mg*) was measured on the skin. The distance between the surface of the skin and the mid-point of the Achilles tendon line of action (*Mt*) was measured on an ultrasound image of the resting Achilles tendon (approximately 0° of dorsiflexion) taken along the longitudinal axis.
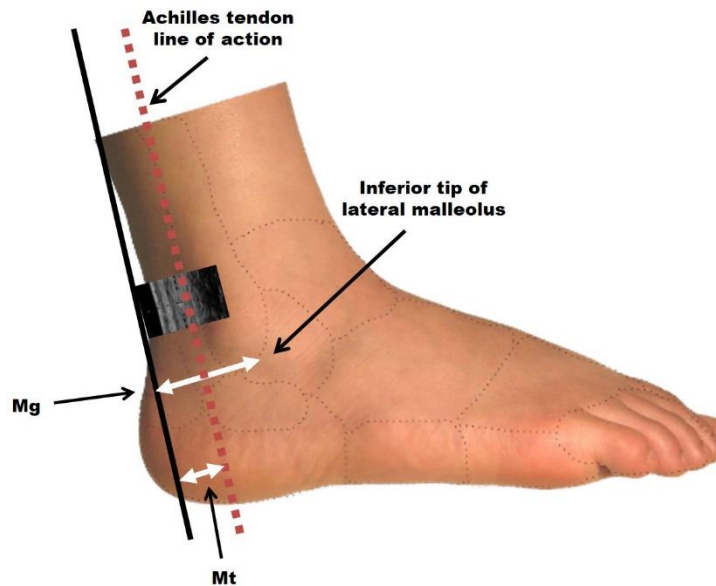
Figure 3.2 - A representation of how the Achilles moment arm was calculated.

Key: Mg = the perpendicular distance between the surface of the skin and inferior tip of the malleolus. Mt = the distance between the surface of the skin and mid-point of Achilles tendon line of action.

3.2.2.6 Measurement of co-contraction torque

To ascertain the level of antagonistic muscle co-contraction torque during plantar flexion MVC, electromyographic (EMG) activity of the tibialis anterior, deemed to be representative of the ankle dorsiflexors, was recorded during each of the MVCs. In accordance with SENIAM guidelines for sensor location (Freriks et al., 1999), 40mm silver/silver chloride EMG electrodes (Cardiocare Limited, Romford, UK) were placed on shaved, cleaned and abraded skin. Electrodes were position 1/3 of the distance between the head of the fibula and the tip of the medial malleolus with an inter electrode distance of 0.02 m and aligned parallel to the direction of the underlying fibres (Clarys & Cabri, 1993). The position of the electrodes for each participant was standardised by measuring the distance from the head of the fibula and the tip of the medial malleolus. This position was also marked on the skin using a non-permanent marker; participants were asked not to wash this off between trials.

EMG activity was recorded at a sampling frequency of 2000 Hz; the high pass filter was set at 20 Hz and the low pass filter 500 Hz, with a mains notch filter (50 Hz) also used. The EMG was recorded using a Powerlab isolated amplifier (Powerlab AD Instruments 4/25T, AD Instruments, Australia). This data was analysed using a computer program (Lab Chart 7, AD instruments, Australia). EMG values were smoothed using the root mean square over 50 ms.

Following the plantar flexion trials, the hinged wall plate was removed from the experimental setup and a foot strap was attached to the load cell. The foot strap was subsequently looped over the participants' dominant foot. Remaining in the same experimental position (hips flexed, knee extended and ankle neutral) subjects then performed four maximal dorsiflexion MVCs by attempting to pull the foot strap away from the dynamometer. The procedure for the dorsiflexion MVC was the same as for the plantar flexion MVC (5 second ramp, 2 second hold, 5 second relaxation). A recovery period of 180 seconds was prescribed between each MVC. Data was captured using the Lab Chart software (Lab Chart 7, AD instruments, Australia) with dynamometer forces inverted to account for the inverse pulling action associated with the dorsiflexion MVC.

To calculate the antagonist co-contraction torque value required for the Achilles tendon force equation, the EMG-torque relationship of the dorsiflexors acting as an agonist was reconstructed using subjects' greatest MVC of the four performed. This was achieved by calculating dorsiflexors torque at the time points where 25, 50, 75 and 100% of MVC were achieved and sampling the EMG values over the 0.1 seconds immediately before and after this time point. These values were fitted with a 2nd order polynomial equation forced through 0.

3.2.2.7 Determination of tendon displacement

The medial gastrocnemius - Achilles tendon complex was imaged during the MVCs using real-time B-mode ultrasonography (Vivid 7, GE Healthcare, Horton, Norway) with a 40 mm linear probe sampling at a rate of 16.8 Hz. The probe was placed over the myotendinous junction of the medial head of the gastrocnemius muscle in the sagittal plane (as shown in Figure 3.3) and sampled at a depth of 35 mm.
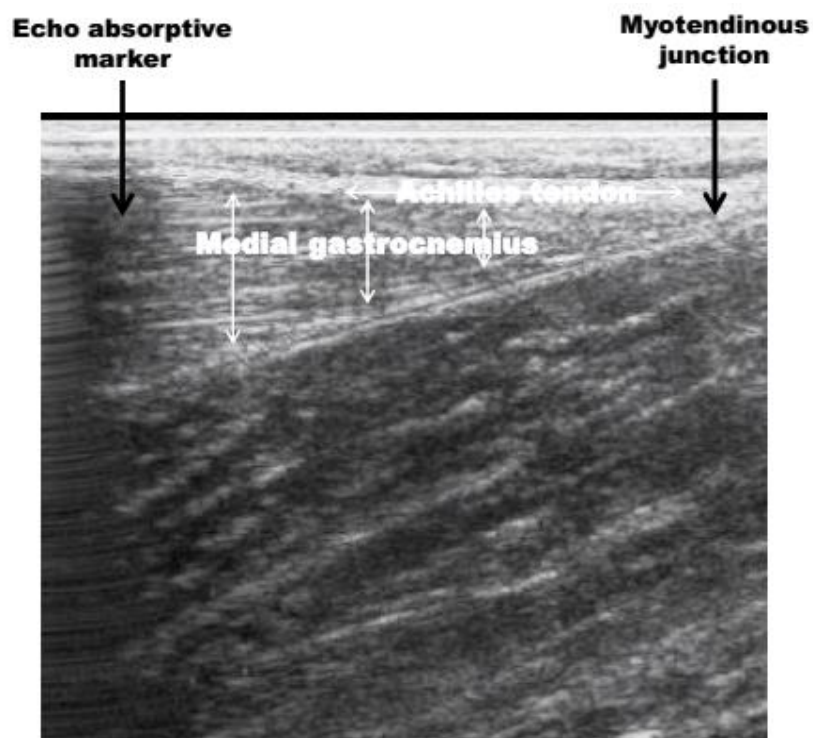
Figure 3.3 - An example ultrasound scan of the myotendinous junction of the medial gastrocnemius and Achilles tendon.

A 5 mm piece of stainless steel wire was used as an echo absorptive marker and served as a fixed reference from which measures of elongation could be made. The wire was placed on the skin in such a manner so that it could be clearly identified on the ultrasound image and secured to the skin with a covering of 10 mm insulating tape to ensure that it remained in the same position during the MVCs.

Achilles tendon elongation during the MVC was calculated as the displacement of the distal myotendinous junction of the medial gastrocnemius relative to the absorptive marker (Maganaris & Paul, 2002; Burgess et al., 2009; Arampatzis et al., 2010). Tendon elongation was measured manually from still images acquired at 10% intervals of MVC force using ImageJ software (1.47t, National Institute of Health, Bethesda, USA) (Burgess et al., 2009). Force output, EMG and ultrasonography outputs were synchronised using a custom made trigger connected between the echocardiogram input of the ultrasound scanner and the PowerLab amplifier. The trigger would begin the sampling of force and EMG in the Lab Chart software and simultaneously place a spike on the ultrasound recording (Figure 3.4) to allow temporal alignment.
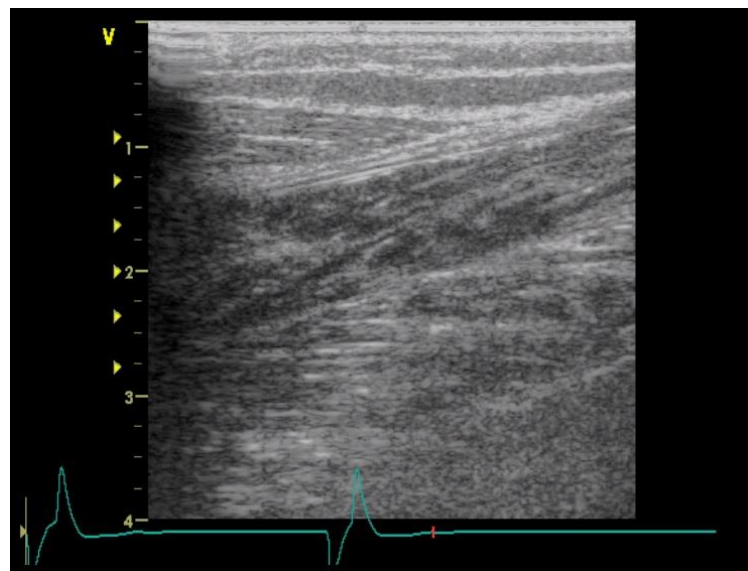
Figure 3.4 - An example of the trigger-induced spike placed onto the ultrasound recording.

3.2.2.8 Determination of tendon stiffness

Achilles tendon stiffness was calculated as the slope of Achilles tendon force versus Achilles tendon elongation between 50% and 90% of the maximum force by means of linear regression (Arampatzis et al., 2010; Houghton et al., 2013). The

current study used 50-90% intervals as opposed to 50-100% intervals as pilot testing indicated that time to 90% force demonstrated less within-participant variance than time to 100% force and to reproduce the protocol employed by Houghton et al. (2013) the only investigators to have reported reliability figures for the force-time variable.

3.2.2.9 Statistical analysis

Shapiro-Wilks were performed to assess for normality; all variables were considered to be normally distributed given an alpha level of $P > 0.05$. A repeated-measures analysis of variance (ANOVA) was used to test for possible systematic bias between trials. A 1 x 4 ANOVA with Sidak post-hoc pair-wise comparisons used to highlight significant pair-wise differences. Pair-wise effect sizes (d) (Cohen, 1998) were calculated and interpreted using the thresholds defined by Hopkins (2003) where: <0.20 = trivial, 0.20-0.59 = small, 0.60-1.19 = moderate, 1.20-1.99 = large, and ≥2 = very large.

Reliability was assessed through the determination of the single (between individual sessions) and average (across all sessions) ICC and by the standard error of measurement (SEM) (Weir, 2005); these figures were calculated with 90% confidence intervals (90% CIs). SEMs were reported as CVs to best allow comparison with the current literature. Descriptive statistics, SEMs, CVs and 90%CIs were computed using a pre-formatted spreadsheet in Microsoft Excel 2007 (Hopkins, 2011). All repeated-measures ANOVAs and ICCs were conducted using the Statistical Package for the Social Sciences (SPSS) for Windows (v21.0; SPSS Inc., Chicago, USA) with $P ≤ 0.05$ considered statistically significant.
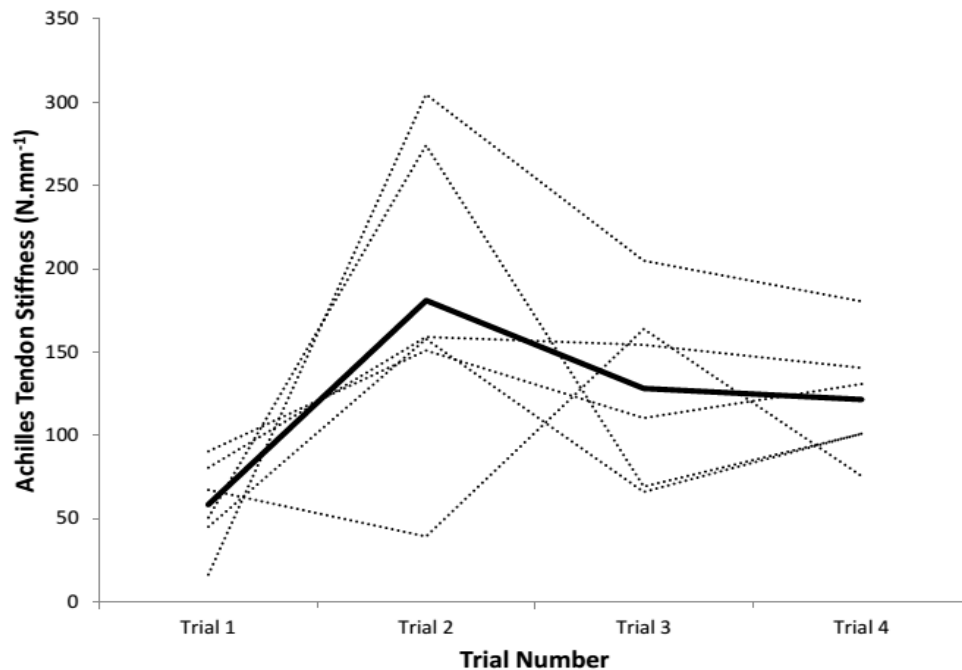
Figure 3.5 - Values for Achilles tendon stiffness calculated across four experimental trials. The solid black line represents average stiffness values, dotted lines represent the individual participants (n = 6).

Peak values for Achilles tendon stiffness were observed in T_2 (Figure 3.5) and coincided with the highest values for Achilles force and with the joint-lowest values for elongation (Table 3.2).

Table 3.2 - Descriptive statistics (mean ± standard deviation) for Achilles tendon stiffness and associated variables across four experimental trials (T_1 - T_4).

Variable	T_1	T_2	T_3	T_4
AT force (N)	187 ± 38	280 ± 86	235 ± 43	228 ± 31
AT elongation (mm)	3.1 ± 0.9	2.2 ± 1.1	2.7 ± 1.1	2.2 ± 0.3
50-90% force (secs)	0.8 ± 0.3	1.4 ± 0.8	2.3 ± 1.1	2.0 ± 0.8
K_{AT} (N.mm^{-1})	58 ± 24	181 ± 88	128 ± 51	122 ± 34
Key: T = trial, AT = Achilles tendon, K_{AT} = Achilles tendon stiffness.				

The average CV for Achilles tendon stiffness across the four trials (T_1-T_4) was 55%, whilst the lowest between-session CV reported was 27%, observed between T_3 and T_4 (Table 3.3).

Table 3.3 - Reliability of Achilles tendon force, medial gastrocnemius aponeurosis elongation, time between 50-90% of maximal force output and Achilles tendon stiffness.

	Mean (T_1-T_4)	T_1-T_2	T_2-T_3	T_3-T_4
Achilles tendon force (N)				
SEM (90%CI)	53.0 (40.9 - 84.8)	74.9 (50.3 - 156.4)	51.8 (34.8 - 108.1)	12.4 (8.3 - 25.9)
CV (%)	23%	32%	22%	5%
ICC (90%CI)	0.25 (-0.11 - 0.73)	-0.08 (-0.71 - 0.62)	0.64 (-0.05 - 0.92)	0.96 (0.82 - 0.99)
Achilles tendon elongation (mm)				
SEM (90%CI)	1.24 (0.96 - 1.98)	1.38 (0.93 - 2.88)	1.48 (0.99 - 3.09)	0.73 (0.49 - 1.53)
CV (%)	49%	54%	58%	29%
ICC (90%CI)	-0.64 (-0.49 - -2.56)	-0.70 (-0.54 - 0.46)	-0.54 (-0.89 - -0.30)	0.46 (-0.30 - 0.86)
Time between 50-90% max force (secs)				
SEM (90%CI)	0.47 (0.36 - 0.75)	0.55 (0.37 - 1.15)	0.42 (0.29 - 0.89)	0.42 (0.28 - 0.88)
CV (%)	29%	33%	26%	26%
ICC (90%CI)	0.84 (0.58 - 0.96)	0.36 (-0.41 - 0.83)	0.92 (0.65 - 0.98)	0.93 (0.68 - 0.99)
Tendon stiffness (N.mm^{-1})				
SEM (90%CI)	67.8 (52.3 - 108.5)	81.4 (54.7 - 170.0)	78.0 (52.4 - 170.0)	33.1 (22.3 - 69.2)
CV (%)	55%	67%	64%	27%
ICC (90%CI)	-0.36 (-0.41 - -0.17)	-0.43 (-0.85 - 0.33)	0.01 (-0.66 - 0.68)	0.64 (-0.06 - 0.92)
Key: T = trial, SEM = standard error of measurement, 90%CI = 90% confidence intervals, ICC = intra-class correlation coefficient.				

Significant differences in Achilles tendon force ($F_{(3,15)} = 3.33$; $P = 0.048$; $\eta^2 = 0.40$), time between 50-90% maximal force ($F_{(3,15)} = 10.04$; $P \le 0.001$; $\eta^2 = 0.67$) and Achilles tendon stiffness ($F_{(3,15)} = 4.45$; $P = 0.020$; $\eta^2 = 0.47$) were observed over the four testing sessions. No significant differences in Achilles tendon elongation ($F_{(3,15)} = 1.09$; $P = 0.38$; $\eta^2 = 0.17$) were reported.

Table 3.4 - Pair-wise comparisons (presented as mean difference ± standard deviation) of Achilles tendon stiffness and associated variables across four experimental trials (T_1 - T_4).

Variable	T_1-T_2	T_1-T_3	T_1-T_4	T_2-T_3	T_2-T_4	T_3-T_4
AT force (N)	-92 ± 106	-47 ± 63	-40 ± 61	45 ± 73	52 ± 79	7 ± 18
AT elongation (mm)	0.9 ± 1.9	0.4 ± 1.1	0.9 ± 0.9*	-0.5 ± 2.1	0.03 ± 1.5	0.5 ± 1.0
50-90% force (secs)	-0.6 ± 0.8	-1.5 ± 1.0*	-1.2 ± 0.7*	-0.9 ± 0.6*	-0.6 ± 0.6	0.3 ± 0.6
K_{AT} (N.mm^{-1})	-123 ± 115*	-70 ± 67	-63 ± 53*	52 ± 110	59 ± 77	7 ± 47

* indicates significant pair-wise difference ($P < 0.05$).

Key: AT = Achilles tendon, K_{AT} = Achilles tendon stiffness.

Significant pair-wise differences for Achilles tendon stiffness were observed between two trials (Table 3.4). Achilles tendon stiffness was lower in T_1 versus T_2 ($P = 0.048$; $d = 2.04$) and T_4 ($P = 0.033$; $d = 1.16$). Achilles tendon elongation was greater in T_1 versus T_4 ($P = 0.044$; $d = -0.94$). Time between 50-90% of maximal force was shorter in T_1 versus both T_3 ($P = 0.014$; $d = 1.69$) and T_4 ($P = 0.008$; $d = 1.34$), and shorter in T_2 versus T_4 ($P = 0.014$; $d = 1.01$).

3.2.4 Discussion

The aim of the pilot study was to assess the inter-session reliability of Achilles tendon stiffness obtained through MVC dynamometry and ultrasonography. Were the reliability of this method found to be acceptable during single-joint, quasi-isometric activity it would allow exploration of the reliability of these techniques during more complex and dynamic movements. In spite of using an experimental protocol based upon previous investigations that have reported low CVs (< 6% (Kubo et al. 2001; 2002)), it was found that Achilles tendon stiffness demonstrates poor reliability over four testing sessions in participants previously unfamiliar with the MVC testing protocol given the CV > 10%, ICC < 0.80 classification proposed by Joseph et al. (2013). The lowest inter-session CV, of 27%, was found between T_3 and T_4. The hypothesis that the CV for tendon stiffness would be > 15% is therefore accepted.

The lowest CV for Achilles tendon stiffness reported in the current study (27%) was higher than has been reported in previous investigations by Kubo et al. (2001; 2002) using a similar experimental protocol. Inter-session CVs as low as 5% have been reported by Kubo et al. (2001) and as high as 15.8% by Mahieu et al. (2004), although CVs toward the upper end of this range appear to be more common (Kongsgaard et al., 2011; Houghton et al., 2013). In addition, significant pair-wise differences and large effect sizes were observed between a number of testing sessions, further questioning the repeatability of inter-session Achilles tendon stiffness measurements.

Achilles tendon stiffness is a direct function of the force and elongation of the tendon (Magnusson et al., 2001). The current study demonstrated Achilles tendon force to be a repeatable measurement following familiarisation; a CV of 5% was

reported between T_3 and T_4. This figure is similar to those reported by Houghton et al. (2013), Kongsgaard et al. (2011) and Mahieu et al. (2004) who have also utilised a ramped, five second contraction, as have Kubo et al. (2001; 2002). Whilst AT force is a strong and repeatable measure, Achilles tendon elongation is highly variable. The variability observed in Achilles tendon stiffness in the current study is therefore a likely consequence of high variability in elongation

Magnusson et al. (2001), Mahieu et al. (2004) and Kongsgaard et al. (2011) have all reported the inter-session CV of Achilles tendon elongation to be > 10%, although the 29% CV reported between T_3 and T_4 is higher than has been previously reported in the literature despite using a similar methodology. A potential explanation for the poor reliability of AT elongation measures could be due to the sampling rate of the ultrasonography. Magnusson et al. (2001) and Kongsgaard et al. (2011) reported sampling at rates of 50 Hz and 25 Hz, respectively. Burgess et al. (2009) also sampled at 25 Hz. The investigations conducted by Kubo et al. (2001; 2002) sampled at 30 Hz. Sampling with a lower frame rate (16.8 Hz in the current study) will have reduced the accuracy of elongation measures as measurements are unlikely to have been taken at the precise time-points that were identified in the higher sampling (1000 Hz) force trace. Moreover, the gap between frames when sampling at these frequencies is relatively large considering the short duration of the contraction and, in particular, the time intervals between 10% force increments. It is perhaps reasonable to suggest that the reliability of Achilles tendon elongation measures is unlikely to achieve comparable reliability to force measurements until higher sampling rates can be utilised. Conversely, the high sampling rate (2000 Hz) and low-pass filter (500 Hz) may also have acted to confound reliability issues. Whilst the contribution of co-contraction torque may be minimal, these frequencies exceed the likely firing

rate of muscle (Gandevia, 2001). This would have created additional noise within the sample and may have contributed to errors in interpreting muscle firing patterns.

Another potential explanation for the poor reliability of Achilles tendon elongation could be the concomitant reliability of time between 50-90% maximal force as stiffness was calculated across this range. This procedure replicates the method of Houghton et al. (2013) whilst Kubo et al. (2001; 2002) plotted a similar slope from 50-100%. Data from the current study (Table 3.3) indicates that participants were not able to perform the contraction in a reproducible manner, a potential consequence of a low skill level and unfamiliarity within the isometric plantar flexion protocol, even after three previous sessions. Participants were instructed to gradually ramp to a maximal contraction over a period of 5 seconds, however, the mean time between 50-90% maximal force was 0.42 seconds (90%CI: 0.28 - 0.88). Only Houghton et al. (2013) have previously reported reliability values for this variable, the investigators observed a CV of 6.7% and ICC of 0.78. Whilst the ICC of 0.93 between T_3 and T_4 may appear relatively strong, this was reported with 90%CI's of 0.68 - 0.99 and a CV of 26%, the latter comparable to the CVs of 27% and 29% reported for Achilles tendon stiffness and elongation respectively. Theis et al. (2012) have demonstrated that tendon stiffness increases linearly with the rate of strain, emphasising the importance of the time component if seeking to measure stiffness. It is possible that better instruction and coaching of the participants during the contraction would enable them to lengthen the relative time between 50-90% maximal force, potentially offsetting some of the aforementioned problems inherent with low sampling rates, and also help them to perform the MVC with greater reproducibility.

The figures reported in the current study for Achilles tendon stiffness (mean: 122 $N.mm^{-1}$) are comparable to those of Kubo et al. (1999; 2007) and Maganaris and Paul (2002). These values are greater than have been reported in some investigations (< 65 $N.mm^{-1}$) (Kubo et al., 2001; Mahieu et al., 2004; Burgess et al., 2009) but substantially lower than a number of other investigations (> 300 $N.mm^{-1}$) (Magnusson et al., 2001; Rosager et al., 2002; Kongsgaard et al., 2011; Houghton et al., 2013). The wide discrepancy in stiffness values (i.e. beyond expected inter-individual differences) highlight the variability in methodologies and the necessity for investigators to determine the reliability of their own specific method.

The Achilles tendon elongation reported in this pilot study (mean: 2.6 mm), although comparable to the figures reported by Kongsgaard et al. (2011), is far lower than has been reported in the majority of investigations (5 - 18 mm) (Maganaris & Paul, 2002; Muramatsu et al., 2002; Rosager et al., 2002; Mahieu et al., 2004; Arampatzis et al., 2005b). Joseph et al. (2012) reported a strong ICC value for the inter-session reliability of Achilles tendon elongation measures (0.93), this is noted alongside a SEM of 1.59 mm. Whilst the current study reports a far weaker ICC (0.46; 90%CI: -0.30 - 0.86) between T_3 and T_4, the SEM observed was actually lower (0.73; 90%CI: 0.49 - 1.53). Were elongation measures in this pilot study to be more in-line with the values reported in the majority of the literature and a similar SEM observed, the CV would be markedly lower. Joseph et al. (2012) did not report any descriptive statistics to allow for calculation of their SEM as a CV, it is recommended that future investigations report such data to allow the reader to contextualise this information and make a more informed judgement as to the reliability of this method.

The reliability of all measures improved in a curvilinear fashion as the number of testing sessions increased; a factor highlighted not only in the reduction of the CVs between later trials, but also in the reduction of the mean differences and the associated effect sizes. For that reason, it is clear that participants unfamiliar with isometric plantar flexion testing require a number of familiarisation sessions to be performed. Whether the reliability of the isometric method can be further improved with additional sessions is a question which subsequent research may wish to explore, however, the clear necessity for multiple familiarisation sessions (no less than four sessions) may discourage researchers and practitioners from using this technique.

If seeking to detect changes in Achilles tendon stiffness, for example in response to an acute or chronic exercise intervention, it is essential that investigators understand the magnitude of change that will be required to detect a statistically meaningful effect. If the current study is indicative of the general reliability of the integration of dynamometry and ultrasonography to approximate tendon stiffness within this participant group, any intervention would therefore need to induce a change in excess of 27%. A change of this magnitude would seem unlikely in a trained population. For example, Houghton et al. (2013) observed non-significant changes in Achilles tendon stiffness of -7.2% and 4.2% following two acute exercise interventions, these figures eclipsed by a CV of 15.6%. Kubo et al. (2001) observed a 10% reduction following a stretching stimulus, greater than their reported CV of 5%, whilst Arampatzis et al. (2010) observed changes of -5% and 17% following two preconditioning interventions without reporting reliability values to contextualise these. If true changes in Achilles tendon stiffness following acute interventions do fall within a ± 10 - 15% range, the reliability values reported by the current study and a number of other investigations (Mahieu et al., 2004;

Kongsgaard et al., 2011; Houghton et al., 2013) suggest that the widely used MVC method may not be a suitable test for evaluating such changes.

Changes in Achilles tendon stiffness in response to chronic interventions appear to be larger than in acute interventions. For instance, Kubo et al. (2002) reported increases of 15 - 19% following a three-week resistance training or stretching intervention and Mahieu et al. (2007) reported a 28% decrease following six weeks of ballistic stretching. The use of dynamometry and ultrasonography to assess changes in tendon stiffness may therefore be more suitable for evaluating the effect of chronic interventions. However, the CV of 27% reported in the current study would still suggest that the test may not be suitable for detecting a meaningful change. Regardless of the intended application, where investigators do choose to employ the isometric plantar flexion method to quantify Achilles tendon stiffness, it is strongly recommended that statistics for each of the reliability measures are calculated for the specific methodology, equipment and participant group to be utilised in the investigation. These figures should be clearly reported in the manuscript and included alongside descriptive statistics for each of the sampled parameters.

3.2.5 Conclusion

This pilot study reports that the widely used measurement method of Achilles tendon stiffness using dynamometry and ultrasonography during a plantar flexion MVC demonstrates a high degree of inter-session variance (> 25%) after multiple familiarisation sessions in healthy male participants. This was larger than has been previously reported in the literature (Kubo et al., 2001; Kubo et al., 2002; Mahieu et al., 2004; Kongsgaard et al., 2011; Houghton et al., 2013) and questions the appropriateness of ultrasonography for detecting changes in Achilles tendon stiffness induced by acute or chronic exercise interventions.

3.2.6 Implications for the thesis

The potential use of ultrasonography to examine direct changes in Achilles tendon stiffness during hopping, drop jumping and changes of direction was not considered in subsequent investigations due to the high variability (CV > 25%) observed in this pilot study.

3.3 Study 1 - Reliability of vertical stiffness

3.3.1 Introduction

Vertical stiffness describes how the body's centre of mass (COM) deforms in response to force during a linear, vertical movement task, such as a vertical hop or jump, and aims to provide a representative measure of musculoskeletal stiffness (Butler et al., 2003). Although the role of vertical stiffness in modulating injury risk and athletic performance may be well established (Butler et al., 2003; Pearson & McMahon, 2012), literature investigating bilateral asymmetry in vertical stiffness is limited. A strong relationship between vertical stiffness asymmetry and soft-tissue injury has been reported by Pruyn et al. (2012); elite Australian Rules Football players who experienced soft-tissue injuries had a greater bilateral difference in vertical stiffness than their non-injured counterparts. Such asymmetry may also be expected to impair athletic performance given the potential for a resultant imbalance in the application of force (Wilson et al., 1994), however, the latter hypothesis has not been systematically explored. The measurement and quantification of vertical stiffness is therefore of important practical relevance to athletes and coaches.

Vertical stiffness is most commonly assessed during the performance of a bilateral 'hopping' task (Joseph et al., 2013; Hobara et al., 2014). As well as offering the simplest spring-mass model with which to assess vertical stiffness (Farley et al., 1991), bilateral hopping has been established to be more efficient in energetic consumption compared to other types of gait (Cavagna et al., 1964) and should therefore provide a strong representation of musculoskeletal stiffness (Farley et al., 1991). Vertical stiffness derived from bilateral hopping has been shown to differentiate between sprint and endurance athletes (Hobara et al., 2008), and

between endurance athletes and untrained controls (Hobara et al., 2010). As such, bilateral hopping would appear to be a valid task by which to assess a determinant of athletic performance (vertical stiffness). During hopping tasks, individuals are required to perform a number of repeated bilateral jumps on a force plate whilst measurements of vertical ground reaction force (vGRF) and negative displacement of the COM are recorded. COM displacement is deemed representative of how much the leg spring deforms, assuming that both limbs function synchronistically, in response to the ground reaction force (Butler et al., 2003). Vertical stiffness is subsequently calculated as the ratio of peak vGRF to the negative COM displacement (Joseph et al., 2013; Hobara et al., 2014).

Whilst bilateral hopping is established to provide a strong representation of musculoskeletal stiffness (Farley et al., 1991), it is important to note that these tasks are typically performed at set hopping frequencies and are submaximal in nature (Joseph et al., 2013; Hobara et al., 2014). The characteristics of bilateral hopping may therefore demonstrate a high degree of correspondence to sub-maximal cyclic performances, such as endurance running (Kunimasa et al., 2014), but not to maximal acyclic performances, such as jumping (Bobbert & Casius, 2005) and changes of direction (Young & Farrow, 2006). For this reason, the utilisation of different movement tasks should be considered if seeking to assess vertical stiffness in athletes required to perform short-duration maximal intensity actions.

The drop jump is an exercise in which an athlete drops from a pre-determined height and attempts to jump immediately on landing (Marshall & Moran, 2013). Given that drop jumping is typically performed in training with a view to inducing chronic enhancements in parameters of neuromuscular force production and lower limb stiffness (Turner & Jeffreys, 2010; Marshall & Moran, 2013), it may therefore

be appropriate to suggest the use of the drop jump as a task by which to assess vertical stiffness. As the drop jump is a maximal, acyclic performance task (Marshall & Moran, 2013), it may be argued to carry greater ecological validity as an assessment tool for power-based athletes when compared to hopping tasks due to it representing a single maximal effort (Flanagan & Harrison, 2007).

Whilst Arampatzis et al. (2001a; 2001b) have modelled vertical stiffness during drop jumping, this task has not been used to examine relationships between vertical stiffness and performance or to examine inter-group differences in vertical stiffness. Moreover, the reliability of drop jump derived stiffness measures has not been evaluated. Were it to be determined that bilateral and unilateral drop jump tasks exhibit comparable reliability to bilateral hopping tasks, drop jumping may provide an alternative assessment task by which to assess vertical stiffness in a manner that could be more representative of maximal intensity athletic performance.

The reliability of vertical stiffness assessment during bilateral hopping tasks has been specifically evaluated in two investigations (McLachlan et al., 2006; Joseph et al., 2013). Study 1 considered the CV as the primary tool to assess reliability as this is a relative measure that allows for a direct comparison between investigations, irrespective of differences in participants' stiffness, and can be easily interpreted by the practitioner (Hopkins, 2000). McLachlan et al. (2006) reported CVs of between 2.7% and 4.9% for vertical stiffness dependant on the frequency and height of hopping; a frequency of 3.2 Hz demonstrated higher reliability than 2.2 Hz and submaximal hopping demonstrated higher reliability than maximal hopping. Joseph et al. (2013) reported a CV of 5.5% for a hopping frequency of 2.2 Hz and 10.2% for a self-selected hopping frequency. Moreover, Joseph et al. (2013) demonstrated that stiff-leg hopping was a more reliable

assessment than bent-leg hopping where the hopping kinematics were self-determined by the individual. For example, a CV of 6.9% was calculated for bent-leg hopping at 2.2 Hz. Bent-leg hopping resulted in greater angular displacement of the knee and ankle, indicating a greater reliance on active force generation during the task. This may explain why the bent-leg technique appears less reliable; the emphasis on maintaining high stiffness in the lower limbs is likely to be reduced if the active component of muscular contraction is greater.

Reliability figures have also been reported in investigations conducted by Moir et al. (2009) and by Brauner et al. (2014). Moir et al. (2009) reported a CV of 14.4% using a 2.0 Hz hopping test with participants asked to hop for maximal height. The CV observed by Moir et al. (2009) appears to be a consequence of variability in COM displacement (CV: 12.4%) and also may be expected given the findings of McLachlan et al. (2006) (i.e. maximal versus submaximal hopping). Brauner et al. (2014) reported a CV of 8.1% using a submaximal 2.2 Hz hopping test although did not provide CVs for COM displacement to allow for comparison.

Moresi et al. (2015) evaluated the impact of data reduction methods (how hops are analysed) on reliability. The investigators' reported CVs ranging from 6.5% to 16.6% depending upon the reduction method used; employing inclusion criteria to sample hops within ± 5% of average contact time appeared to provide the most suitable trade-off between reliability and data exclusion, providing CVs in the region of 9%. Stricter criteria for sampling were set by McLachlan et al. (2006) and Joseph et al. (2013) with hops required to be within ± 2% of the set hopping frequency. Although Moresi et al. (2015) found such criteria to infer a marginal reduction in the CV (< 1%), using this sampling method resulted in the exclusion of a large number of trials and greatly reduced the overall sample size. Whilst the vertical stiffness values reported by Moresi et al. (2015) (between 16-21 kN.m^{-1})

were much lower than those reported by Joseph et al. (2013) (~57 kN.m^{-1}), they were similar to those reported by McLachlan et al. (2006) for hopping at 2.2 Hz (16-20 kN.m^{-1}). This discrepancy is a likely consequent of the participant population sampled; Joseph et al. (2013) tested active males whilst both Moresi et al. (2015) and McLachlan et al. (2006) both sampled females.

Stiffness measures obtained from bilateral versus unilateral hopping tasks have been compared by Brauner et al. (2014). The investigators demonstrated that vertical stiffness values were 24% lower ($P < 0.001$) during unilateral versus bilateral hopping although observed no effect of leg dominance during the unilateral task. Inter-limb differences during bilateral hopping were not assessed by Brauner et al. (2014). Indeed, to this author's knowledge, the potential presence of vertical stiffness asymmetry between the left and right limbs during bilateral hopping has not been investigated by the literature. It is important to understand how the individual limbs function during bilateral performance, where matched stiffness properties would be desired, as this may not be represented by how the individual limb functions in isolation during unilateral hopping. For example, Benjanuvatra et al. (2013) compared impulses generated by the left and right limbs during bilateral and unilateral jumping, observing that the limb producing the largest impulse during the unilateral task did not always produce largest impulse in the bilateral task.

The purpose of Study 1 was to assess the inter-session reliability of left and right limb vertical stiffness during bilateral hopping, bilateral drop jumping and unilateral drop jumping. Were appropriate reliability to be demonstrated for these methods this would justify their potential inclusion in subsequent investigations within this thesis. It was hypothesised that all three performance tasks would demonstrate CVs of < 10%.

3.3.2 Method

3.3.2.1 Experimental overview

Study 1 was a randomised and counterbalanced repeated measures experiment designed to assess the inter-session reliability of independent left and right limb measures of vertical stiffness derived from bilateral hopping, bilateral drop jump and unilateral drop jumping. On four occasions, separated by six to ten days, participants performed two bilateral hopping trials, three bilateral drop jumps and six unilateral drop jumps (three each for the left and right limbs) on a dual force plate system.

3.3.2.2 Participants

Fourteen healthy males (age: 22 ± 2 years; height: 1.77 ± 0.08 m; body mass: 73.5 ± 8.0 kg) volunteered to participate in the study. Participants were recreationally active (≥ 2.5 hours of physical activity per week), reported no previous (within the last 12 months) or present lower limb injury and provided informed consent (Appendix A1) to participate in the study. A minimum sample size of eight participants was determined from an *a priori* power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon the ICC values reported in the literature for vertical stiffness derived from bilateral hopping (0.85) (Joseph et al., 2013) and a power of 0.80. Full ethical approval was granted by the review board of the Institute for Physical Activity Research, University of Bedfordshire (Appendix A1) and all procedures were conducted in accordance with the Declaration of Helsinki.

3.3.2.3 Experimental protocol

All trials were conducted at the same time of day for each participant (09:30 - 11:00), to alleviate the effects of circadian rhythms, and repeated between six to ten days apart to minimise the risk of the previous testing session carrying any residual effects on vertical stiffness. The testing laboratory was controlled at an ambient temperature of 25ºC. Participants were instructed to prepare for testing as they would for training. Participants were asked to refrain from all forms of training for at least 24 hours prior to testing.

Table 3.5 - The experimental warm up protocol completed in each trial.

Warm-up phase	Exercise	Prescription (sets x reps)
Generic movement preparation	Inchworm	1x6
	Quadruped thoracic rotation	1x6 each
	Push up to 'T'	1x6 each
	Supine glute bridge with abduction	1x12
	Mountain climber	1x6each
	Squat thrust to squat	1x6
	Squat to Stand	1x6
	Single leg, stiff-legged deadlift to reverse lunge	1x6 each
Plyometric and stiffness preparation	Lateral step down	1x8 each
	Single leg calf raise	1x8 each
	Alternate leg ankling drill	1x8 each
	Vertical countermovement jump	1x4
Specific movement preparation	Bilateral hopping	1x10
	Bilateral drop jump (from 0.18 m)	1x2
	Unilateral drop jump (from 0.18 m)	1x2 each

Participants completed the same warm-up procedure in each experimental trial (Table 3.5). The warm-up procedure consisted of 15 dynamic exercises progressing from low to high intensities and from generic to specific movement patterns; the warm-up was designed to replicate a typical athletic warm-up that

would be undertaken prior to training or competition (Bishop, 2003). A rest period of 60 seconds was prescribed between each of the exercises from the specific movement preparation phase of the warm-up, all other exercises were not prescribed with rest periods. A rest period of 180 seconds was prescribed between the termination of the warm-up and commencement of the testing protocol.

3.3.2.4 Bilateral hopping protocol

During each session, participants performed 30 unshod bilateral hops on a dual force plate system (Kistler 9281, Kistler Instruments, Winterthur, Switzerland) with data recorded independently for the left and right limbs; 30 hop trials were chosen as this would allow for the greatest number of potential methods of data reduction (Moresi et al., 2015). The plates each measured 0.6 m x 0.4 m, were set flush into the laboratory floor as per manufacturer guidelines and spaced by a distance of 0.05 m. Participants performed two hopping trials (two, 30 hop trials) in each experimental session; these were separated by a recovery period of 180 seconds. The execution of each hopping trial was monitored by a United Kingdom Strength and Conditioning Association and National Strength and Conditioning Association (United States of America) accredited strength and conditioning coach to ensure for consistency of technique. Hops were performed at a self-selected frequency as pilot testing indicated that participants were unable to satisfactorily perform the task at a set hopping frequency of 2.2 Hz. At a frequency of 2.2 Hz, the ground contact time of each hop did not always fall within the ± 5% recommendation outlined below.

Five consecutive hops from 6th to the 10th hop were sampled for data collection (Hobara et al., 2014). For inclusion in the reliability analyses, the ground contact time of each of the 5 hops was required to fall within ± 5% of the average ground

contact time for the 5 hop sample (Moresi et al., 2015); this was assessed during the post-test data analysis and all hopping trials met these criteria.

3.3.2.5 Drop jumping protocol

Participants performed all nine drop jumps in each experimental trial from a drop height of 0.18 m onto a dual force plate system as outlined in Section 3.3.2.4. Bilateral, left leg and right leg drop jumps were performed in a randomised, crossover fashion in an attempt to alleviate any pre-conditioning or fatiguing effect of the previous jump.

For the execution of each drop jump, participants were instructed to step, not jump, off a 0.18 m box. The box height of 0.18 m was chosen as participants were unable to minimise ground contact time effectively at additional height increments (0.30 m and 0.45 m) during pilot testing. For the bilateral drop jump, participants were instructed to step off with either foot and land with one foot on each force plate to allow for data to be recorded for the left and right limbs independently; each participant's leading foot was established in the participants' first trial by noting which foot they stepped off the box with and remained consistent thereafter. For the unilateral drop jump, participants were instructed to step off the box with the designated foot for that particular trial. Each drop jump repetition was separated by 60 seconds to facilitate full recovery between efforts (Read & Cisar, 2001). The execution of each jump was monitored for consistency of technique. Participants were instructed to spend as little time in contact with the floor as possible during each jump and cued to imagine the floor as "hot coals". Trials would have been excluded if participants landed heel first and a distinctive double peak in the vertical force trace was observed. All trials met the required criteria.

3.3.2.6 Data analysis
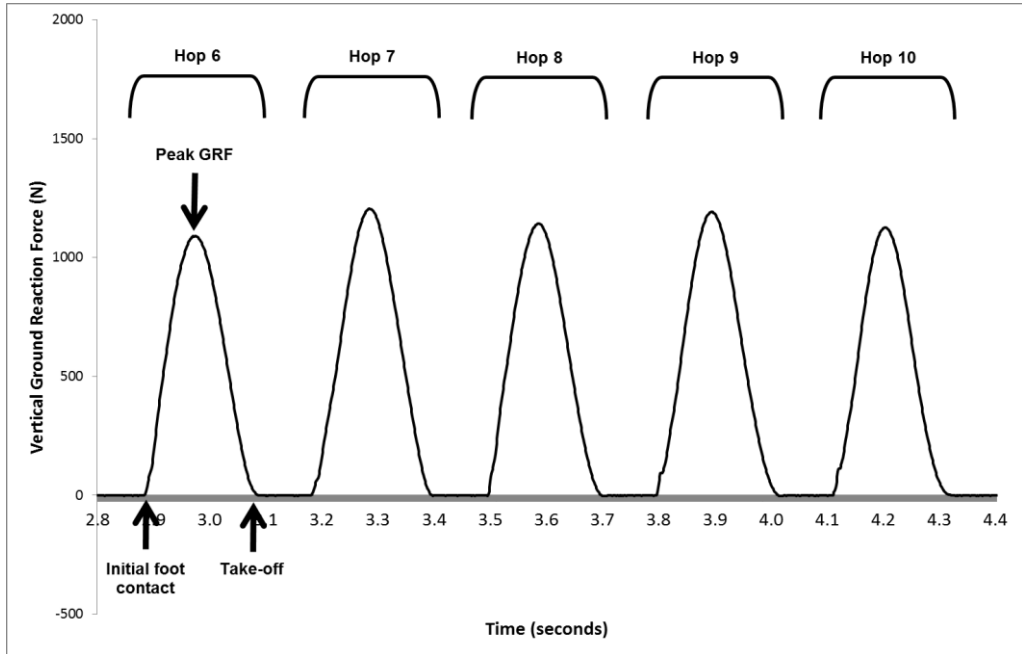
Figure 3.6a - An example of the vertical force trace associated with bilateral hopping and the identification of instants of initial foot contact, take-off and separation of individual hops.
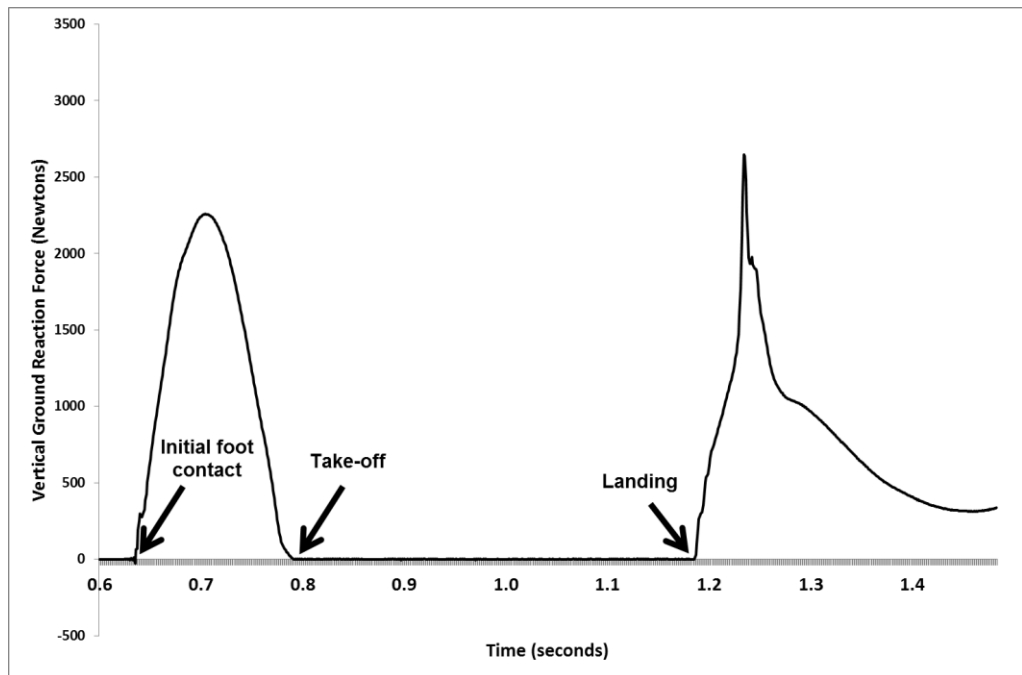
Figure 3.6b - An example of the vertical force trace associated with bilateral and unilateral drop jumping, and the identification of instants of initial foot contact, take-off and landing.

Kinetic data was sampled at 1000 Hz and saved with the use of the manufacturer supplied software (BioWare 3.24, Kistler, Winterthur, Switzerland) for later offline analysis. Instants of initial foot contact, take-off and landing were identified from the vGRF trace (Figures 3.6a and 3.6b); this was determined as the time-point at which a clear change in force (≥ 10 N) was observed (Lloyd et al., 2009). For bilateral hopping and bilateral drop jumps, all values were calculated independently for the left and right limbs, assuming an equal distribution of mass between the left and right limbs. For the unilateral drop jumps it was assumed that the full body mass was supported by the limb.

3.3.2.7 Determination of vertical stiffness

Acceleration, velocity and COM displacement at time intervals of 0.001 sec were determined from the vertical force trace using the biomechanical principles described by Blazevich (2007) and Hall (2012), the inverse dynamics equations used to determine these variables are detailed in Appendix A2. The initial velocity value used for integration in bilateral hopping trials was calculated using the Equation 3.1 as previously described by Hobara et al. (2013). For the bilateral and unilateral drop jump trials an initial velocity of -1.88 m.s^{-1} was utilised. This would be the expected velocity of a mass falling from a height of 0.18 m using Equation 3.1.

Equation 3.1: $V_0 = -0.5 * 9.81 * t_a$ (Hobara et al., 2013)

Where V_0 = initial velocity, t_a = aerial time.

Vertical stiffness was calculated as the ratio of peak vGRF relative to the peak negative displacement of the COM during the initial ground contact phase (Farley & Morgenroth, 1999). In an effort to ensure the efficacy of the spring-mass model

during all tasks, the force-displacement correlation coefficient during the landing phase of each individual hop or drop jump was required to be ≥ 0.8 (Padua et al., 2005); all trials met these criteria. For each bilateral hopping trial, vertical stiffness was averaged over the five sampled hops. As vertical stiffness is affected by body size, stiffness values were reported relative to body mass (Farley et al., 1993).

3.3.2.8 Statistical analysis

For bilateral hopping, inter-session reliability was calculated using each participant's average values across the two hopping trials they performed within each testing session. For bilateral and unilateral drop jumping, the average values recorded across the three jumps performed within each testing session were used. Pilot studies undertaken within the same participant population (n = 8) indicated that inter-session reliability was improved by using average values.

Reliability was assessed through determination of single (pair-wise) and average ICCs as well as the standard error of measurement (Weir, 2005); these figures were calculated with 90% confidence intervals (90% CI). Average values were determined across testing sessions 2-4 as it was deemed a familiarisation session was necessary to accustom participants to the experimental protocol; session 1 was therefore classified as the familiarisation session. The standard error of measurement was reported as a CV to allow comparison with the current literature.

Shapiro-Wilks tests were performed to assess for normality; all variables were considered to be normally distributed given an alpha level of $P > 0.05$. Separate 4 x 2 (testing session x limb) repeated measures analyses of variance (ANOVAs) were performed for bilateral hopping, bilateral drop jumping and unilateral drop jumping. An additional one-way ANOVA was performed to examine differences in the average values for each variable between performance tasks; this used data

from testing sessions 2-4 (three trials) for both limbs (two limbs) and from all participants (a total of 84 data sets). For ANOVA procedures, the effect size was measured using the partial Eta-squared (η^2) and Sidak post-hoc analyses were performed where appropriate

Descriptive statistics, standard errors of measurement, CVs and 90%CIs were computed using a pre-formatted spreadsheet in Microsoft Excel 2007 (Hopkins, 2011); while ICCs and ANOVA procedures were performed using the Statistical Package for the Social Sciences for Windows (v21.0; SPSS Inc., Chicago, USA).

3.3.3 Results

3.3.3.1 Intra-session reliability

For bilateral hopping, intra-session CVs for vertical stiffness were 8.1% (ICC: 0.87) and 7.1% (ICC: 0.91) for the left and right limbs respectively. For bilateral drop jumping, CVs for vertical stiffness were 11.7% (ICC: 0.88) and 13.4% (ICC: 0.85). For unilateral drop jumping, CVs were 7.3% (ICC: 0.95) and 7.5% (ICC: 0.93).

3.3.3.2 Comparison of performance tasks

Table 3.6 - Vertical ground reaction force, negative centre of mass displacement and vertical stiffness for bilateral hopping, bilateral drop jumping and unilateral jumping across testing sessions 2-4. Values are presented as mean ± standard deviation.

Limb	Bilateral hopping	Bilateral drop Jump	Unilateral drop jump
Vertical group reaction force (N)			
Left	1377 ± 213	1671 ± 309 *	2370 ± 387 *†
Right	1413 ± 221	1692 ± 298 *	2330 ± 359 *†
Centre of mass displacement (m)			
Left	0.098 ± 0.031	0.172 ± 0.046 *	0.221 ± 0.055 *†
Right	0.099 ± 0.034	0.160 ± 0.042 *	0.226 ± 0.061 *†
Vertical leg stiffness (N.m^{-1}.kg^{-1})			
Left	210.6 ± 52.2	150.5 ± 58.2 *	159.7 ± 61.6 *
Right	217.5 ± 58.6	160.7 ± 52.0 *	151.1 ± 55.1 *
Reactive strength index (flight time : contact time)			
Left		1.83 ± 0.55	0.89 ± 0.25 †
Right		1.80 ± 0.51	0.91 ± 0.24 †
* indicates significantly different from bilateral hopping ($P < 0.05$) † indicates significantly different from bilateral drop jumping ($P < 0.05$)			

Vertical stiffness was statistically different between performance tasks ($F_{(2,81)} = 8.26$; $P = 0.001$). Vertical stiffness was greater in bilateral hopping than in bilateral drop jumping and unilateral drop jumping (both $P = 0.02$) whilst differences

between bilateral and unilateral drop jumping were not significant ($P = 1.00$) (Table

3.6).

Table 3.7 - Inter-session reliability for vertical ground reaction force, negative centre of mass displacement and vertical stiffness for bilateral hopping, bilateral drop jumping and unilateral jumping across testing sessions 2-4. Values are presented as mean (90% confidence intervals).

Limb	Variable	Bilateral hopping	Bilateral drop Jump	Unilateral drop jump
Vertical group reaction force (N)				
Left	SEM	37.8 (29.8 - 53.2)	92.1 (72.6 - 129.5)	58.4 (46.1 - 82.2)
	ICC	0.98 (0.94 - 0.99)	0.93 (0.84 - 0.97)	0.98 (0.96 - 0.99)
	CV	2.7%	5.5%	2.5%
Right	SEM	44.8 (35.4 - 63.1)	94.1 (74.2 - 132.3)	61.3 (48.3 - 86.2)
	ICC	0.97 (0.93 - 0.99)	0.92 (0.82 - 0.97)	0.98 (0.95 - 0.99)
	CV	3.1%	5.6%	2.6%
Centre of mass displacement (m)				
Left	SEM	0.012 (0.009 - 0.016)	0.018 (0.014 - 0.026)	0.019 (0.015 - 0.027)
	ICC	0.86 (0.71 - 0.95)	0.87 (0.72 - 0.95)	0.90 (0.78 - 0.96)
	CV	11.8%	10.6%	8.8%
Right	SEM	0.011 (0.009 - 0.015)	0.020 (0.015 - 0.028)	0.021 (0.016 - 0.029)
	ICC	0.91 (0.80 - 0.97)	0.81 (0.61 - 0.93)	0.90 (0.78 - 0.96)
	CV	10.9%	12.2%	9.1%
Vertical stiffness (N.m^{-1}.kg^{-1})				
Left	SEM	29.9 (23.6 - 42.1)	19.4 (15.3 - 27.3)	10.6 (8.4 - 14.9)
	ICC	0.73 (0.48 - 0.89)	0.91 (0.80 - 0.97)	0.98 (0.85 - 0.99)
	CV	14.5%	12.9%	6.7%
Right	SEM	28.2 (22.2 - 39.7)	18.3 (14.4 - 25.7)	11.6 (9.1 - 16.3)
	ICC	0.81 (0.61 - 0.93)	0.90 (0.78 - 0.96)	0.96 (0.91 - 0.99)
	CV	13.2%	11.4%	7.6%
Key: SEM = standard error of measurement, CV = coefficient of variation, ICC = average intra-class correlation coefficient (across sessions 2-4).				

Table 3.7 (cont.) - Inter-session reliability for vertical ground reaction force, negative centre of mass displacement and vertical stiffness for bilateral hopping, bilateral drop jumping and unilateral jumping across testing sessions 2-4. Values are presented as mean (90% confidence intervals).

Reactive strength index (flight time : contact time)				
Left	SEM		0.12 (0.09 - 0.16)	0.04 (0.03 - 0.05)
	CV		0.96 (0.92 - 0.99)	0.98 (0.96 - 0.99)
	ICC		6.4%	4.3%
Right	SEM		0.13 (0.10 - 0.19)	0.04 (0.03 - 0.05)
	CV		0.94 (0.87 - 0.98)	0.98 (0.96 - 0.99)
	ICC		7.4%	4.1%
Key: SEM = standard error of measurement, CV = coefficient of variation, ICC = average intra-class correlation coefficient (across sessions 2-4).				

For vertical stiffness, CVs were lowest in unilateral drop jumping and highest in bilateral hopping (Table 3.7).

3.3.3.3 Bilateral hopping

Table 3.8 - Vertical ground reaction force, negative centre of mass displacement, vertical stiffness and hopping frequency across four bilateral hopping testing sessions. Values are presented as mean ± standard deviation.

Variable	Limb	Session 1	Session 2	Session 3	Session 4
Vertical ground reaction force (N)	Left	1463 ± 214	1435 ± 199	1412 ± 213	1380 ± 211
	Right	1513 ± 194	1471 ± 201	1456 ± 229	1420 ± 223
COM displacement (m)	Left	0.127 ± 0.051	0.102 ± 0.030	0.101 ± 0.027	0.094 ± 0.029
	Right	0.128 ± 0.056	0.104 ± 0.033	0.101 ± 0.030	0.096 ± 0.032
Vertical stiffness (N.m^{-1}.kg^{-1})	Left	176 ± 52	217 ± 59	198 ± 44	217 ± 51
	Right	186 ± 58	220 ± 63	208 ± 54	224 ± 55
Hopping frequency (Hz)	Both	2.57 ± 0.25	2.73 ± 0.32 *	2.78 ± 0.32 *	2.78 ± 0.36 *
* indicates significantly different from Session 1.					
Key: COM = centre of mass.					

VGRF ($F_{(3,39)}$ = 4.43; P = 0.010; η^2 = 0.28), COM displacement ($F_{(3,39)}$ = 5.69; P = 0.003; η^2 = 0.34) and vertical stiffness ($F_{(3,39)}$ = 3.08; P = 0.041; η^2 = 0.22) were statistically different between sessions (Table 3.8), although no significant pair-wise differences were observed. Hopping frequency was statistically different between sessions ($F_{(3,13)}$ = 14.02; P < 0.001; η^2 = 0.56) such that hopping frequency was lower in testing session 1 versus all other sessions (Table 3.8).

Pair-wise inter-session comparisons for vertical stiffness revealed CVs in excess of 20% between testing session 1 and all other testing sessions.

3.3.3.4 Drop jumping

Table 3.9 - Vertical ground reaction force, negative centre of mass displacement, and vertical stiffness across four bilateral and unilateral drop jump testing sessions. Values are presented as mean ± standard deviation.

Variable	Limb	Session 1	Session 2	Session 3	Session 4
Bilateral drop jump					
Vertical ground reaction force (N)	Left	1676 ± 264	1651 ± 262	1697 ± 328	1665 ± 294
	Right	1733 ± 369	1686 ± 277	1686 ± 317	1702 ± 260
Centre of mass displacement (m)	Left	0.166 ± 0.030	0.169 ± 0.045	0.171 ± 0.041	0.176 ± 0.045
	Right	0.172 ± 0.060	0.152 ± 0.038	0.163 ± 0.033	0.165 ± 0.047
Vertical stiffness ($N.m^{-1}.kg^{-1}$)	Left	155 ± 38	147 ± 51	155 ± 57	148 ± 58
	Right	171 ± 65	165 ± 51	153 ± 46	164 ± 52
Unilateral drop jump					
Vertical ground reaction force (N)	Left	2356 ± 303	2306 ± 343	2292 ± 355	2287 ± 313
	Right	2299 ± 421	2269 ± 350	2290 ± 342	2252 ± 300
Centre of mass displacement (m)	Left	0.241 ± 0.053	0.242 ± 0.047	0.241 ± 0.049	0.227 ± 0.034
	Right	0.267 ± 0.087	0.228 ± 0.051	0.243 ± 0.047	0.246 ± 0.060
Vertical stiffness ($N.m^{-1}.kg^{-1}$)	Left	143 ± 39	137 ± 44	136 ± 41	140 ± 34
	Right	128 ± 43	142 ± 42	135 ± 36	133 ± 42

For bilateral drop jumping, vGRF ($F_{(3,39)}$ = 0.14; P = 0.93; η^2 = 0.01), COM displacement ($F_{(3,39)}$ = 0.57; P = 0.64; η^2 = 0.05) and vertical stiffness ($F_{(3,39)}$ = 0.21; P = 0.89; η^2 = 0.02) were not statistically different between sessions (Table 3.9). Likewise, for unilateral drop jumping, vGRF ($F_{(3,39)}$ = 0.23; P = 0.67; η^2 = 0.05), COM displacement ($F_{(3,39)}$ = 0.91; P = 0.45; η^2 = 0.08) and vertical stiffness ($F_{(3,39)}$ = 0.17; P = 0.92; η^2 = 0.02) were not statistically different between sessions (Table 3.9).

Pair-wise reliability comparisons between testing session 1 and all other testing sessions revealed CVs for vertical stiffness in excess of 15% for bilateral drop jumping and 12% for unilateral drop jumping.

3.3.4 Discussion

General discussion

Study 1 examined the reliability of vertical stiffness when calculated independently for the left and right limbs during bilateral hopping, bilateral drop jumping and unilateral drop jumping. The hypothesis that all three tasks would report CVs < 10% is rejected by the current study. During bilateral hopping, respective CVs of 14.5% and 13.2% were reported for the left and right limbs across three testing sessions. CVs of 12.9% and 11.4% were reported for the left and right limbs during bilateral drop jumping and CVs of 6.7% and 7.6% were reported for the left and right limbs during unilateral drop jumping. These results suggest that unilateral drop jumping provides a more reliable measure of vertical stiffness when compared to bilateral drop jumping or bilateral hopping. This finding may appear counterintuitive given that the unilateral drop jump exposes the limbs to significantly greater vGRFs and may be classified as the highest intensity performance task. However, Jarvis et al. (2016) have previously reported lower CVs for vGRF in a unilateral drop jump task (CV: 4.0%) versus a bilateral drop jump task from 0.30 m (CV: 5.3%).

The independent determination of vertical stiffness for the left and right limbs during a bilateral task is a technique that had not been previously evaluated by the literature. Determining unilateral vertical stiffness values may allow the coach to build a more complete profile of an individual's stiffness profile, identifying any potential asymmetries between the left and right limbs which may be associated with an increased injury risk (Pruyn et al., 2012) or impaired performance (Wilson et al., 1994). This knowledge should better inform the training process.

The reliability of vertical stiffness derived from bilateral or unilateral drop jumping had also not been explored by the literature. Given the similarity between the CVs for vertical stiffness observed for bilateral drop jumping and bilateral hopping, the bilateral drop jump may serve as an alternative performance task by which to assess vertical stiffness. Although the unilateral drop jump is associated with lower CVs and greater vertical stiffness than bilateral drop jumping and bilateral hopping, when choosing the most appropriate task to assess stiffness the sporting profile of the individual athlete must be considered. Study 2 will consider the most appropriate performance task by which to assess vertical stiffness.

Bilateral hopping

The CVs of 14.5% and 13.2% reported for vertical stiffness in the current study is comparable to the figure of 14.4% reported by Moir et al. (2009) for bilateral hopping, however, is greater than other figures previously reported of 2.7% (McLachlan et al., 2006), 5.5% (Joseph et al., 2013), 8.1% (Brauner et al., 2014) and 9.8% (Moresi et al., 2015) where a set hopping frequency has been determined. Joseph et al. (2013) indicates that reliability is improved by hopping at a set versus a self-selected hopping frequency; the investigators reported a CV of 10.2% for hopping at a self-selected frequency. However, pilot testing (n = 8) conducted prior to the current study indicated that a representative group of participants were unable to hop consistently at the frequency of 2.2 Hz recommended by Joseph et al. (2013) and would not have been able to fulfil the necessary sampling criteria for analysis of the hops (each hop within ± 5% of the average ground contact time). Whilst the representative participant group sampled in the pilot study were all physically active individuals, few were regularly engaging in plyometric activities and demonstrated the ability to successfully deviate from a self-selected hopping frequency when asked to do so. The current study observed

that participants were able to hop at a repeatable frequency following a single familiarisation session (CV: 1.9%). However, substantial inter-individual variance was observed in the hopping frequency employed (1.96 - 3.28 Hz). It is established that increased hopping frequency results in a reduction in COM displacement and resultant increase in vertical stiffness (Farley et al., 1991; Hobara et al., 2011), the observed discrepancy in hopping frequency may therefore explain the large inter-participant variance in vertical stiffness observed in the current study. Whilst the maintenance of a set, pre-determined frequency where possible is likely to reduce inter-participant variation and improve the reliability of the method, it is important to state that a set frequency is likely to have little relationship to the frequencies used in sporting actions. It may therefore be questioned how useful this type of measurement may be in the exploration of human performance. Whilst it may be argued that the potential applicability of hopping tasks may be increased by employing maximal height hopping, the cyclic nature of the task is still not representative of typical sporting actions such as a change of direction. Moreover, it does not appear that substantial differences in vertical stiffness are observed between maximal and normal height hopping. Farley et al. (1991) reported values of 49.5 ± 1.8 and 45.7 ± 1.5 $kN.m^{-1}$ for maximal and normal (self-selected by the participant) height hopping respectively.

Given that low CVs for vGRF were reported in the current study (~3%), the observed variability of vertical stiffness measures in the current study is a consequence of variability in COM displacement. The current study observed CVs of 12 - 13% for COM displacement, suggesting that individuals were demonstrating some inconsistency in hopping strategy between trials despite maintaining a steady hopping frequency. Given both the significant effect reported for COM displacement and the linear decrease observed over the four trials (Table 3.8), it

may be interpreted that individuals were experiencing either a learning effect or a training effect over the testing period which affected their execution of the hopping task. As four trials were undertaken over a period approximately 28 days in recreationally-trained individuals, it is reasonable to suggest the occurrence of a small training effect.

Study 1 observed an average COM displacement of ~0.10 m. It is important to note that the displacement observed in the population sampled by Joseph et al. (2013) was substantially lower - an average displacement of 0.05 m during 2.2 Hz hopping was reported. This is surprising given that the frequency of hopping was faster in the current study; it would be predicted that faster frequencies should require a stiffer leg-spring system and demonstrate less COM displacement as a consequence (Hobara et al., 2011). Moir et al. (2009) and Brauner et al. (2014) are the only other investigators to present displacement figures, reporting values of 0.12 m and 0.11 m respectively. The similarity of these investigators' figures to those of the current study may explain why the CVs for vertical stiffness are also more comparable than those of Joseph et al. (2013). Demonstrating less displacement during the ground contact phase of hopping is likely to be indicative of participants with a greater capability to utilise the stretch-shortening cycle and who may be classified as more 'skilled' performers in plyometric activities; for example, Hobara et al. (2010) has reported greater displacement in untrained individuals in comparison to trained endurance runners (0.11 vs. 0.08 m; $P < 0.001$).

Drop jumping

Whilst the reliability of vertical stiffness measures had not been previously evaluated during bilateral drop jumping, figures have been reported for related

parameters. Feldmann et al. (2012) have previously evaluated the reliability of reactive strength index during bilateral drop jumping, a variable which has been closely linked to stiffness (Turner & Jeffreys, 2010; Marshall & Moran, 2013), and reported a CV of 8.4%. The values of 6.4% and 7.4% observed for the reactive strength index of the left and right limbs during bilateral drop jumping in the current study are comparable to those reported by Feldmann et al. (2012). Reliability figures for vGRF during bilateral drop jumping from 0.40 m reported by Ortiz et al. (2007), when interpreted as a CV, yield a value of 8.6%. Jarvis et al. (2016) reported a value of 5.3% from a drop height of 0.30 m. The reliability of ground reaction forces, both vertical and horizontal, have also been measured during unilateral drop jumps performed with a horizontal emphasis by Stålbom et al. (2007), the investigators reported CVs between 5-6% although derived these values from the standard deviation and not the standard error of measurement. The current study reports CVs of 5.5% and 5.6% for the vGRF of the left and right limbs during bilateral drop jumping, reducing to 2.5% and 2.6%, respectively, during unilateral drop jumping. This further highlights that participants were able to execute the drop jumps in a reliable and repeated fashion.

As with bilateral hopping, CVs for COM displacement in Study 1 were greater than for vGRF (bilateral drop jump: 10 - 12%, unilateral drop jump: ~9%) and therefore contribute more strongly to explaining the observed variance in vertical stiffness. This is perhaps to be expected given that related kinematic parameters, such as angular displacements of the hip, knee and ankle, have demonstrated greater variance during drop jumping than kinetic parameters (Ortiz et al., 2007). The observed displacements for both bilateral and unilateral drop jumping in the current study are greater than figures reported for bilateral hopping. This was not unexpected given the greater vGRF associated with drop jumping. It should be

noted that this study used an estimated velocity of falling (-1.88 m.s^{-1}) from which subsequent integration was performed. The efficacy of this value is dependent upon the participant dropping from an exact height of 0.18 m. Were participants to partially step down from the box, effectively reducing the drop height, this would result in the overestimation of falling velocity. Such an overestimation would lead to the calculation of larger COM displacements. Although participants were not observed to step down during the current study, future studies will attempt to limit this confounding variable by estimating falling velocity using direct measurements of velocity obtained using two-dimensional motion capture.

Vertical stiffness values have been reported in two bilateral drop jump (drop height: 0.2 m) investigations (Arampatzis et al., 2001a; 2001b). Arampatzis et al. (2001b) report bilateral values ranging from 32.4 ± 7.7 kN.m^{-1} in the most compliant group up to 78.7 ± 15.3 kN.m^{-1} in the stiffest group. Hopping on a sprung surface, values reported by Arampatzis et al. (2001a) ranged from 27.7 ± 8.4 kN.m^{-1} in the compliant group to 80.9 ± 16.8 kN.m^{-1} in the stiff group. Data from the bilateral drop jumps performed in the current study report values slightly lower than observed in the aforementioned compliant groups, single limb stiffness values of 10.8 ± 3.9 and 11.7 ± 4.2 kN.m^{-1} were observed for the left and right limbs respectively. Arampatzis et al. (2001a; 2001b) report an average COM displacement of approximately 0.13 - 0.14 m (estimated from figures) in the compliant groups. This is less than the 0.16 – 0.17 m observed in the current study. An overestimation of COM displacement may have been observed in the current study as a consequence of the estimated falling velocity, may contribute to the explanation of this disparity.

<u>Experimental considerations</u>

For bilateral hopping, the current study reported notable differences in all measured parameters between the first testing session and all other testing sessions, particularly for hopping frequency. A marked reduction in the pair-wise CVs was also reported for bilateral and unilateral drop jumping following the first session. It may therefore be concluded that one familiarisation session was necessary to accustom participants to all three protocols; this should be of consideration to future investigations employing this method of vertical stiffness assessment. No obvious benefit of undertaking more than one familiarisation session was apparent in the population sampled.

It is possible that the participant population sampled in Study 1 may exhibit greater variance in vertical stiffness as a consequence of being less skilled in performing stretch shortening cycle activities. Skilled performers would be expected to be able to reproduce these activities with greater consistency given a familiarity with the plyometric nature of the activity (Seifert et al., 2013) and a greater capacity to utilise the stretch-shortening cycle (Hobara et al., 2010). It is therefore possible that sampling plyometric-trained participants would further improve the reliability of the methodologies employed in Study 1 and mitigate any potential learning or training effects. Moreover, the sampling of such participants should also facilitate the utilisation of increased drop jump heights. This would allow the identification of an optimal drop height for each individual and may further enhance the validity of the bilateral drop jump test. However, such individualisation may be contraindicated in the athletic training environment given the time constraints commonly associated with testing procedures. It is also likely that any optimal height identified would be dependent upon fatigue and/or training status at the time of testing and therefore require frequent reassessment.

3.3.5 Conclusion

Study 1 reported that unilateral drop jumping exhibits stronger reliability as an assessment task for vertical stiffness than bilateral hopping and bilateral drop jumping. Unilateral drop jumping was the only task to report CVs < 10%. Moreover, unilateral drop jumping exposes the limbs to greater vGRFs.

3.3.6 Implications for the thesis

Unilateral drop jumping was the only task to report CVs < 10% and therefore appears to be the most reliable measure of vertical stiffness of the three performance tasks. The most valid task by which to assess vertical stiffness asymmetries for an individual athlete now needed to be considered; this was evaluated in Study 2.

Chapter 4 - Determination of Stiffness Asymmetries

4.1 Overview

The purpose of chapter 4 was to establish the most ecologically valid performance task by which to assess vertical stiffness and vertical stiffness asymmetries in subsequent investigations. Determining the most valid task will provide athletes, coaches and applied practitioners with the most appropriate assessment tool to assess vertical stiffness and vertical stiffness asymmetries.

Study 1 demonstrated that the unilateral drop jump provided a reliable assessment of vertical stiffness. This task may demonstrate greater correspondence to change of direction speed (CODS) in comparison than bilateral hopping or bilateral drop jumping. Whether the unilateral drop jump can effectively identify vertical stiffness asymmetry must now be determined.

The chapter will report the results of the following investigation:

Study 2: A comparison of methods to determine vertical stiffness asymmetries

4.2 Introduction

Stiffness describes the resistance of an object to deformation (Brughelli & Cronin, 2008). Specifically, vertical stiffness may be described by changes in the body's centre of mass (COM) in response to force (Pearson & McMahon, 2012) - a concept described in Section 2.3.1. Although the role of vertical stiffness in modulating injury risk and athletic performance may be well established (Butler et al., 2003; Pearson & McMahon, 2012), literature investigating bilateral asymmetry in vertical stiffness is limited. A significant link between vertical stiffness asymmetry and soft-tissue injury has been reported in Australian rules footballers (Pruyn et al., 2012) and such asymmetry may also be expected to impair athletic performance given a likely imbalance in the application of force (Wilson et al., 1994). Whilst it is important to note that the latter hypothesis has not been properly explored, it is clear that the measurement and quantification of vertical stiffness asymmetry is of important practical relevance to athletic performance.

Vertical stiffness may be assessed during a variety of performance tasks, including running (Coleman et al., 2012) and drop jumping (Arampatzis et al., 2001b), but is most commonly assessed during the performance of a bilateral 'hopping' task (Joseph et al., 2013; Hobara et al., 2014). During hopping tasks, individuals are required to perform an uninterrupted sequence of repeated bilateral jumps on a force plate. Measurements of vertical ground reaction force (vGRF) and negative displacement of the COM are recorded, and vertical stiffness is subsequently calculated as the ratio between these two measures (Joseph et al., 2013; Hobara et al., 2014). Hopping tasks have been shown to differentiate between certain groups, for example, it has been demonstrated that power-trained athletes (≥ 9 years of sprint training experience) exhibited greater vertical stiffness than endurance-trained athletes (≥ 7 years of endurance training) (Hobara et al., 2008),

and that endurance-trained athletes (varsity endurance athletes with ≥ 9 years of training experience) exhibited greater vertical stiffness than untrained individuals (Hobara et al., 2010). Pruyn et al. (2014) split a cohort of netball players into high- and low-stiffness groups based upon vertical stiffness; whilst inter-group differences were not significant, performances in a number of speed and power tests were superior in the high-stiffness group and were reported with 'moderate' effect sizes ($d > 0.7$).

One potential problem with hopping tasks is that they are typically performed at set hopping frequencies and are inherently submaximal in nature (Joseph et al., 2013; Hobara et al., 2014). As such, bilateral hopping tasks may demonstrate greater correspondence to sub-maximal cyclic performances, such as endurance running, rather than short-term maximal performances, such as jumping. For this reason, it may be desirable to assess vertical stiffness during a maximal performance task such as a drop jump. Given that the drop jump is an acyclic action performed with the intent to maximise jump height whilst minimising ground contact time (Marshall & Moran, 2013), it may carry greater ecologically validity as an assessment tool for vertical stiffness when compared to hopping tasks and be more representative of a single maximal jumping effort (Flanagan & Harrison, 2007). Whilst vertical stiffness has been modelled during drop jumping by Arampatzis et al. (2001a; 2001b), this task has not been used to examine relationships with performance or to examine inter-group differences in the same way as bilateral hopping tasks. Further research is required to determine if vertical stiffness values achieved during drop jumping demonstrate similar relationships with performance and training status as those achieved during bilateral hopping.

As previously highlighted, literature investigating bilateral asymmetry in vertical stiffness is limited. Bachman et al. (1999), Heise and Bachman (2000) and Divert

et al. (2005) all observed no significant vertical stiffness asymmetries during running, although the cyclic, submaximal limb action and bilateral nature of locomotion may be expected to encourage symmetry. When the results of Bachman et al. (1999) are presented as a symmetry angle, a method used to quantify asymmetry (Zifchock et al., 2008), average differences between the left and right limbs were -3.8% and -2.7% at running speeds of 3.5 m.s^{-1} and 5.3 m.s^{-1}, respectively. Similarly, Hobara et al. (2013) did not report significant vertical stiffness asymmetries between non-dominant and dominant limbs during unilateral hopping; average differences of -4.9%, 1.1% and -3.0% were observed at hopping frequencies of 1.5 Hz, 2.2 Hz and 3 Hz, respectively.

Flanagan and Harrison (2007) compared asymmetries during unilateral drop jumps and repeated drop jumps performed on a sledge apparatus. The investigators reported that no asymmetries were apparent during the cyclic, repeated jumps, however, significant asymmetry in reactive strength index - which may be closely linked to leg stiffness (discussed in Section 2.6) - was evident during the acyclic drop jump task. When presented as a symmetry angle, average differences in vertical stiffness between limbs were -1.1% for drop jumping and 0.4% for repeated drop jumping. Whilst the observations of Flanagan and Harrison (2007) demonstrate that the type of performance task chosen to assess stiffness carries the potential to modulate how asymmetries may be expressed, further research is necessary to elucidate this effect.

As cyclic, submaximal versus acyclic, maximal performance tasks may differently express asymmetries, so too may bilateral versus unilateral performance tasks. Benjanuvatra et al. (2013) compared impulses of the left and right limbs during bilateral and unilateral countermovement jumping, finding that asymmetries presented in the bilateral jump did not correspond to asymmetries in the unilateral

jump. For example, individuals may express a right-side dominance during the bilateral task but a left-side dominance in the unilateral task. These observations led the investigators to conclude that asymmetry in bilateral tasks is driven by neural factors, a proposition supported by earlier investigations conducted by Simon and Ferris (2008). As unilateral jumping tasks rely on the extension forces generated from a single limb, such tasks would appear to be a more suitable choice if seeking to quantify functional parameters of the limb such as vertical stiffness. However, such propositions are yet to be evaluated by the literature and further research is required to explore this hypothesis.

The purpose of Study 2 was to investigate the expression of bilateral asymmetry in vertical stiffness during three different performance tasks: a) bilateral hopping, b) bilateral drop jumping, and c) unilateral drop jumping. As the unilateral drop jump task demonstrates the greater correspondence to CODS, it must now be determined if this task is capable of detecting bilateral asymmetries in order to explore their relationship with CODS performance. It was hypothesised that the presentation of vertical stiffness and vertical stiffness asymmetries would be different between performance tasks. Specifically, it was hypothesised that: i) asymmetries would be significantly greater in the maximal drop jump tasks versus the submaximal hopping task, and ii) asymmetries would be significantly greater in the unilateral versus bilateral drop jump task.

4.3 Method

4.3.1 Experimental overview

Study 2 was a randomised and counterbalanced experiment designed to assess how the type of performance task affected the expression of vertical stiffness and vertical stiffness asymmetry. Following a familiarisation session, participants performed three different performance tasks during which vertical stiffness asymmetries were calculated using dual force plate data and an inverse dynamics model. The three performance tasks were: a) bilateral hopping, b) bilateral drop jumping, and c) unilateral drop jumping.

4.3.2 Participants

Thirteen healthy males (age: 22 ± 3 years; height: 1.78 ± 0.06 m; body mass: 72.9 ± 6.9 kg), recruited from a university campus, volunteered to participate in the study. A minimum sample size of twelve participants was determined from *a priori* power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon an estimated squared multiple correlation of 0.45 (Benjanuvatra et al., 2013), single input variable (vertical stiffness asymmetry) and a power of 0.8 (Beck, 2013). Participants were recreationally active (undertaking ≥ 2.5 hours of physical activity per week), reported no previous (within the last 12 months) or present lower limb injury and provided informed consent (Appendix A1) to participate in the study. Full ethical approval was granted by the review board of the Institute for Physical Activity Research, University of Bedfordshire (Appendix A1) and all procedures were conducted in accordance with the Declaration of Helsinki.

4.3.3 Experimental trials

A familiarisation session was performed seven days prior to the experimental trial; Study 1 had previously indicated that a single familiarisation session was appropriate for all testing methods and experimental variables within the same participant population. The familiarisation session was a complete simulation of the experimental trial outlined below.

All trials were conducted at the same time of day (09:30 - 11:00) for each participant, to alleviate the effects of circadian rhythms. The testing laboratory was controlled at an ambient temperature of $25^{\circ}C$. Participants were instructed to prepare for testing as they would for training. The execution of each experimental trial was monitored by a United Kingdom Strength and Conditioning Association accredited strength and conditioning coach to ensure for consistency of technique.

4.3.4 Warm-up

All participants completed the same warm-up procedure outlined in Study 1 (Section 3.3.2.3; Table 3.5). The warm-up procedure consisted of 15 dynamic exercises progressing from low to high intensities and from generic to specific movement patterns. A recovery period of 180 seconds was prescribed between the termination of the warm-up and commencement of the testing protocol.

4.3.5 Stiffness assessments

All vertical stiffness assessments were performed on a dual force plate system (Kistler 9281, Kistler Instruments, Winterthur, Switzerland) as outlined in Study 1.

The bilateral hopping protocol is outlined in Section 3.3.2.4. Unshod, participants performed a series of 30 consecutive bilateral hops. Participants performed two hopping trials in each experimental trial; these were separated by a recovery period

of 180 seconds. Hops were performed at a self-selected frequency (mean hopping frequency: 2.8 ± 0.3 Hz; mean ground contact time: 0.175 ± 0.023 sec) as pilot testing prior to Study 1 had indicated that participants were unable to satisfactorily perform the task at the recommended hopping frequency of 2.2 Hz. Participants were instructed to "hop on the balls of your feet at a constant rhythm." Five consecutive hops from 6th to the 10th hop were sampled for data collection (Hobara et al., 2014). The ground contact time of each of the 5 hops was required to fall within ± 5% of the average ground contact time for the 5 hop sample (Moresi et al., 2015); all hopping trials met these criteria.

The drop jump protocols are outlined in Section 3.3.2.5. Following a recovery period of 180 seconds, participants performed three unshod bilateral drop jumps and three unshod unilateral drop jumps for each limb from a drop height of 0.18 m. The box height of 0.18 m was chosen as participants were unable to minimise ground contact time effectively at additional height increments (0.30 m and 0.45 m) during pilot testing. The order in which participants performed bilateral and unilateral drop jumps was randomised and counterbalanced.

4.3.6 Data analysis

Procedures for data analysis (Section 3.3.2.6) and the calculation of vertical stiffness (Section 3.3.2.7) have been previously described in detail. Inverse dynamics was used to express acceleration, velocity and COM displacement; this was determined from the vertical force trace using the equations described by Blazevich (2007) and Hall (2012) (detailed in Appendix A2). Vertical stiffness was calculated as the ratio of peak vGRF relative to the peak negative COM displacement during the initial ground contact phase (Farley & Morgenroth, 1999); this was averaged over the five sampled hops or the three recorded drop jumps in

each condition. In an effort to ensure the efficacy of the spring-mass model, the force-displacement correlation coefficient during landing of each trial was required to be ≥ 0.8 (Padua et al., 2005); all trials met these criteria. As vertical stiffness is affected by body size, vertical stiffness values were reported relative to body mass (Farley et al., 1993).

4.3.7 Statistical analysis

Limbs were independently categorised as either stiff or compliant based upon the vertical stiffness values achieved within each of the three testing methods. Asymmetries were quantified using the symmetry angle (θ_{SYM}), calculated using the procedures outlined by Zifchock et al. (2008) detailed in Section 2.5.1 and shown in Equation 4.1.

$$\textbf{Equation 4.1: } SYM\alpha\% = \frac{(45° - \arctan(\frac{X\,left}{X\,right}))}{90°} * 100$$

<div align="right">(Zifchock et al., 2008)</div>

Where SYMα% = symmetry angle, X left = left side value, X right side value.

As θ_{SYM} values may be negative or positive to reflect left or right side dominance, negative values were transformed to positive values prior to statistical analysis in order to evaluate differences solely in the magnitude of asymmetry.

Shapiro-Wilks tests were performed to assess for normality; all variables were considered to be normally distributed given an alpha level of $P > 0.05$. A 2 x 3 (limb x method) repeated-measures analysis of variance (ANOVA) was used to test for differences between methods. ANOVA effect sizes were measured using the partial Eta-squared (η^2) and Sidak post-hoc analyses were performed where appropriate. A 1 x 3 repeated measures ANOVA was performed to analyse for

differences in θ_{SYM} between methods. Pair-wise effect sizes (d) (Cohen, 1998) were calculated and interpreted using the thresholds defined by Hopkins (2003) where: <0.20 = trivial, 0.20-0.59 = small, 0.60-1.19 = moderate, 1.20-1.99 = large, and ≥2 = very large. All analyses of variance were conducted using the Statistical Package for the Social Sciences for Windows (v21.0; SPSS Inc., Chicago, USA) with an alpha level of $P \le 0.05$.

4.4 Results

4.4.1 Vertical stiffness

Table 4.1 - A comparison of force, displacement and stiffness between the stiff and compliant limb identified in the three types of performance task. Figures are presented as the mean ± standard deviation.

Variable	Bilateral hopping		Bilateral drop jump		Unilateral drop jump	
	Stiff limb	Compliant limb	Stiff limb	Compliant limb	Stiff limb	Compliant limb
vGRF (N)	1476 ± 193	1428 ± 188 *	1759 ± 259 †	1655 ± 309 *†	2423 ± 380 †‡	2342 ± 362 *†‡
ΔCOM (m)	0.100 ± 0.028	0.104 ± 0.032 *	0.137 ± 0.025 †	0.178 ± 0.047 *†	0.207 ± 0.050 †‡	0.226 ± 0.054 *†‡
K$_{vert}$ (N.m^{-1}.kg^{-1})	223 ± 57	211 ± 56 *	184 ± 49	141 ± 51 *	175 ± 61	154 ± 49 *

* indicates significantly different from the stiff limb ($P < 0.05$), † significantly different from bilateral hopping ($P < 0.01$), ‡ significantly different from bilateral drop jump ($P < 0.01$).

Key: vGRF = vertical ground reaction force, ΔCOM = centre of mass displacement, K$_{vert}$ = vertical stiffness.

Vertical stiffness was significantly different between methods ($F_{(2,24)} = 3.96$; $P = 0.033$; $\eta^2 = 0.25$) (Table 4.1), however, pairwise comparisons did not show significant differences. Vertical stiffness was not significantly higher in bilateral hopping than in bilateral drop jumping (25.2%; $P = 0.11$; $d = 0.99$) or unilateral drop jumping (24.2%; $P = 0.16$; $d = 0.93$), although effect sizes reported 'moderate' differences. Differences in vertical stiffness between bilateral drop jumping and unilateral drop jumping were also not significant (-2.2%; $P = 1.00$; $d = -0.04$).

Vertical stiffness was significantly lower in the compliant limb than in the stiff limb ($F_{(1,12)} = 66.18$; $P < 0.001$; $\eta^2 = 0.85$) with a significant interaction effect between limb and method ($F_{(2,24)} = 5.26$; $P = 0.013$; $\eta^2 = 0.31$). Asymmetry percentages between compliant and stiff limbs were 5.6% ($P < 0.001$; d: 0.22), 23.3% ($P =$

0.001; $d = 0.86$) and 12.4% ($P = 0.001$; $d = 0.39$) for the bilateral hopping, bilateral

drop jumping and unilateral drop jumping methods respectively.

Table 4.2 - Quantification of individual participants' asymmetries in vertical stiffness between the stiff and compliant limbs limb identified in three types of performance task.

Participant	Bilateral hopping		Bilateral drop jump		Unilateral drop jump	
	ASYM %	θ_{SYM}	ASYM %	θ_{SYM}	ASYM %	θ_{SYM}
1	6.4%	2.1%	46.0%	18.5%	28.1%	10.3
2	10.3%	-3.4%	14.2%	4.9%	2.7%	-0.9%
3	11.5%	3.9%	46.5%	18.7%	8.6%	-2.9%
4	6.2%	-2.0%	1.2%	0.4%	19.9%	-7.0%
5	3.2%	1.0%	14.0%	-4.8%	11.0%	3.7%
6	3.7%	-1.2%	18.6%	6.5%	6.1%	-2.0%
7	0.0%	0.0%	49.4%	20.2%	2.1%	0.7%
8	2.6%	-0.8%	55.6%	-23.4%	9.6%	-3.2%
9	6.3%	2.1%	27.7%	10.1%	7.3%	-2.4%
10	5.6%	1.8%	20.1%	-7.1%	10.5%	3.5%
11	7.8%	2.6%	3.5%	1.1%	10.6%	3.6%
12	3.3%	1.1%	2.9%	-0.9%	10.5%	-3.5%
13	9.1%	3.0%	3.9%	1.3%	20.1%	-7.1%
Mean ± SD	5.8 ± 3.2%	1.9 ± 1.1%	23.3 ± 19.0%	9.1 ± 8.3% *	11.3 ± 7.1%	3.9 ± 2.7% *

Negative θ_{SYM} values indicate a more compliant right limb, positive values indicate a more compliant left limb.

Mean values represent the **θ_{SYM}** when the direction of asymmetry is discounted.

* indicates significantly greater than bilateral hopping ($P < 0.05$).

Key: ASYM % = asymmetry percentage, θ_{SYM} = symmetry angle, SD = standard deviation.

Vertical stiffness θ_{SYM} was significantly different between methods ($F_{(2,24)} = 6.26$; $P = 0.006$; $\eta^2 = 0.34$) (Table 4.2). 'Large' differences were observed, such that vertical stiffness θ_{SYM} was significantly greater in bilateral drop jumping than bilateral hopping ($P = 0.036$; $d = 1.77$) but this difference was not significant versus

unilateral drop jumping ($P = 0.20$; $d = 1.28$). A 'small' and significant difference between bilateral hopping and unilateral drop jumping was also observed ($P = 0.043$; $d = -0.49$). Only four participants exhibited the same direction of asymmetry across all three tasks (Table 4.2).

4.4.2 Vertical ground reaction force

Landing vGRF was significantly different between methods ($F_{(2,24)} = 71.62$; $P < 0.001$; $\eta^2 = 0.86$) (Table 4.1). vGRF was lower in bilateral hopping than in bilateral drop jumping (-17.6%; $P = 0.015$; $d = 1.06$) and unilateral drop jumping (-64.1%; $P < 0.001$; $d = 3.29$). vGRF was lower in bilateral drop jumping than in unilateral drop jumping (-39.6%; $P < 0.001$; $d = 2.04$).

Landing vGRF was significantly different between the compliant and stiff limbs ($F_{(1,12)} = 18.11$; $P = 0.001$; $\eta^2 = 0.60$), there was no significant interaction effect between limb and method ($F_{(2,24)} = 1.41$; $P = 0.26$; $\eta^2 = 0.11$). In bilateral hopping, landing vGRF was 3.4% lower in the compliant limb versus the stiff limb ($P = 0.001$; $d = 0.25$). In bilateral drop jumping and unilateral drop jumping, vGRF was 6.3% ($P = 0.006$; $d = 0.37$) and 3.5% ($P = 0.026$; $d = 0.22$) lower in the compliant limb.

vGRF θ_{SYM} was significantly different between methods ($F_{(2,24)} = 5.64$; $P = 0.010$; $\eta^2 = 0.32$). vGRF θ_{SYM} was greater in bilateral drop jumping than in bilateral hopping ($P = 0.044$; $d = 1.13$) but not unilateral drop jumping ($P = 0.13$; $d = 0.90$); there were no differences between bilateral hopping and unilateral drop jumping ($P = 0.80$; $d = -0.24$).

4.4.3 Centre of mass displacement

COM displacement was significantly different between methods ($F_{2,24} = 29.08$; $P < 0.001$; $\eta^2 = 0.71$) (Table 4.1). In comparison to bilateral hopping, displacement was

greater in both bilateral drop jumping (35.1%; $P = 0.002$; $d = 1.53$) and unilateral drop jumping (52.8%; $P < 0.001$; $d = 2.75$). Displacement was also greater in unilateral drop jumping than bilateral drop jumping (27.2%; $P = 0.004$; $d = 1.23$).

COM displacement was significantly different between compliant and stiff limbs ($F_{(1,12)} = 19.56$; $P = 0.001$; $\eta^2 = 0.62$), with a significant interaction effect between limb and method ($F_{(2,24)} = 5.58$; $P = 0.010$; $\eta^2 = 0.32$). Differences between compliant and stiff limbs were 3.9% ($P = 0.033$; $d = 0.14$), 22.6% ($P = 0.006$; $d = 1.12$) and 8.5% ($P = 0.008$; $d = 0.37$) for the bilateral hopping, bilateral drop jumping and unilateral drop jumping methods respectively.

COM displacement θ_{SYM} was significantly different between methods ($F_{(2,24)} = 8.94$; $P = 0.001$; $\eta^2 = 0.43$). COM displacement θ_{SYM} was greater in bilateral drop jumping than in bilateral hopping ($P = 0.011$; $d = 1.87$) but not unilateral drop jumping ($P = 0.061$; $d = 1.44$); both effect sizes were large. There were no differences between bilateral hopping and unilateral drop jumping ($P = 0.43$; $d = -0.43$).

4.5 Discussion

The purpose of Study 2 was to investigate the expression of vertical stiffness and vertical stiffness asymmetry during three different types of performance task: bilateral hopping, bilateral drop jumping and unilateral drop jumping. Study 2 was the first study to examine how the type of performance task may affect the expression of vertical stiffness and vertical stiffness asymmetry. It was hypothesised that asymmetries would be significantly greater in the maximal drop jumping tasks versus the submaximal hopping task. Asymmetries observed in the bilateral drop jump task were significantly greater than in the bilateral hopping task. Whilst differences between the unilateral drop jump and bilateral hopping tasks were not significant, a large effect size was indicative of greater asymmetry during unilateral drop jumping. The current study therefore accepts the first hypothesis. It was further hypothesised that asymmetries would be significantly greater in the unilateral versus bilateral drop jump. This hypothesis is rejected as asymmetries were not different between bilateral and unilateral drop jumping.

The current study reported that all three performance tasks were able to detect significant asymmetries in vertical stiffness. As such, all three tasks could be used as a diagnostic tool to directly assess and quantify vertical stiffness asymmetry. Given that force-displacement correlations for all three methods were greater than 0.8, it may also be determined that they all represent the simple spring-mass model effectively (Padua et al., 2005). It was shown that the two acyclic, maximal performance tasks (bilateral and unilateral drop jumps) detected larger vertical stiffness asymmetries than the cyclic, submaximal task (bilateral hopping), although this difference was not significant for the unilateral drop jump and the effect size was 'small' ($d = 0.49$).

Study 2 is the first study to report that vertical stiffness asymmetries present differently in acyclic versus cyclic performance tasks. Flanagan and Harrison (2007) reported no asymmetry in vertical stiffness to be evident during acyclic or cyclic single leg sledge jumps, although demonstrated an asymmetry in reactive strength index - a property closely linked to stiffness (Flanagan & Comyns, 2008) - to be expressed during the acyclic jump. When the investigators' data is presented as a symmetry angle, average differences in reactive strength index were 1.1% for drop jumping and 0.4% for repeated drop jumping. The findings of the current study, in addition to the observations of Flanagan and Harrison (2007), suggest that asymmetries are differently expressed during acyclic, maximal performance tasks and cyclic, submaximal performance tasks. Importantly, the current study demonstrates this in a manner that is more indicative of human locomotion than the sledge ergometry testing protocols employed by Flanagan and Harrison (2007). Understanding the methodological factors which may contribute to the expression of asymmetry is of important practical relevance to athletes, coaches and applied practitioners seeking to quantify stiffness asymmetries.

Whilst it may appear that acyclic, maximal performance tasks are superior for identifying vertical stiffness asymmetry within individual athletes, careful consideration should be given to how the limbs will be required to function during sporting performance. For example, cyclic, submaximal tests, such as bilateral hopping, would be expected to be a more representative assessment of vertical stiffness asymmetry in endurance runners given a greater correspondence of the test to the submaximal, cyclic action of locomotion. The potential impact of increasing bilateral drop jump intensity (i.e. increasing the height of the box and subsequent vGRF upon landing) was not examined in the current study due to the training/skill level of the participants and should be explored in future

investigations. Whilst intuitively it may seem that increasing intensity would result in larger vertical stiffness asymmetries, this relationship has not been observed during unilateral hopping; Hobara et al. (2013) reported that the number of participants with an asymmetry percentage of ≥ 10% was greater when hopping at 1.5 Hz than at 2.2 or 3.0 Hz. Indeed, the current study reports smaller asymmetries during the more intense unilateral drop jump task (symmetry angle: 3.9 ± 2.7%) than during the bilateral drop (symmetry angle: 9.1 ± 8.3%).

It is important to note that the limb identified as the stiff limb for an individual within each performance task was not always the same limb (Table 4.2). For example, an individual may demonstrate greater vertical stiffness in the right limb during the bilateral drop jump but greater vertical stiffness in the left limb during the unilateral drop jump. In the current study, only four participants exhibited the same direction of asymmetry across all three tasks. Benjanuvatra et al. (2013) reported similar findings for vGRF impulse asymmetries during bilateral and unilateral countermovement jumping with only 46% of the participants demonstrated the same asymmetry/symmetry profile across the two jumps. It was hypothesised by the investigators that asymmetries during bilateral performances were governed by a neural control mechanism, agreeing with previous conclusions drawn by Simon and Ferris (2008) who observed isokinetic force asymmetries in bilateral exercise but not in unilateral exercise. Ultimately, unilateral jumping performance is reliant solely on the forces transferred and generated through a single limb as opposed to an inter-limb 'trade-off' that is apparent during bilateral jumping. Moreover, as the current study demonstrated that the unilateral drop jump elicited the greatest absolute values of vGRF and vertical stiffness, it may be inferred that the unilateral drop jump imposes a greater mechanical load on the lower limb. As the current study has demonstrated the ability of this task to identify vertical

stiffness asymmetry, the unilateral drop jump is proposed as a superior tool for the assessment of asymmetries in maximal properties such as peak vertical stiffness.

Vertical stiffness is a direct function of vGRF and COM displacement during the ground contact phase of the hop or jump (Joseph et al., 2013; Hobara et al., 2014). Asymmetries in vertical stiffness are therefore a consequence of asymmetries in vGRF and/or COM displacement. 'Small' but significant differences in vGRF were observed between the stiff and compliant limbs during bilateral hopping (3.4%; P = 0.001) and bilateral drop jumping (6.3%; P = 0.006), whilst the differences detected during unilateral drop jumping were 'trivial' (3.5%; P = 0.026). It is likely that vertical stiffness asymmetries observed during bilateral hopping and bilateral drop jumping may be partially dependant on vGRF asymmetry, whereas this was not the case during unilateral drop jumping.

Significant between-limb differences for COM displacement were observed during all three performance tasks. For bilateral hopping, the difference in COM displacement (3.9%; P = 0.033) was only marginally greater than the difference in vGRF. During bilateral hopping it would therefore appear that vertical stiffness asymmetries are a consequence of asymmetries in both vGRF and COM displacement and that these asymmetries are of a similar magnitude. During the bilateral and unilateral drop jump tasks, between-limb differences in COM displacement were larger than differences in vGRF (22.6%; P = 0.006 and 8.5%; P = 0.008 respectively). Vertical stiffness asymmetries during these maximal drop jump tasks appear to be a consequence of the greater differences in COM displacement.

The COM displacement observed during bilateral hopping in the current study (~0.10 m) is comparable to figures reported in other investigations (Joseph et al.,

2013; Hobara et al., 2014). COM displacement was greater in bilateral drop jumping (0.13 and 0.18 m for the stiff and compliant limbs) and greater still in unilateral (0.21 and 0.23 m) drop jumping; this is a likely consequence of increased vGRF. As vGRF was greatest in unilateral drop jumping, this task placed the highest mechanical demand on the leg-spring. For this reason, the unilateral drop jump could be considered the most appropriate task to assess stiffness properties if seeking to explore relationships with maximal sporting performance. The ability of the leg-spring to function in the presence of high force is critical given the likely demands to be placed upon it during a change of direction (Glaister et al., 2008; Spiteri et al., 2013).

4.6 Conclusion

In conclusion, all three types of performance task (bilateral hopping, bilateral drop jumping and unilateral drop jumping) demonstrate the potential to detect vertical stiffness asymmetry; such asymmetries may be greatest in bilateral drop jumping and lowest in bilateral hopping. Vertical stiffness asymmetry has been linked to an increased incidence of soft-tissue injury (Pruyn et al., 2012) and has been hypothesised to impair athletic performance as the application of force to each limb may be imbalanced (Wilson et al., 1994). Although further research is required to fully explore the impact of vertical stiffness asymmetry on both injury incidence and athletic performance, it would appear prudent to screen individuals for vertical stiffness asymmetry as this is a highly trainable and modifiable parameter. It is recommended that practitioners and researchers use the performance task that demonstrates the greatest correspondence to an individual's sport.

4.7 Implications for the thesis

The results of Study 2 demonstrate that vertical stiffness asymmetry may be detected using all three of the performance tasks evaluated. However, asymmetry was expressed differently in cyclic versus acyclic and bilateral versus unilateral tasks. As this thesis sought to examine the influence of stiffness on CODS - acyclic and unilateral in its nature - the unilateral drop jump test may demonstrate a higher degree of correspondence than bilateral hopping or bilateral drop jumping. As Study 2 demonstrated this to be an appropriate tool for the identification of vertical stiffness asymmetry, the unilateral drop jump was used to evaluate vertical stiffness in subsequent studies.

Chapter 5 - Stiffness Asymmetries and Change of Direction Speed

5.1 Overview

The primary purpose of this chapter was to establish if vertical stiffness and vertical stiffness asymmetries influenced change of direction speed (CODS). Were it to be determined that vertical stiffness and/or vertical stiffness asymmetries influenced CODS, this would a) highlight the importance of testing for these variables, and b) influence how interventions to improve CODS may be devised and structured.

The secondary purpose of this chapter was to establish the determinants of bilateral asymmetry in vertical stiffness. Specifically, this chapter sought to evaluate the relative importance of the ankle, knee and hip in modulating asymmetry.

The chapter will report the result of the following investigation:

Study 3: Do stiffness asymmetries predict change of direction speed?

5.2 Introduction

The ability to quickly and effectively change direction underpins performance in a wide range of sports. For example, CODS has been linked to performance outcomes in sports such as badminton (Sturgess & Newton, 2008), soccer (Reilly et al., 2000), field hockey (Keogh et al., 2003), rugby league (Meir et al., 2001) and basketball (McGill et al., 2012). Ultimately, improving an athlete's CODS has the potential to positively impact sporting performance. It is therefore important to understand the potential determinants of CODS in order to better inform the interventions devised to augment performance.

Young et al. (2002) proposed three physical factors which may underpin CODS - strength, power and reactive strength. Of these factors, reactive strength (a function of the flight time divided by ground contact time recorded during a drop jump) demonstrated the strongest relationship with CODS test time (r = -0.54; P < 0.05). Similar relationships have since been observed by Young et al. (2015) (r = -0.65; P = 0.001) and by Delaney et al. (2015) in both dominant (r = -0.44; P < 0.05) and non-dominant limbs (r = -0.45; P < 0.05). Reactive strength is a quality which may be closely linked to vertical stiffness; a stiffer system should facilitate a more rapid release of elastic energy under circumstances where minimal joint or centre of mass displacement is desired, such as during a drop jump or change of direction (Bret et al., 2002). Indeed, Arampatzis et al. (2001b) noted that higher vertical stiffness is associated with shorter ground contact times during drop jumping and shorter ground contact times are associated with quicker CODS (Sasaki et al., 2011; Marshall et al., 2014). Although multi-planar CODS performance does demonstrate kinematic differences to sagittal plane drop jumping, notably the lateral inclination of the whole body, the kinetic demands placed upon the leg-spring are comparable. During changes of direction, a single limb is required to

resist deformation in the presence of substantial ground reaction forces (Glaister et al., 2008; Spiteri et al., 2013). As highlighted within this thesis, these are characteristics shared with the unilateral drop jump. Vertical stiffness derived during unilateral drop jumping provides an appropriate tool for the assessment of this quality (resistance to deformation in the presence of high force) and for athletes participating in sports where CODS is an important determinant performance.

To this author's knowledge, only one investigation has sought to examine the correlation between stiffness and CODS. Pruyn et al. (2014) observed no significant relationship between vertical stiffness and 5-0-5 CODS test performance ($r = 0.05$), although they did report significant relationships between performance and stiffness of the musculature surrounding the ankle (medial gastrocnemius: $r = -0.53$, soleus: $r = -0.47$; both $P < 0.05$). Pruyn et al. (2014) determined vertical stiffness during a cyclic, unilateral hopping task and it has been observed in Study 2 that the expression of vertical stiffness and associated asymmetries is highly task dependant. As a change of direction may be characterised as acyclic and ballistic in nature, the unilateral drop jump is likely to demonstrate a higher degree of correspondence to CODS tasks than unilateral hopping, and therefore carry greater validity as an assessment of vertical stiffness. In addition, it is important to consider the homogeneity of population sampled by Pruyn et al. (2014); all 18 participants were trained netball players (15.4 ± 3.0 years of training experience) and exhibited minimal variance in 5-0-5 performance (performance time: 2.72 ± 0.18 sec). The potential relationship between stiffness and CODS would need to be examined in different, possibly less homogenous, populations before conclusions may be drawn.

Several investigations have reported that asymmetries in force/power qualities may be detrimental to athletic performance (Bailey et al., 2013; Bazyler et al., 2014;

Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), however, this relationship is not clear in regards to CODS. Whilst eccentric strength asymmetry has been linked to impaired CODS in some investigations (Chaouachi et al., 2012; Lockie et al., 2012), Lockie et al. (2014) reported that athletes with 'typical' asymmetries in unilateral jump performance (vertical jump: ~10%; horizontal jump: ~3%; lateral jump: ~5%) did not experience speed detriments.

Asymmetries in CODS performance when pushing off the dominant versus non-dominant limb have been reported in several investigations (Young et al., 2002; Henry et al., 2013; Hart et al., 2014a). For example, Hart et al. (2014a) reported that Australian Rules footballers demonstrated a performance deficit of 5 - 10% between limbs (~0.72 seconds; $P \leq 0.001$) with all players tested exhibiting a directional preference. Given the deterministic model proposed by Young et al. (2002) and modified model proposed in Section 2.10 (Figure 2.3), such asymmetry could be a consequence of an asymmtery in physical qualities. Indeed, Young et al. (2002) noted that athletes who displayed a lateral dominance in CODS tasks were likely to have a reactive strength dominance in the limb responsible for the push-off action. Such a relationship is supported by an investigation conducted by Henry et al. (2013) that reported asymmetries in reactive agility performance (discounting decision making time: 5.6%; $P = 0.04$) to mirror asymmetries in reactive strength index (4.4%; $P = 0.03$), although a direct correlation was not reported. Whether asymmetries in dominant versus non-dominant CODS are similarly detrimental to overall CODS performance has not been investigated. Whilst it may seem reasonable to hypothesise that asymmetries in CODS and/or stiffness parameters would be detrimental to overall CODS performance, given the current body of evidence, such propositions need to be examined directly.

Vertical stiffness is based on the premise that the legs function as a global spring-mass system (Butler et al., 2003) and do not consider how the ankle, knee and hip joints contribute to the summative stiffness of the overall system (Pearson & McMahon, 2012). In order to elucidate the potential determinants of asymmetries in stiffness properties, it is important to consider the respective contribution of the stiffness of individual joints as well as vertical stiffness. Two-dimensional computer simulation models created by Farley et al. (1998) and Farley and Morgenroth (1999) demonstrated that vertical stiffness during bilateral hopping was modulated as a consequence of changes in ankle stiffness and was not affected by changes in knee stiffness. This proposition has been supported in hopping investigations by Kuitunen et al. (2011) and Kim et al. (2013), and in drop jumping by Arampatzis et al. (2001b). Such a relationship would suggest that asymmetries in ankle stiffness are likely to lead to asymmetries in vertical stiffness. In contrast, Hobara et al. (2009) reported that knee stiffness, but not ankle stiffness, explained variance in vertical stiffness during maximal bilateral hopping. In addition, Horita et al. (2002) and Kuitunen et al. (2011) demonstrate that knee stiffness, whilst not affecting vertical stiffness, plays an important role in modulating mechanical output and overall performance. For these reasons, the role of the knee joint in modulating vertical stiffness asymmetries should not be discounted. To this author's knowledge, no investigations have examined how asymmetries in joint stiffness may affect asymmetries in vertical stiffness.

Ankle stiffness contributes strongly to summative leg stiffness during tasks where minimal joint or centre of mass displacement is desired, for example, during cyclic bilateral hopping (Farley et al., 1998; Farley & Morgenroth, 1999; Kuitunen et al., 2011; Kim et al., 2013) and drop jumping (Arampatzis et al., 2001b). It is likely that this relationship also holds true for CODS given the findings of Pruyn et al. (2014)

- previously discussed - and Marshall et al. (2014). Marshall et al. (2014) did not examine ankle stiffness directly, but correlated ankle power ($r = 0.77$; $P < 0.01$), plantar flexion moment ($r = 0.65$; $P < 0.01$) and ground contact time ($r = -0.48$; $P = 0.01$) with faster CODS test performance. For this reason, stiffness and asymmetries surrounding the ankle joint may be of particular relevance to CODS. Sugiyama et al. (2014) has previously reported that asymmetries in jump performance were positively correlated with symmetry indices for angular velocity ($r = 0.41$; $P < 0.05$) and various parameters of angular displacement ($r = 0.41$ - 0.52; $P < 0.05$) of the ankle. These findings suggest that asymmetries in ankle stiffness may negatively influence performance outcomes and further underline the importance of ankle kinematics during performance tasks which require an effective contribution from the stretch shortening cycle.

In summary, variables pertaining to musculoskeletal stiffness have been linked to CODS performance. Force-related and kinematic asymmetries have been linked to impaired performance outcomes, but this has not been evaluated in regards to CODS. The primary aim of Study 3 was therefore to establish if vertical stiffness and vertical stiffness asymmetry influenced CODS. It was hypothesised that vertical stiffness would be significantly and positively correlated to CODS performance (i.e. greater stiffness would be associated with faster performances). It was also hypothesised that the symmetry angle of vertical stiffness would be significantly and negatively correlated to CODS performance (i.e. greater asymmetries would be associated with slower performances).

The secondary aim of Study 3 was to establish the determinants of bilateral asymmetry in vertical stiffness. It was hypothesised that regression analyses would reveal ankle stiffness symmetry angle to be the strongest predictor of vertical stiffness symmetry angle.

5.3 Method

5.3.1 Experimental overview

Study 3 was a randomised and counterbalanced experiment designed to determine the influence of vertical stiffness and vertical stiffness asymmetry on CODS. Following a familiarisation session, participants performed a unilateral drop jump task to assess the vertical and joint stiffness of each limb. Participants then completed a CODS test consisting of two 90° cuts; this was performed in both clockwise and anti-clockwise directions to obtain CODS performance for each limb.

5.3.2 Participants

Eighteen healthy males (age: 22 ± 4 years; height: 1.80 ± 0.08 m; body mass: 81.7 ± 14.9 kg) volunteered to participate in the study. A minimum sample size of eighteen participants was determined from *a priori* power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon an estimated squared multiple correlation of 0.45 (Delaney et al., 2015), 12 likely predictor variables (jump height, ground contact time, vertical, ankle, knee and hip stiffness, together with the asymmetries for these variables) and a power of 0.8 (Beck, 2013). Participants were recreationally active (undertaking ≥ 2.5 hours of physical activity per week), reported no previous (within the last 12 months) or present lower limb injury and provided informed consent (Appendix A1) to participate in the study. Full ethical approval was granted by the review board of the Institute for Physical Activity Research, University of Bedfordshire (Appendix A1) and all procedures were conducted in accordance with the Declaration of Helsinki.

5.3.3 Experimental trials

A familiarisation session - a complete simulation of the experimental trial outlined below - was performed seven days prior to the experimental trial. Study 1, which examined the reliability of the unilateral drop jump, was conducted within the same experimental cohort and had indicated that a single familiarisation session was appropriate for unilateral drop jump testing. Pilot testing indicated that this was also appropriate for the CODS test.

All trials were conducted at the same time of day (10:00 - 12:00) for each participant, to alleviate the effects of circadian rhythms. The testing laboratory was controlled at an ambient temperature of 25°C. Participants were instructed to prepare for testing as they would for training. The execution of each experimental trial was monitored by a United Kingdom Strength and Conditioning Association accredited strength and conditioning coach to ensure for consistency of technique.

5.3.4 Warm-up

All participants completed the same warm-up procedure outlined in Study 1 (Section 3.3.2.3; Table 3.5). The warm-up procedure consisted of 15 dynamic exercises progressing from low to high intensities and from generic to specific movement patterns. A recovery period of 180 seconds was prescribed between the termination of the warm-up and commencement of the testing protocol.

5.3.5 Drop jump testing

In a counterbalanced order, participants performed three, unshod unilateral drop jumps for each limb on a force plate system (Kistler 9281, Kistler Instruments, Winterthur, Switzerland). The procedure for the unilateral drop jumps has been described in detail in Chapter 3 (Section 3.3.2.5). Drop jumps were performed from

a height of 0.18 m and participants instructed to minimise ground contact time during the landing phase. Repetitions were separated by 60 seconds to facilitate recovery (Read & Cisar, 2001).

<u>5.3.6 Kinematic analysis</u>

Drop jumping trials were recorded in the sagittal plane using a high-speed video camera (Quintic High-Speed LIVE USB 2, Quintic Consultancy Ltd., Coventry, United Kingdom) recording at 100 Hz. Relative to the force plate, the camera was orientated perpendicular to the anterior-posterior axis, centralised and positioned at a distance of 3.3 m. The camera was mounted on a tripod and set at the height of the participants' knee marker when standing on the box. Reflective joint markers were placed on the distal head of the fifth metatarsal bone (toe), distal aspect of the lateral malleolus (ankle), lateral collateral ligament of the knee at the tibiofemoral gap (knee), greater trochanter (hip) and anterolateral point of 11th rib (torso) on both the left and right sides of the body; the distance between the ankle and hip was used to represent participant's leg length and was used to calibrate each video recording. Unilateral drop jumps on the left limb were recorded with the participants' left side of the body facing the camera; unilateral drop jumps on the right limb were recorded with the participants' right side of the body facing the camera. Video recordings were automatically digitised using manufacturer provided software (Quintic Biomechanics v21, Quintic Consultancy Ltd., Coventry, United Kingdom). Kinematic data were filtered using a Butterworth fourth-order zero-lag filter (cut-off frequency 20 Hz). Cut-off frequency was determined by plotting the root-mean squared residuals of the raw data and fitting a linear regression line (Winter, 2009a).

5.3.7 Kinetic analysis

Instants of initial foot contact, take-off and landing were identified from the vertical ground reaction force of each drop jump trial; this was determined as the time-point at which a clear change in force (≥ 10 N from zero) was observed (Lloyd et al., 2009). Force traces were filtered with a low-pass Butterworth filter (cut-off frequency: 50 Hz). Cut-off frequency was determined by plotting the root-mean squared residuals of the raw data and fitting a linear regression line (Winter, 2009a). Inverse dynamics was used to express acceleration, velocity and negative displacement of the centre of mass; this was determined from the vertical force trace as outlined in Section 3.3.2.7 and Appendix A2. In Study 3, the vertical velocity of the hip joint marker at the instant of ground contact was used as the initial value for integration.

Net muscle moments were determined using a rigid linked segment model, anthropomorphic data, and an inverse dynamics analysis using the procedures outlined in Winter (2009b) and detailed in Appendix A2; the linked segment model was created using Dempster's body segment parameter data (Dempster, 1955). Kinetic and kinematic data were synchronised to calculate joint moments at 100 Hz. Synchronisation was achieved using a customised trigger to initiate force plate sampling and simultaneously activate a light-emitting diode (LED) clearly visible on the video recordings.

5.3.8 Drop jump variables

Vertical stiffness was calculated as the ratio of peak vertical ground reaction force (N) relative to the peak negative displacement of the centre of mass displacement (m) during the initial ground contact phase (Farley et al., 1998; Farley & Morgenroth, 1999); this was averaged over the three recorded drop jumps. The

force-displacement correlation coefficient of the landing phase of each trial was required to be ≥ 0.8 in an effort to ensure the efficacy of the spring-mass model (Padua et al., 2005). As vertical stiffness is affected by body size, vertical stiffness values were reported relative to body mass (Farley et al., 1993).

Torsional stiffness of the ankle, knee and hip joints were calculated as the ratio of the change in net muscle moment (N) to joint angular displacement (rad) between the initial ground contact phase and instant of peak angular displacement (Farley et al., 1998; Farley & Morgenroth, 1999); these were averaged over the three recorded drop jumps. Pilot testing indicated that the timing of peak vertical ground reaction forces occurred at the instant of peak joint moments and maximum joint flexions as previously observed by Kuitunen et al. (2011) and that moment-displacement correlation coefficients were ≥ 0.8. However, the phase shift for the moment displacement curve of the hip was > 10% (Figure 5.1). This has been previously specified as exclusion criteria in bilateral hopping trials (Farley et al., 1998) and stiffness of the hip was therefore not calculated in the current study.
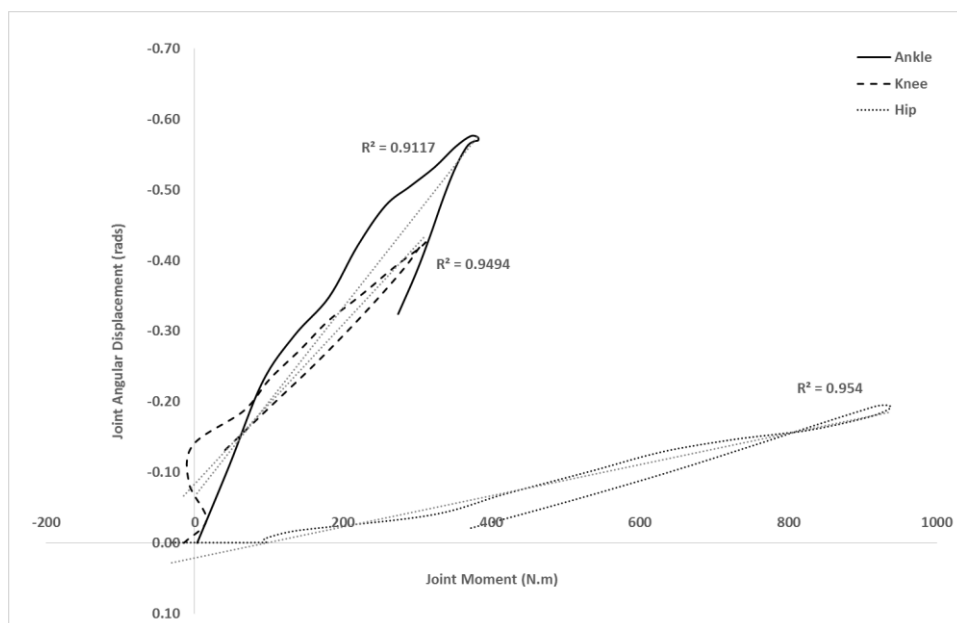

Figure 5.1 - Example moment-displacement curves for the ankle, knee and hip of a single participant.

Jump height was determined using the flight-time method as outlined by Linthorne (2001). Reactive strength index was determined as the ratio of flight time to ground contact time (Newton & Dugan, 2002). Time to peak force was determined as the time difference between the identified instant of initial foot contact and the instant of peak vertical ground reaction force. Overall performance outcomes in the drop jump (vertical stiffness, joint stiffness, jump height, reactive strength index and time to peak force) were obtained by averaging values for the left and right limbs.

5.3.9 Change of direction speed testing

CODS was assessed using a double cut task highlighted in Figure 5.2 and performed in a shod condition using participant's preferred footwear.
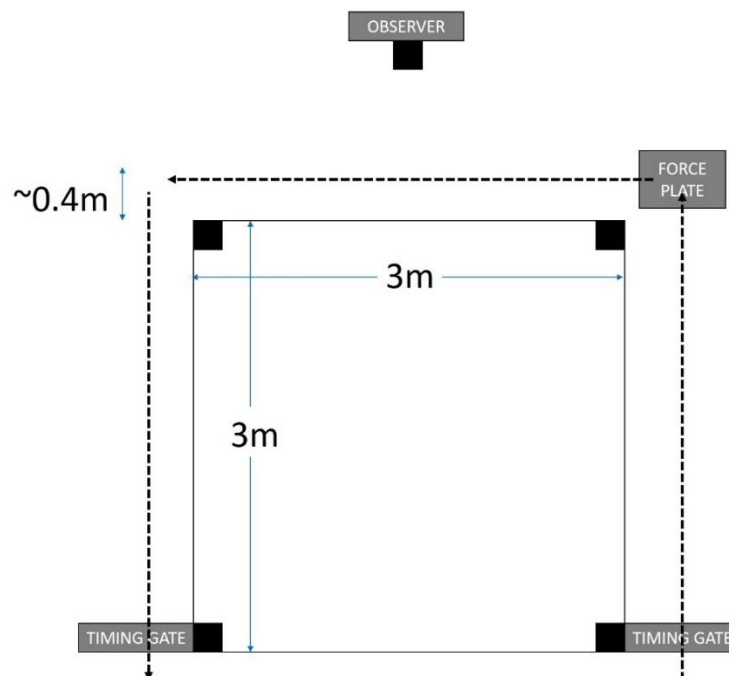

Figure 5.2 - An example of the experimental set-up for the change of direction speed test set up to examine right leg cutting performance, the set-up would be mirrored to examine left leg performance.

Participants were required to perform two 90° cuts in the same direction (clockwise for the left leg trials or anti-clockwise for the right leg trials) during each trial and

were instructed to complete the task "as quickly as possible." Each cut was required to be a definitive power cut performed at a 90° angle and was observed by a United Kingdom Strength and Conditioning Association accredited strength and conditioning coach to ensure for consistency of technique (Figure 5.2). Participants were instructed of the requirements during the familiarisation process. Any deviation from these criteria (i.e. curved approach into the cut) would have resulted in the disqualification of the trial. A distance between the direction changes of 3 m (total distance covered: 9 m) was chosen as this is representative of typical sprint activity profiles in team-sports such as rugby league (Gabbett, 2012) and soccer (Andrzejewski et al., 2013). A cutting angle of 90° was chosen as this is representative of an attacking player attempting to create space and evade defenders in team-sports such as soccer (Bloomfield et al., 2007) and Gaelic games (Marshall et al., 2014).

Performance time was recorded using two sets of timing gates (TC-Timing System, Brower Timings, Utah, USA) (one set to start the clock, one set to stop the clock) set at the height of the participants' anterior superior iliac spine. Participants performed four consecutive trials in one direction before performing four trials in the other direction; the order in which directions were tested was randomised and counterbalanced. Participants' fastest trial in each direction was subsequently analysed; pilot testing (n = 7) indicated that the inter-session coefficient of variation (CV; three sessions) for fastest overall CODS test time was 1.1% (SEM: 0.04 sec; ICC: 0.97). Overall CODS performance was the sum of participants' fastest trials in both directions (best clockwise time + best anticlockwise time). Trials were separated by a recovery duration of 60 seconds.

To obtain ground reaction force data during the CODS test, the first cut was performed with the push-off (outside) foot contacting entirely within the force plate

(Kistler 9281, Kistler Instruments, Winterthur, Switzerland). Data were sampled at 1000 Hz and saved with the use of the manufacturer supplied software (BioWare 3.24, Kistler, Winterthur, Switzerland) for later analysis. Trials were excluded if the participant landed outside the confines of the force plate, this was retrospectively checked using video analysis. Considering all trials, a total of seven were excluded, none of which were a participant's fastest trial.

5.3.10 Intra-session reliability

Intra-session CVs (listed respectively for the stiff and compliant limbs): for vertical stiffness were 5.3% and 6.5%. CVs for centre of mass displacement were 7.2% and 4.3%. CVs for joint stiffness were 1.6% and 2.2% for the ankle, 2.6% and 4.7% for the knee, and 4.1% and 4.9% for the hip, CVs for joint angular displacement were 3.8% and 5.3% for the ankle, 5.5% and 7.0% for the knee, and 10.9% and 11.0% for the hip. Intra-session CVs for the CODS test were 1.9% (SEM: 0.05 sec; ICC: 0.95) and 1.9% (SEM: 0.05 sec; ICC: 0.95) for the clockwise and anti-clockwise directions respectively.

5.3.11 Statistical analysis

Asymmetries were quantified using the symmetry angle, calculated using the procedures outlined by Zifchock et al. (2008). Shapiro-Wilks tests were performed to assess for normality; all variables were considered to be normally distributed given an alpha level of $P > 0.05$. Pair-wise effect sizes (d) (Cohen, 1998) were calculated and interpreted using the thresholds defined by Hopkins (2003) where: <0.20 = trivial, 0.20-0.59 = small, 0.60-1.19 = moderate, 1.20-1.99 = large, and ≥2 = very large. Statistical significance for all analyses was set at an alpha level of $P \leq 0.05$ and all statistical procedures were conducted using the Statistical Package for the Social Sciences for Windows (v21.0; SPSS Inc., Chicago, USA).

Change of direction speed

For the presentation of results, independent variables were grouped into two categories (CODS test variables and drop jump variables) - a total of 32 variables. The dependant variable was overall CODS performance time. The correlation between each variable and overall CODS time was examined using Pearson's r. A forward step-wise regression analysis was performed for overall CODS performance using all independent variables. Analysis of standard residuals showed that the data contained no outliers (std. residual min: -1.53, std. residual max: 1.79). Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (minimum tolerance: 0.86, maximum VIF: 1.16). The data met the assumption of independent errors (Durbin-Watson value: 1.44). For further analysis, performers were median-split into 'fast' (n = 9) and 'slow' (n = 9) groups based upon overall CODS time. One-way analysis of variance (ANOVA) tests were performed to analyse differences between fast and slow groups.

Vertical stiffness asymmetry

Two additional forward step-wise regression analyses were performed, the first to determine the influence of vertical ground reaction force, centre of mass displacement, joint stiffness, joint angular displacement and reactive strength index symmetry angles on the vertical stiffness symmetry angle. The second analysis excluded vertical ground reaction force and centre of mass displacement in an attempt to increase the level of determinism of the model. In regards to the second model, analysis of standard residuals showed that the data contained no outliers (std. residual min: -1.84, std. residual max: 1.24), multicollinearity was not a concern (minimum tolerance: 0.92, maximum VIF: 1.09) and that the data met the assumption of independent errors (Durbin-Watson value: 1.11).

5.4 Results

5.4.1 Determinants of change of direction speed

Table 5.1 - The step-wise regression model for the prediction of change of direction speed test time.

Model	b	SE-b	Beta	t	P
2 (Constant)	6.028	0.247		24.398	<0.001
Vertical stiffness (N.m^{-1}.kg^{-1})	-0.005	0.001	-0.561	-3.316	0.005
Jump height α (%)	2.410	1.043	0.391	2.312	0.035
Dependant variable was change of direction test performance time (sec). Model 2: $r^2 = 0.629$, adjusted $r^2 = 0.580$, $P = 0.001$. *Key*: SE-b = standard error of b, α = symmetry angle.					

A two-variable regression model explained 63% ($r^2 = 0.63$; adjusted $r^2 = 0.58$; $F_{(2,15)}$ = 12.73; P = 0.001) of CODS test performance (Table 5.1). The regression equation is shown in Equation 5.1.

> **Equation 5.1:** CODS test time = 6.028 - 0.005(K_{vert}) + 2.410(DJ α)
>
> Where CODS = change of direction speed, K_{vert} = vertical stiffness, DJ α = drop jump height symmetry angle.

CODS time was predicted by vertical stiffness in the drop jump (Beta = -0.56; P = 0.005) and by drop jump height asymmetry (Beta = 0.39; P = 0.035).

Table 5.2 - The association of drop jump test variables with change of direction speed test performance.

Variable	Fast group (n = 9)	Slow group (n = 9)	Effect size	P Value	Correlation with CODS	P Value
Jump height (m)	0.12 ± 0.05	0.11 ± 0.03	0.25	0.532	-0.319	0.197
Jump height α (%)	2.4 ± 3.9	7.2 ± 3.8	-1.28	0.026*	0.598	0.009**
RSI (flight time / contact time)	1.02 ± 0.22	1.00 ± 0.10	0.13	0.771	-0.337	0.172
RSI α (%)	3.7 ± 3.2	5.0 ± 3.2	-0.41	0.443	0.214	0.395
Ground contact time (sec)	0.298 ± 0.03	0.305 ± 0.02	-0.28	0.586	0.296	0.232
Vertical stiffness (N.m^{-1}.kg^{-1})	176 ± 25	132 ± 25	1.76	0.003*	-0.705	0.001**
Vertical stiffness α (%)	6.6 ± 5.4	5.8 ± 3.3	0.18	0.733	-0.022	0.932
Vertical GRF (N.kg^{-1})	30.32 ± 2.79	28.61 ± 1.55	0.79	0.149	-0.391	0.109
COM displacement (m)	-0.17 ± 0.03	-0.19 ± 0.06	-0.49	0.380	0.035	0.890
Ankle stiffness (N.m^{-1}.rad^{-1})	602 ± 273	488 ± 92	0.62	0.280	-0.008	0.974
Ankle stiffness α (%)	2.8 ± 1.2	3.5 ± 2.0	-0.47	0.379	0.247	0.322
Ankle displacement (rad)	-0.61 ± 0.14	-0.65 ± 0.06	0.40	0.465	0.079	0.757
Knee stiffness (N.m^{-1}.rad^{-1})	2075 ± 576	2195 ± 499	-0.22	0.661	0.044	0.863
Knee stiffness α (%)	2.4 ± 2.0	2.5 ± 1.8	-0.05	0.868	-0.138	0.586
Knee displacement (rad)	-0.49 ± 0.12	-0.46 ± 0.07	0.24	0.652	0.048	0.850
Hip stiffness (N.m^{-1}.rad^{-1})	7808 ± 3338	8444 ± 3553	-0.19	0.716	0.102	0.686
Hip stiffness α (%)	2.8 ± 2.7	3.6 ± 2.6	-0.30	0.585	-0.042	0.869
Hip displacement (rad)	-0.22 ± 0.10	-0.20 ± 0.07	0.22	0.735	0.155	0.539

* indicates significant difference between 'fast' and 'slow' groups (P ≤ 0.01), ** indicates significant correlation with CODS test time (P ≤ 0.01).

Key: CODS = change of direction speed, α = symmetry angle, RSI = reactive strength index, GRF = ground reaction force, COM = centre of mass.

Table 5.3 - The association of CODS test variables with change of direction speed test performance.

Variable	Fast group (n = 9)	Slow group (n = 9)	Effect size	P Value	Correlation with CODS	P Value
CODS performance time (s)	5.18 ± 0.18	5.64 ± 0.14	-2.86	<0.001*		
CODS time α (%)	0.8 ± 1.2	1.2 ± 0.4	-0.50	0.396	0.367	0.134
Ground contact time (s)	0.25 ± 0.04	0.31 ± 0.05	-1.33	0.018*	0.496	0.036**
Ground contact time α (%)	2.2 ± 3.3	3.4 ± 3.2	-0.37	0.472	0.005	0.985
Summed GRF (N.kg^{-1})	46.9 ± 6.4	45.7 ± 5.7	0.20	0.691	-0.116	0.647
Summed GRF α (%)	3.8 ± 2.8	4.5 ± 3.3	-0.23	0.661	0.470	0.049**
Vertical GRF (N.kg^{-1})	24.2 ± 4.4	24.2 ± 3.8	0.00	0.991	0.001	0.996
Vertical GRF α (%)	5.8 ± 4.1	6.6 ± 5.4	-0.17	0.743	0.315	0.203
Vertical GRF / Total GRF (%)	51.1 ± 2.8	52.5 ± 3.1	-0.47	0.337	0.236	0.345
Med-Lat GRF (N.kg^{-1})	11.0 ± 1.4	10.4 ± 1.8	0.38	0.459	-0.100	0.692
Med-Lat GRF α (%)	2.5 ± 1.0	4.2 ± 2.7	-0.92	0.117	0.347	0.159
Med-Lat GRF / Total GRF (%)	23.6 ± 1.1	22.9 ± 2.7	0.37	0.504	0.020	0.938
Ant-Post GRF (N.kg^{-1})	11.8 ± 1.3	11.1 ± 1.4	0.52	0.352	-0.391	0.109
Ant-Post GRF α (%)	4.9 ± 4.0	4.1 ± 2.3	0.19	0.623	0.136	0.589
Ant-Post GRF / Total GRF (%)	25.3 ± 2.3	24.5 ± 2.4	0.34	0.522	-0.325	0.188
* indicates significant difference between 'fast' and 'slow' groups ($P \leq 0.05$), ** indicates significant correlation with CODS test time ($P \leq 0.05$). *Key*: CODS = change of direction speed, α = symmetry angle, GRF = ground reaction force, med-lat = medio-lateral, ant-post = anterior-posterior.						

5.4.2 Drop jump variables and change of direction speed

Drop jump height was negatively correlated with CODS test time (r = -0.71; P = 0.001). Drop jump height asymmetry was positively correlated with CODS test time (r = 0.60; P = 0.009). The faster group demonstrated greater vertical stiffness ($F_{(1,15)}$ = 12.40; P = 0.003) and less asymmetry in jump height ($F_{(r=1,15)}$ = 6.02; P = 0.026) during the drop jump (Table 5.2); these effect sizes were 'large' and 'moderate' (vertical stiffness: d = 1.76, jump height asymmetry: d = -1.28). Effect size analyses also revealed a 'moderate' difference in ankle stiffness (P = 0.28; d = 0.62) and vertical ground reaction force relative to body mass (P = 0.15; d = 0.79).

5.4.3 Change of direction speed test variables

Performance times in the CODS test were significantly different between fast and slow groups ($F_{(1,15)}$ = 32.02; P < 0.001) and associated with a 'very large' effect size (d = -2.86) (Table 5.3). The faster group also displayed shorter ground contact times during the test ($F_{(1,15)}$ = 6.98; P = 0.018), this was associated with a 'large' effect size (d = -1.33). Ground contact time correlated significantly with performance time (r = 0.50; P = 0.036). In regards to force application, asymmetry in summed ground reaction force correlated with performance time (r = 0.47; P = 0.049), but between-group differences were not significant and the effect size was 'small' (d = -0.23; P = 0.66). A 'moderate' between-group effect size (d = -0.92) was observed for asymmetry in medio-lateral ground reaction force, although differences were not significant (P = 0.12) and did not correlate to performance time (r = 0.35; P = 0.16).

5.4.4 Determinants of vertical stiffness asymmetry

A model including centre of mass displacement and vertical ground reaction force explained 99% of vertical stiffness asymmetry (Equation 5.2; $r^2 = 0.99$; adjusted $r^2 = 0.99$; $F_{(1,15)} = 638.36$; $P < 0.001$).

Equation 5.2: K_{vert} α = 0.000 - 0.980(COM α) + 0.850(vGRF α)

Where K_{vert} α = vertical stiffness symmetry angle, COM α = centre of mass displacement symmetry angle, vGRF α = vertical ground reaction force symmetry angle.

A model including centre of mass displacement alone explained 90% of vertical stiffness asymmetry ($r^2 = 0.90$; adjusted $r^2 = 0.90$; $F_{(1,15)} = 147.17$; $P < 0.001$).

Table 5.4 - Results of the step-wise regression analysis for vertical stiffness symmetry angle.

Model		b	SE-b	Beta	*t*	*P*
2	(Constant)	-0.008	0.009		-0.914	0.375
	K_{ankle} α (%)	1.299	0.263	0.617	4.939	<0.001
	RSI α (%)	0.633	0.164	0.481	3.851	0.002
Dependant variable was vertical stiffness symmetry angle (%).						
Model 2: $r^2 = 0.79$, adjusted $r^2 = 0.76$, $P < 0.001$.						
Key: SE-b = standard error of b, K_{ankle} = ankle stiffness, α = symmetry angle, RSI = reactive strength index.						

When centre of mass displacement and vertical ground reaction force were excluded, regression analyses revealed that a model including ankle stiffness and reactive strength index symmetry angles explained 79% of the variance in vertical stiffness asymmetry angle ($r^2 = 0.79$; adjusted $r^2 = 0.76$; $F_{(1,15)} = 27.41$; $P < 0.001$) (Table 5.4; Equation 5.3).

Equation 5.3: K_{vert} α = -0.008 + 1.299(K_{ankle} α) + 0.633(RSI α)

Where K_{vert} α = vertical stiffness symmetry angle, K_{ankle} α = ankle stiffness symmetry angle, RSI α = reactive strength index symmetry angle.

5.4.5 Stiff versus compliant limbs

Table 5.5 - Differences in kinetic and kinematic variables between the stiff and compliant limbs during unilateral drop jumping.

	Stiff limb	Compliant limb	t_{17}	d	P
Stiffness					
Vertical stiffness (N.m.kg^{-1})	190 ± 52	156 ± 44	5.49	0.70	<0.001*
Ankle stiffness (N.m.rad^{-1})	564 ± 230	526 ± 194	2.68	0.18	0.016*
Knee stiffness (N.m.rad^{-1})	2171 ± 539	2099 ± 559	1.65	0.13	0.188
Forces / moments					
vGRF (N.kg^{-1})	29.44 ± 2.68	28.77 ± 2.58	1.27	0.25	0.222
Ankle moment (N.m.kg^{-1})	4.04 ± 0.69	3.94 ± 0.95	0.43	0.11	0.670
Knee moment (N.m.kg^{-1})	12.40 ± 2.24	12.01 ± 3.47	0.55	0.14	0.591
Hip moment (N.m.kg^{-1})	18.19 ± 7.59	19.71 ± 7.97	-0.78	-0.20	0.449
Displacement					
D_{COM} (m)	0.17 ± 0.05	0.19 ± 0.05	-2.19	-0.36	0.043*
Ankle displacement (rad)	0.63 ± 0.11	0.61 ± 0.15	0.42	0.11	0.677
Knee displacement (rad)	0.48 ± 0.10	0.47 ± 0.13	0.13	0.03	0.899
Hip displacement (rad)	0.20 ± 0.08	0.22 ± 0.10	-1.43	-0.27	0.170
Temporal					
RSI (flight time / GCT)	1.030 ± 0.198	1.001 ± 0.193	1.73	0.34	0.259
GCT (s)	0.297 ± 0.029	0.301 ± 0.035	-5.13	-0.14	0.616
Time to peak force (s)	0.151 ± 0.036	0.155 ± 0.039	-1.17	-0.19	0.102

* indicates a significant difference between stiff and compliant limbs ($P < 0.05$).

Key: vGRF = vertical ground reaction force, D_{COM} = centre of mass displacement, RSI = reactive strength index, GCT = ground contact time.

Vertical stiffness was significantly different between the stiff and compliant limbs, such that an asymmetry percentage of 17.8% was observed in the compliant limb and associated with a 'moderate' effect size (Table 5.5). An asymmetry percentage of 6.8% was observed for ankle stiffness although the effect size was 'trivial'. Centre of mass displacement was an average of 9.4% greater in the compliant

limb; the effect size between limbs was 'small'. No other significant differences were observed between the stiff and compliant limbs, although differences in vertical ground reaction force, angular hip displacement and reactive strength index were associated with 'small' effect sizes.

5.5 Discussion

The primary aim of Study 3 was to establish if vertical stiffness and vertical stiffness asymmetry influenced CODS. It was hypothesised that vertical stiffness would be significantly and positively correlated to CODS performance (i.e. greater stiffness would be associated with faster performances). This hypothesis is accepted as vertical stiffness was the strongest predictor of CODS in the regression model. It was also hypothesised that the symmetry angle of vertical stiffness would be significantly and negatively correlated to CODS performance (i.e. greater asymmetries would be associated with slower performances). This hypothesis is rejected as vertical stiffness asymmetry angle was not associated with CODS. A secondary aim of the current study was to ascertain the determinants of vertical stiffness asymmetry; it was hypothesised that ankle stiffness asymmetries would determine vertical stiffness asymmetries. This hypothesis is accepted as regression analyses demonstrated that ankle stiffness symmetry angle was the strongest predictor of vertical stiffness symmetry angle.

Mean vertical stiffness and asymmetry in jump height, both determined during a unilateral drop jump test, were the strongest predictors of the time taken to complete the CODS test employed in Study 3. As such, whilst vertical stiffness asymmetry was not a predictor of performance, both vertical stiffness and asymmetry (drop jump height) were strongly associated with CODS as separate entities. Vertical stiffness was the strongest predictor of CODS according to the regression model, greater vertical stiffness led to quicker performance times. Between-group analyses also revealed a 'large' and significant difference between fast and slow groups such that faster athletes exhibited greater vertical stiffness. However, it is important to acknowledge the limitations inherent with regression and correlation analyses. This study is unable to demonstrate a cause and effect

relationship between vertical stiffness and CODS as a consequence. The mechanisms which may explain this relationship must therefore be explored. Also, it is important to note that the current study cannot differentiate between the linear acceleration/deceleration and turning components within the CODS test itself. For example, approach and exit speeds into the turn were not measured. It therefore cannot be determined if faster performances are a consequence of faster linear accelerations, faster cuts or a combination of these factors. Nonetheless, vertical stiffness is correlated with linear acceleration (i.e. $r = 0.8$; $P < 0.01$ (Chelly & Denis, 2001) and would therefore positively influence both components of the CODS test. It is also the overall performance time that is of greatest importance to the athlete and would be therefore be the primary target of any intervention.

Pruyn et al. (2014) had previously examined the potential relationship between stiffness and CODS, although employed a unilateral hopping task which may not represent the acyclic, ballistic nature of CODS tasks. Contrary to the results of the current study, Pruyn et al. (2014) reported that vertical stiffness was not correlated to CODS and that performance times of median-split stiff and compliant groups were not different. The reduced homogeneity of the population sample in the current study in comparison to that of Pruyn et al. (2014) (highly trained female netballers) may explain this discordance in results. Intuitively, it would seem likely that athletes exhibiting greater vertical stiffness during the drop jump would exhibit greater leg stiffness during a change of direction, although this cannot be definitively concluded from this study. The current study does report that faster athletes displayed shorter ground contact times than slower performers ($P = 0.018$; $d = -1.33$), in line with the results of previous investigations (Sasaki et al., 2011; Marshall et al., 2014). This is likely to be indicative of greater leg stiffness during

the change of direction (Arampatzis et al., 2001a; 2001b) and would suggest a greater level of change of direction ability within these athletes.

Whilst the unilateral drop jump provides a reliable measure of vertical stiffness, it must be recognised that this task does not impose the medio-lateral and anterior-posterior demands present during a change of direction. It also clear that the CODS test imposes greater ground reaction forces on the lower limb at ground contact. Greater ground reaction forces may be expected to increase joint angular displacements, potentially increasing the demands placed upon the knee (versus the ankle) joint (Kuitunen et al., 2011). Nonetheless, the unilateral drop jump is a maximal, acyclic and unilateral task that describes resistance to deformation in the presence of high-force. These are key characteristics shared with changes of direction (Glaister et al., 2008; Spiteri et al., 2013). Ground contact times between the two tasks are also similar (unilateral drop jump: ~0.31 sec, CODS test: 0.28 sec). Moreover, the stiffness of the muscle-tendon unit would not be dependent upon the vector of force application (i.e. Butler et al., 2003). Future research should seek to directly examine leg stiffness during changes of direction in order to better provide greater depth to explain the relationship between stiffness and CODS, the absence of a three-dimensional motion capture system precluded such measurements to be used in this thesis. However, the use of such equipment in unlikely to be viable in an athletic training environment given the monetary cost, expertise requirement and the time required for set-up and analysis. It is important to state that the current study demonstrates the unilateral drop jump to provide a test with high logistical value and that may be realistically administered within the athletic training environment.

Regression analyses revealed that asymmetry in unilateral drop jump height was the second strongest predictor of CODS performance time such that lesser

asymmetries were associated with quicker times. Between-group analyses also indicated a 'large' and significant difference between median-split fast and slow performers. Whilst previous investigations have associated asymmetries in force-related parameters with impaired athletic performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), the relationship between asymmetry and CODS is not clear. Two investigations have noted reductions in CODS performance where an eccentric strength asymmetry is apparent (Chaouachi et al., 2012; Lockie et al., 2012); eccentric strength is likely to underpin an athlete's ability to effectively utilise the stretch shortening cycle during movements such as a drop jump or a change of direction where minimal joint displacement may be desired (Cormie et al., 2010). Given the association of eccentric strength in modulating stiffness (Lindstedt et al., 2001) it is perhaps surprising that asymmetries in vertical stiffness did not influence CODS performance in a similar manner. As the investigations by Chaouachi et al. (2012) and Lockie et al. (2012) were conducted in elite Tunisian soccer players and strength trained team-sport athletes, respectively, it is possible the effects of asymmetries are modulated by the athletic background of the participant population sampled. As will be discussed, a similar effect has been reported by Bazyler et al. (2014) in relation to force asymmetry.

Lockie et al. (2014) examined the relationship between multi-planar unilateral jumping performance and CODS in well-trained, multidirectional team-sport athletes. Lockie et al. (2014) noted asymmetries of 10.4% (± 10.8%), 3.3% (± 3.0%) and 5.1% (± 3.9%) in vertical, horizontal and lateral jump performance respectively, but reported that these asymmetries were not related to 5-0-5 or T-test performance. Previously, Hoffman et al. (2007) had also reported that asymmetries in unilateral vertical jump power of 9.7% (± 6.9%) were not associated

with reductions in CODS performance (3-cone drill) in collegiate American footballers. In neither of these studies do the investigators' data permit the calculation of a symmetry angle. The average jump height asymmetry in the current study was 13% (± 12%) when expressed as a symmetry index as in Lockie et al. (2014) and Hoffman et al. (2007), equating to a symmetry angle of 4.3%. The larger asymmetries present in the current population could potentially explain why CODS impairments were observed.

It is also possible that the athletic background of participants could explain why asymmetry was detrimental to CODS in this instance. Lockie et al. (2014) hypothesised that more skilled performers may be better able to initiate technical adjustments in response to strength or power asymmetries than recreationally trained participants such as those sampled in the current study. However, investigations have not considered whether technical factors, such as foot placement and stride adjustment, may contribute to CODS asymmetries. In the current study, the direction of asymmetries in drop jump variables did not correspond well with the direction of asymmetry in the CODS test. It is therefore conceivable that the observed association between asymmetry and CODS performance is purely indicative of participants' current athletic ability or training status. Indeed, Bazyler et al. (2014) reported that asymmetries are likely to be greater in weaker individuals. Across a seven-week bilateral training programme, Bazyler et al. (2014) also noted that as strength increased there was a concomitant decrease in asymmetry in weaker individuals. Future investigations should seek to determine whether asymmetries in the variables highlighted in the current study are associated with CODS in an athletic population. Investigators should also consider the role of technical factors and their potential contribution to asymmetries.

In addition to the asymmetries in jump height observed during the drop jump test, the results of the current study suggest that asymmetries in the application of force during the CODS test may also be linked to performance time. Most notably, asymmetries in summed ground reaction force were linked to impaired performance. Condello et al. (2016) similarly reported between-limb differences in ground reaction forces, although reported no difference in ground contact time (no overall 'performance' time was recorded). If greater forces, relative to body mass, can be applied to the ground without negatively affecting ground contact time then this is likely to be beneficial to CODS performance due to the necessary impulse required to change direction being generated quicker. Between-group differences in the current study also suggested that slower performers exhibited 'moderately' greater asymmetry in medio-lateral ground reaction force, however, this variable did not directly correlate to performance time. The amount of force expressed in the medio-lateral direction (i.e. the direction of intended travel) is most likely to result in improved CODS performance (Shimokochi et al., 2013) and would appear to be an important variable. Nonetheless, the current study did not observe notable correlations or inter-group differences in CODS test force profiles when these asymmetries were not considered.

Reactive strength index is a quality purported to be closely linked to vertical stiffness as greater vertical stiffness should facilitate shorter ground contact times and improved reactive strength index scores (Arampatzis et al., 2001b; Bret et al., 2002). Whilst previous investigations had reported significant correlations ($r = -0.44$ - -0.65) between reactive strength index and CODS performance in athletic populations (Young et al., 2002; Delaney et al., 2015; Young et al., 2015), the current study did not observe this relationship to be significant in recreationally trained individuals. It should also be noted that the current study examined CODS

performance using a task employing two 90° cuts and that the cutting angle is not consistent between investigations. Young et al. (2002) tested over three different cutting angles (20°, 40°, and 60°) with the investigators' results suggesting that the strength of the correlation reduced as cutting angle increased (r = -0.65, -0.53 and -0.35, respectively), although Young et al. (2002) reported a stronger correlation when the number of direction changes was increased (four consecutive 60° cuts: r = -0.54). Sharper direction changes are associated with longer ground contact times (Condello et al., 2016), so it is possible that the influence of reactive strength and stiffness is slightly diminished as the cutting angle increases. As Young et al. (2015) also used a shallower cutting angle (45°), this could contribute to the discrepancies observed within the current study. In contrast, Delaney et al. (2015) employed a sharp 180° change of direction (5-0-5 CODS test) which may be associated with a different kinematic profile versus a 90° cut - such as a deeper squat into the turn and pronounced heel contact (Hewit et al., 2012) - which are likely to impose different demands on the leg-spring. Importantly, vertical stiffness was not assessed in the aforementioned investigations (Young et al., 2002; Delaney et al., 2015; Young et al., 2015), further emphasising the novelty of the current study. The effect of cutting angle on the relationship between ankle and knee stiffness has not been explored and would prove an interesting area for future investigation. It would be anticipated that the influence of knee stiffness would increase in response to larger cutting angles given that longer contact times and greater angular displacements would increase the reliance on active force generation (Kuitunen et al., 2011). However, it is important to state that shorter ground contact times, regardless of task, are strongly related to performance. For example, Sasaki et al. (2011) examined a 180° task and Marshall et al. (2014) a 75° task. Stiffer systems are likely to transfer force more efficiently (Bret et al., 2002) and reduce ground contact times (Arampatzis et al., 2001b).

It is also clear that parameters such as vertical stiffness and ground contact time would be affected by the shoe-surface interaction (i.e. Ferris & Farley, 1997). Athletes would be expected to increase stiffness of the lower limb on a more compliant surface and reduce stiffness on a stiffer surface in order to maintain total stiffness of the body/surface interface (Ferris & Farley, 1997). Such adjustments can be made in a single step and allow the body to minimise changes in centre of mass displacement (Ferris et al., 1999). The extent to which CODS variables may differ between a stiffer indoor surface and a more compliant grass surface warrants specific investigation. As the current study sought to replicate movement patterns associated with field-based sport, the use of an indoor surface must be acknowledged as a limitation but balanced by the indoor environment allowing greater control of confounding variables such as surface stiffness. In the current study, participants performed the test on the same surface and used the same footwear in each trial to ensure the body/surface interaction remained consistent.

Vertical stiffness is a function of vertical ground reaction force and centre of mass displacement (Farley et al., 1998; Farley & Morgenroth, 1999), therefore asymmetries in either of these variables could influence asymmetries in vertical stiffness. In line with the findings of Study 2, Study 3 reports that asymmetries in vertical stiffness are determined by asymmetries in centre of mass displacement ($r^2 = 0.90$). However, centre of mass displacement is a global representation of how the leg-spring deforms in response to ground reaction force (Butler et al., 2003), and does not consider the respective contribution of individual joints or 'springs' (Pearson & McMahon, 2012). It is therefore important to determine if a particular joint/s is responsible for dictating vertical stiffness asymmetries as this could influence the design of subsequent exercise interventions.

Simulation models had previously determined that vertical stiffness was regulated by ankle stiffness and not by knee stiffness (Farley et al., 1998; Farley & Morgenroth, 1999). This position has been supported in hopping investigations by Kuitunen et al. (2011) and Kim et al. (2013), and in drop jumping by Arampatzis et al. (2001). Given these observations it is not surprising that asymmetries in vertical stiffness appear to be predicted by asymmetries in ankle stiffness within this thesis. In a fixed system with multiple springs, the least stiff joint would be expected to undergo the greatest angular displacement in response to a given force (Farley et al., 1998; Kuitunen et al., 2011). During the unilateral drop jump task performed in Study 3, the ankle was the least stiff spring within the system and underwent the greatest angular displacement. The results of the current study support the notion that the least stiff joint will have the greatest influence on the overall stiffness of the leg-spring system (Kuitunen et al., 2011) and, perhaps, bilateral asymmetries therein.

Adjustments in knee stiffness appear important in optimising torque output rather than in the modulation of vertical stiffness (Kuitunen et al., 2011); the anatomy of the knee extensors in relation to the plantar flexors facilitates greater moments at the knee versus the ankle (Alexander & Ker, 1990). Comparisons between the fast and slow groups (Table 5.3) suggest a potential reliance on different movement strategies during the drop jump; the fast group exhibit 'moderately' greater ankle stiffness but lower values for knee and hip stiffness. In line with the findings of Bobbert et al. (1987) this could infer that faster performers are utilising a more reactive 'bounce' drop jump strategy whereas slower performers are utilising something closer to a 'countermovement' drop jump strategy. These differences in ankle stiffness may ultimately explain the differences in CODS performance.

In the investigation by Pruyn et al. (2014), stiffness of the medial gastrocnemius and soleus, determined by quasi-isometric myometry, was shown to differentiate fast and slower performers where vertical stiffness did not. Marshall et al. (2014) also observed a significant correlation plantar flexor moment at the ankle ($r = -0.65$) and ankle power ($r = -0.77$) with the time to complete a lateral cutting task. These results suggest that stiffness around the ankle may contribute to CODS although this was not examined directly in either investigation. The current study reports a 'moderate' between-group difference in ankle stiffness and 'small' difference in ankle stiffness asymmetry such that faster performers had stiffer ankles and displayed less asymmetry. However, correlations with CODS performance time were not observed. Whilst ankle stiffness is no doubt important during a change of direction, particularly given its likely governance of vertical stiffness (Farley et al., 1998; Farley & Morgenroth, 1999; Arampatzis et al., 2001b; Kuitunen et al., 2011; Kim et al., 2013), it appears that this is not an important determinant of CODS performance in its own right, at least when evaluated in a drop jump task. As previously discussed, it is possible that the increased ground reaction forces associated with the change of direction increased the relative important of stiffness at the knee joint as a consequence (Kuitunen et al., 2011). The current study suggests that summative stiffness of the leg may be more important to CODS than the stiffness of any individual joint, but future investigations should seek to examine joint stiffness during the CODS task directly. A three-dimensional motion analysis of the CODS test would demonstrate how additional kinematic factors (i.e. pelvic lateral tilt and thorax rotation (Marshall et al., 2014) influence and interact with stiffness variables and CODS performance.

5.6 Conclusion

In conclusion, mean vertical stiffness and jump height asymmetry, both determined during a unilateral drop jump, were the strongest predictors of CODS in recreationally trained males. The unilateral drop jump test may provide coaches and practitioners with a tool to not only assess an individual's stiffness profile, but also to quantify specific factors linked to CODS. However, the efficacy of this tool should be further evaluated in athletic populations. This assessment may be used to inform the training process and evaluate the impact of specific exercise interventions, although further research is required to determine if the modulation of these factors through training may improve CODS.

5.7 Implications for the thesis

The results of Study 3 demonstrated that vertical stiffness was the strongest predictor of CODS. This was the first study to report a relationship between stiffness variables and CODS. It is therefore hypothesised that interventions designed to augment vertical stiffness would improve CODS as a consequence of reducing ground contact time. This hypothesis was to be evaluated in Study 4.

Study 3 was the first study to evaluate determinants of vertical stiffness asymmetry, reporting that ankle stiffness symmetry angle was the strongest predictor of vertical stiffness symmetry angle. Less asymmetry in ankle stiffness was also observed in faster performers. In Study 4 it was to be explored whether vertical stiffness asymmetries are reduced in response to the stiffness intervention and whether this directly modulates the effect of the intervention on CODS. As a result of the findings of Study 3, the protocols used as part of the intervention in Study 4 sought to augment vertical stiffness with a particular focus on stiffness at the ankle joint.

Chapter 6 - Acute Stiffness Interventions and Change of Direction Speed

6.1 Overview

The primary purpose of this chapter was to establish if acute exercise interventions designed to augment vertical stiffness would improve change of direction speed (CODS). Were it to be determined that such interventions could impact performance this could influence the performance preparation strategies of athletes, coaches and applied practitioners.

The secondary purpose of this chapter was to establish if the effects of the intervention on CODS was linked to the modulation of vertical stiffness and stiffness asymmetries. For this reason, this chapter sought to evaluate bilateral and unilateral focused interventions.

The chapter will report the results of the following:

Study 4: The acute effects of bilateral and unilateral stiffness interventions on change of direction speed.

6.2 Introduction

The importance of CODS in athletic performance is well established (Reilly et al., 2000; Meir et al., 2001; Keogh et al., 2003; Sturgess & Newton, 2008; McGill et al., 2012) and has been previously discussed in Section 2.10; interventions designed to improve CODS are therefore likely to carry a beneficial effect to performance. Acute pre-conditioning interventions employing heavy resistance exercise (Zois et al., 2011) and loaded ballistic exercise (i.e. weight vest loaded warm-up) (Maloney et al., 2014b; Nava, 2015) have been demonstrated to favourably affect CODS although the reasons behind these performance enhancements are yet to be elucidated.

Considering ballistic exercise as the pre-conditioning stimulus, plyometric exercises emphasising the development of high levels of musculoskeletal stiffness may carry the greatest benefit to performance (Maloney et al., 2014a). Explanations of the post-activation potentiation effect tend to focus on physiological (such as the phosphorylation of myosin regulatory light chains (Sweeney et al., 1993) and increases in pennation angle (Mahlfeld et al., 2004)) and neural (such as the recruitment of higher order motor units (Gullich & Schmidtbleicher, 1996)) factors. Augmentations in any of these parameters would be expected to increase the rate of force development within skeletal muscle (Maloney et al., 2014a) and therefore benefit CODS performance. However, it is also important to consider the potential role of acute modulations in stiffness (Maloney et al., 2014a). Heavy resistance exercise has been shown to augment vertical stiffness in studies by Comyns et al. (2007) and Moir et al. (2011), the investigators noting increases of 10.9% ($P < 0.05$) and 16% ($P = 0.013$; d: 0.52) respectively. A weight vest loaded dynamic warm-up has also been demonstrated to augment vertical stiffness by 20% (d: 0.76; 90% confidence interval: ± 4%)

during a plyometric jumping task (Barnes et al., 2015). The modified deterministic model of CODS (Figure 6.1, discussed in Section 2.10) highlights the role of stiffness as a physical quality which not only allows efficient transmission of the generated impulse, but also its role in facilitating shorter ground contact times. Study 3 lends weight to this theory as it demonstrated that faster performers exhibited greater vertical and ankle stiffness during drop jumping along with shorter ground contact times during the CODS test. Given the importance of stiffness in maximising CODS, particularly at the ankle joint, it is possible that the performance improvements observed following pre-conditioning interventions are related to augmentations in stiffness, however, such propositions must be examined directly.
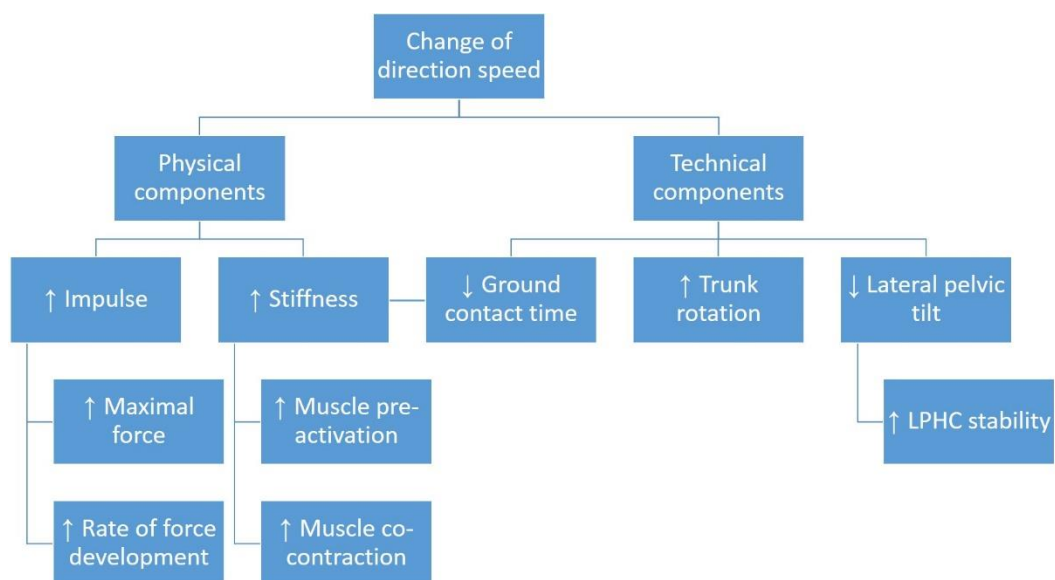
Figure 6.1 - The modified deterministic model of change of direction speed. Key: LPHC = lumbo-pelvic hip complex.

Asymmetries in force-related properties have been linked to impaired performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), discussed in detail in Section 2.7. However, the literature had not previously investigated the effects of asymmetries in stiffness. Study 3 demonstrated that faster performers (symmetry angle: 2.4 ± 3.9%) exhibited

significantly less asymmetry in drop jump height than slower performers (7.2 ± 3.8 %) and reported a significant correlation ($r = 0.60$; $P < 0.01$) for this variable with CODS performance. Investigations by Lockie et al. (2014) and Hoffman et al. (2007) had previously reported that asymmetries in jump performance were not associated with impairments in CODS performance, although the asymmetry observed in Study 3 (asymmetry percentage: 13 ± 12%) was greater than reported by the previous investigations (Lockie et al. (2014): 10.4 ± 10.8%, Hoffman et al. (2007): 9.7 ± 6.9%). Effect size comparisons within Study 3 also revealed that asymmetries in ankle stiffness ($d = -0.47$), although not vertical stiffness, were lower in faster performers.

It has been reported that asymmetries are likely to be linked to training status, weaker athletes demonstrating greater asymmetry during isometric squat testing (Bazyler et al., 2014). Following a seven-week training programme, Bazyler et al. (2014) subsequently observed concomitant reductions in force production asymmetry and increases in maximal force in weak athletes, but in not strong athletes. Whether acute reductions in asymmetry are associated with increased performance has not been investigated, although it has been demonstrated that asymmetry may be acutely reduced in response to exercise. Hodges et al. (2011) reported reductions in vertical ground reaction force asymmetry following a back squat protocol (5 sets of 8 repetitions) in athletes who exhibited an initial asymmetry (>1.7% in set 1). Whilst it is likely that exercise interventions will have a greater impact where pre-intervention asymmetries are more pronounced, discussed further in Section 2.9, it is not known how the modulation of asymmetries may contribute to CODS performance. Moreover, no studies have examined how exercise interventions may modulate stiffness asymmetries.

The findings of Golik-Peric et al. (2011) suggest that unilateral versus bilateral training may differently affect inter-limb asymmetries, also discussed in Section 2.9. Whilst the potential applicability of these findings is limited by the population sampled (individuals were selected because of their asymmetry) and the training modalities employed (unilateral knee extensions versus bilateral half-squats), it does appear that unilateral versus bilateral performances are governed differently. As discussed in Section 2.6, the findings of a number of studies suggest the performance of each limb during bilateral tasks may be more closely regulated by neural mechanisms than during unilateral tasks (Flanagan & Harrison, 2007; Simon & Ferris, 2008; Benjanuvatra et al., 2013). This proposition is supported by the findings of Study 2 with unilateral versus bilateral tasks differently exhibiting stiffness asymmetries. It may appear likely that unilateral and bilateral exercise interventions would differently affect stiffness asymmetries but this is yet to be determined.

Whilst there is no data comparing the effects of acute bilateral and unilateral interventions on CODS, Fisher and Wallin (2014) compared the effects of six-week unilateral and bilateral training interventions on CODS in collegiate rugby players. Incorporating a combination of resistance and plyometric exercises, the investigators observed greater improvements following unilateral training in both T-Test (unilateral: -0.63 ± 0.36 seconds, bilateral: -0.11 ± 0.03 seconds; $P < 0.05$) and Illinois agility test (unilateral: -0.80 ± 0.25 seconds, bilateral: -0.50 ± 0.06 seconds; $P = 0.05$) performances. Fisher and Wallin (2014) highlight that the absence of force production or muscle activation data precluded an explanation of why the unilateral intervention appeared superior. In addition, the authors did not perform any unilateral measures to permit calculations of asymmetry. Whether the greater performance enhancements elicited by the unilateral regimen were

associated with reductions in asymmetry remains an unanswered question. Perhaps more pertinently, whether unilateral interventions are also superior to bilateral interventions when administered acutely is yet to be established.

The primary aim of the Study 4 was to establish if acute exercise interventions designed to augment vertical stiffness influenced CODS. Previous investigations have not sought to determine a mechanistic basis for the acute enhancement of CODS and Study 3 had shown that vertical stiffness was the strongest determinant of CODS. It was hypothesised that both bilateral and unilateral 'stiffness' interventions would significantly improve CODS performance versus a control strategy of additional CODS practice. In addition, it was hypothesised that improvements in performance would be significantly greater following the unilateral intervention than following the bilateral or control interventions.

The secondary aim of Study 4 was to establish if the effects of the intervention on CODS was linked to the modulation of vertical stiffness and vertical stiffness asymmetries. It was hypothesised that the unilateral intervention would increase vertical stiffness and reduce vertical stiffness asymmetry significantly more than the bilateral or control interventions.

6.3 Method

6.3.1 Experimental overview

Study 4 was a repeated measures experiment designed to compare the effects of different pre-conditioning interventions on stiffness, asymmetries and CODS. Following a familiarisation session, participants performed three different 'stiffness' interventions in a randomised and counterbalanced order. The three interventions were a) bilateral-focused (BILATERAL), b) unilateral-focused (UNILATERAL), and c) a control of CODS test practice (CONTROL). Vertical stiffness was determined pre- and post-intervention whilst CODS test performance was assessed post-intervention.

6.3.2 Participants

Fourteen healthy males volunteered to participate in the study. Ten participants completed all three experimental trials (age: 22 ± 2 years; height: 1.78 ± 0.05 m; body mass: 75.1 ± 8.7 kg), four did not complete all three trials due to time commitments. A minimum sample size of nine participants was determined from *a priori* power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon an estimated effect size (*d*) of 0.6 and a power of 0.8 (Beck, 2013). Participants were recreationally active (undertaking ≥ 2.5 hours of physical activity per week), reported no previous (within the last 12 months) or present lower limb injury and provided informed consent to participate in the study. Full ethical approval was granted by the review board of the Institute for Physical Activity Research, University of Bedfordshire and all procedures were conducted in accordance with the Declaration of Helsinki.

6.3.3 Experimental trials

A single familiarisation session was performed seven days prior to the experimental trial. Study 1 had indicated that a single familiarisation session was appropriate for unilateral drop jumping and pilot testing prior to Study 3 indicated that this was also appropriate for the CODS test. During the session, participants were also familiarised with all the warm-up exercises including both the bilateral and unilateral intervention exercises.

An outline of the experimental trials is shown in Figure 6.2. All trials were conducted at the same time of day (09:30 - 12:00) for each participant, to alleviate the effects of circadian rhythms. The testing laboratory was controlled at an ambient temperature of 25°C. Participants were instructed to prepare for testing as they would for training. The execution of each experimental trial was monitored by a United Kingdom Strength and Conditioning Association accredited strength and conditioning coach to ensure for consistency of technique.
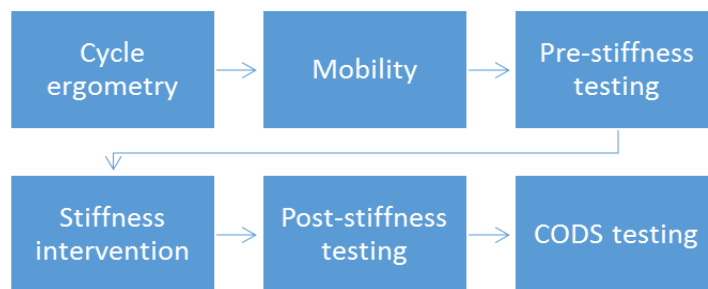
Figure 6.2 - The design of each experimental trial. Key: CODS = change of direction speed.

6.3.4 Warm-up

Participants completed 5 minutes of cycle ergometry at a self-determined power output (135 ± 22 W). During the familiarisation session, participants were instructed to find a cadence and loading which allowed them to achieve a rating of perceived

exertion of 5-7 (0-10 scale), this cadence and loading combination was then employed during the experimental trials. Immediately following the completion of the cycle ergometry, participants performed the exercises from the 'generic movement preparation' section of the warm-up outlined in Section 3.3.2.3 (Table 3.5); this is termed as the 'mobility' component within Figure 6.2.

6.3.5 Stiffness interventions

In a randomised cross-over design, participants completed experimental trials with the bilateral, unilateral and control stiffness interventions outlined in Figure 6.3; trials were separated by no less than six and no more than fourteen days. For the unilateral exercises, the number of prescribed repetitions was performed on both legs. For the bilateral and unilateral exercises, sets and exercises were separated by 60 seconds (Read & Cisar, 2001), in the unilateral intervention there was no recovery between limbs for any of the exercises.

Bilateral intervention (sets x reps)	Unilateral intervention (sets x reps)	Control intervention
• 1x20 'soft' pogo hops • 2x10 'stiff' pogo hops • 1x5 drop jumps (from 0.45 m)	• 1x20 'soft' pogo hops • 2x10 'stiff' pogo hops • 1x5 drop jumps (from 0.18 m)	• 5 circuits of the CODS test in each direction

Figure 6.3 - Exercises performed in each of the three stiffness inventions. Key: CODS = change of direction speed.

Bilateral and unilateral interventions were cued using the same terminology. The 'soft' set of pogo hops was cued to be performed in a "spongy and relaxed" manner. The 'stiff' pogo hops and drop jumps were cued to be performed in a "stiff" manner; participants were instructed to spend as little time in contact with the floor as possible during each jump and cued to imagine the floor as "hot coals". For the control intervention, participants performed circuits of the CODS test. CODS

practice was chosen as the control intervention as this would be more representative of a 'typical' warm-up strategy which would attempt to replicate the types of subsequent activity to be undertaken (McGowan et al., 2015). Circuits of the CODS test were performed alternating between clockwise and anti-clockwise directions, each separated by 60 seconds. Participants were instructed to perform the first circuit at 50% intensity and the subsequent four with maximal effort.

6.3.6 Stiffness testing

Vertical and joint stiffness of the left and right limbs was assessed before and after the stiffness intervention (Figure 6.2) using the unilateral drop jump protocol. These general procedures have been described in detail in Sections 5.3.5 - 5.3.8. Participants performed two unshod drop jumps for each limb at each time point.

Drop jumps were performed from a height of 0.18 m onto a force plate system (Kistler 9281, Kistler Instruments, Winterthur, Switzerland) and were recorded in the sagittal plane using a high-speed video camera (Quintic High-Speed LIVE USB 2, Quintic Consultancy Ltd., Coventry, United Kingdom) at a frame-rate of 100 Hz. Inverse dynamics was used to determine vertical stiffness and joint stiffness of the ankle and knee.

6.3.7 Change of direction speed testing

CODS performance was assessed following each of the stiffness interventions (Figure 6.2) using the double-cut test shown in Figure 6.4 and described in detail in Section 5.3.9.
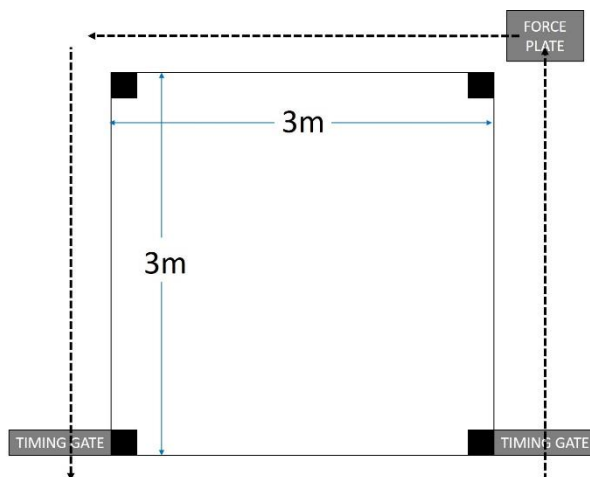
Figure 6.4 - An example of the experimental set-up for the change of direction speed test set up to examine right leg cutting performance, the set-up would be mirrored to examine left leg performance.

Participants were required to perform two 90° cuts in the same direction (clockwise for the left leg trials or anti-clockwise for the right leg trials) during each trial and were instructed to complete the task as quickly as possible. Performance time was recorded using two sets of timing gates (TC-Timing System, Brower Timings, Utah, USA). Participants performed four consecutive trials in one direction before performing four trials in the other direction; the order in which directions were tested was randomised and counterbalanced. Participants' fastest trial in each direction was subsequently analysed. Overall CODS performance was the sum of participants' fastest trials in the clockwise and anticlockwise directions. Trials were separated by a recovery duration of 60 seconds.

To obtain ground reaction force data during the CODS test, the first cut was performed with the push-off (outside) foot contacting entirely within the force plate. Trials were excluded if the participant landed outside the confines of the force plate, this was retrospectively checked using video analysis. All of the participants' fastest trials met these criteria.

6.3.8 Statistical analysis

Asymmetries were quantified using the symmetry angle, calculated using the procedures outlined by Zifchock et al. (2008). As symmetry angle values may be negative or positive to reflect left or right side dominance, negative values were transformed to positive values prior to examining the relationship with performance in order to evaluate differences solely in the magnitude of asymmetry.

Shapiro-Wilks tests were performed to assess for normality; all variables were considered to be normally distributed given an alpha level of $P > 0.05$. Pair-wise effect sizes (d) (Cohen, 1998) were calculated and interpreted using the thresholds defined by Hopkins (2003) where: <0.20 = trivial, 0.20-0.59 = small, 0.60-1.19 = moderate, 1.20-1.99 = large, and ≥ 2 = very large. Statistical significance for all analyses was set at an alpha level of $P \leq 0.05$ and all statistical procedures were conducted using the Statistical Package for the Social Sciences for Windows (v21.0; SPSS Inc., Chicago, USA)

A 3 (condition) x 2 (pre- to post-intervention) repeated measures analysis of variance (ANOVA) was performed to analyse for the effect of the interventions and subsequent interactions. An additional repeated measures ANOVA was performed for post-intervention values alone, to analyse for differences between the interventions. The correlation between post-intervention vertical stiffness and overall CODS time was examined using Pearson's r.

6.4 Results

6.4.1 Change of direction speed
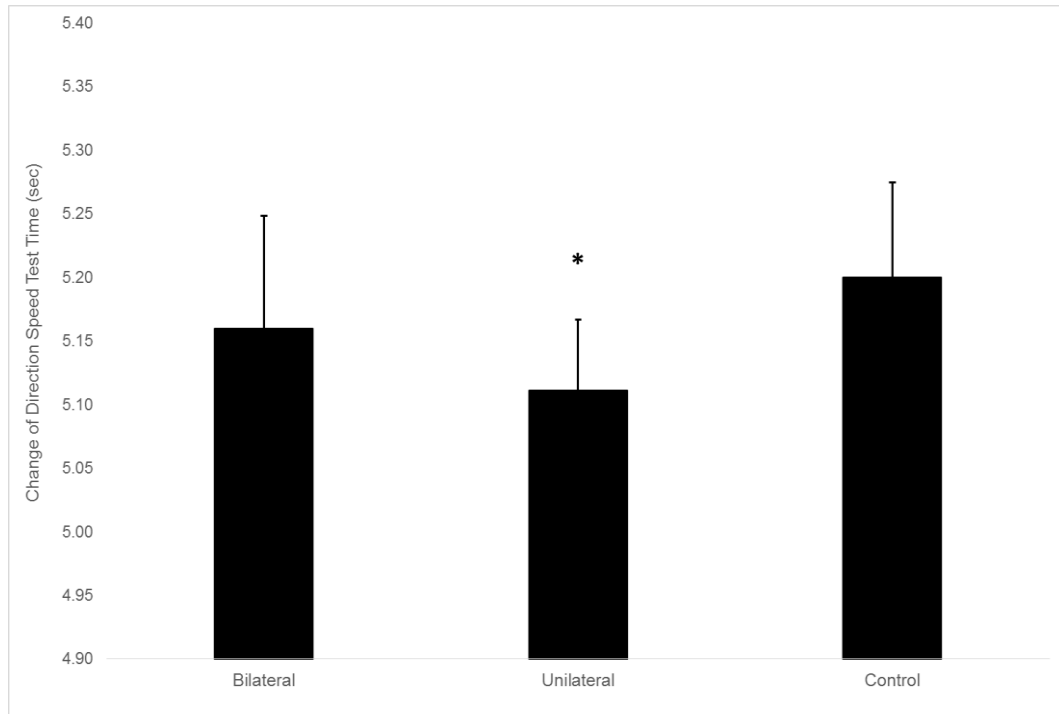
Figure 6.5 - Mean (± standard deviation) change of direction speed test performances following each of the three interventions. * indicates significantly faster than control (P < 0.05).

CODS performances were significantly different between conditions ($F_{(2,18)}$ = 7.14; P = 0.005). Performances in UNILATERAL were 1.7% faster than CONTROL (P = 0.011; d = -1.08), but not BILATERAL (1.0% faster; P = 0.14; d = -0.59); these effect sizes were both 'moderate'. BILATERAL performances were not different from CONTROL (0.8% faster; P = 0.41; d = -0.48) although the effect size was also moderate. CODS performance time was significantly correlated to post-intervention vertical stiffness (r = -0.31; P = 0.046).
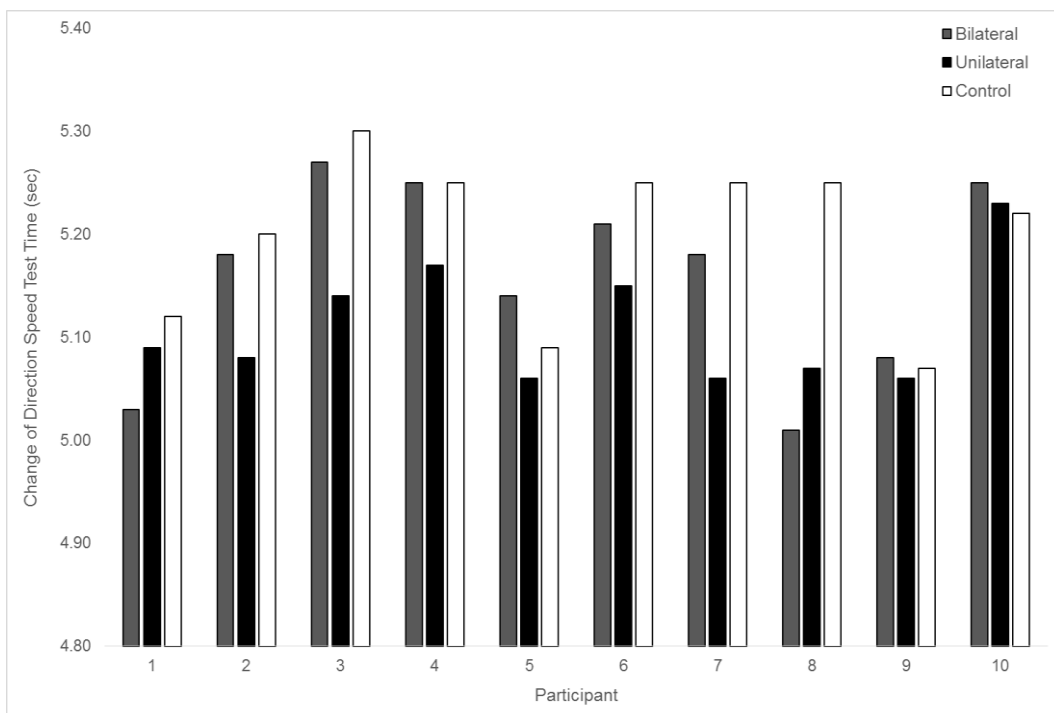
Figure 6.6 - Participants' change of direction speed test performances following each of the three interventions.

There was evidence of some inter-individual variability in response to the interventions (Figure 6.6). Seven participants recorded their quickest CODS test performance following UNILATERAL, two following BILATERAL and one following CONTROL.

Table 6.1 - Change of direction speed test performance and ground contact times, and the associated symmetry angles, following the three interventions.

Variable	Bilateral	Unilateral	Control
Faster limb			
Performance time (sec)	2.56 ± 0.04	2.53 ± 0.03	2.58 ± 0.05
Slower limb			
Performance time (sec)	2.60 ± 0.05	2.58 ± 0.05 *	2.62 ± 0.05
Symmetry			
Performance time SYM (%)	0.5 ± 0.3	0.6 ± 0.7	0.6 ± 0.5
GCT SYM (%)	2.1 ± 1.3	2.2 ± 0.7	3.1 ± 1.9
* indicates significantly different from control ($P < 0.05$).			
Key: SYM = symmetry angle.			

There was a main effect of intervention on CODS performance time for participants' faster ($F_{(2,18)}$ = 3.56; P = 0.050) and slower ($F_{(2,18)}$ = 6.70; P = 0.007) limbs (Table 6.1). Pair-wise comparisons were not significant for the faster limb, although the faster performances following UNILATERAL were associated with moderate effect sizes versus CONTROL (P = 0.079; d = -1.12) and BILATERAL (P = 0.37; d = -0.69). Performances for the slower limb were significantly faster following UNILATERAL than following CONTROL (P = 0.017; d = -0.86).
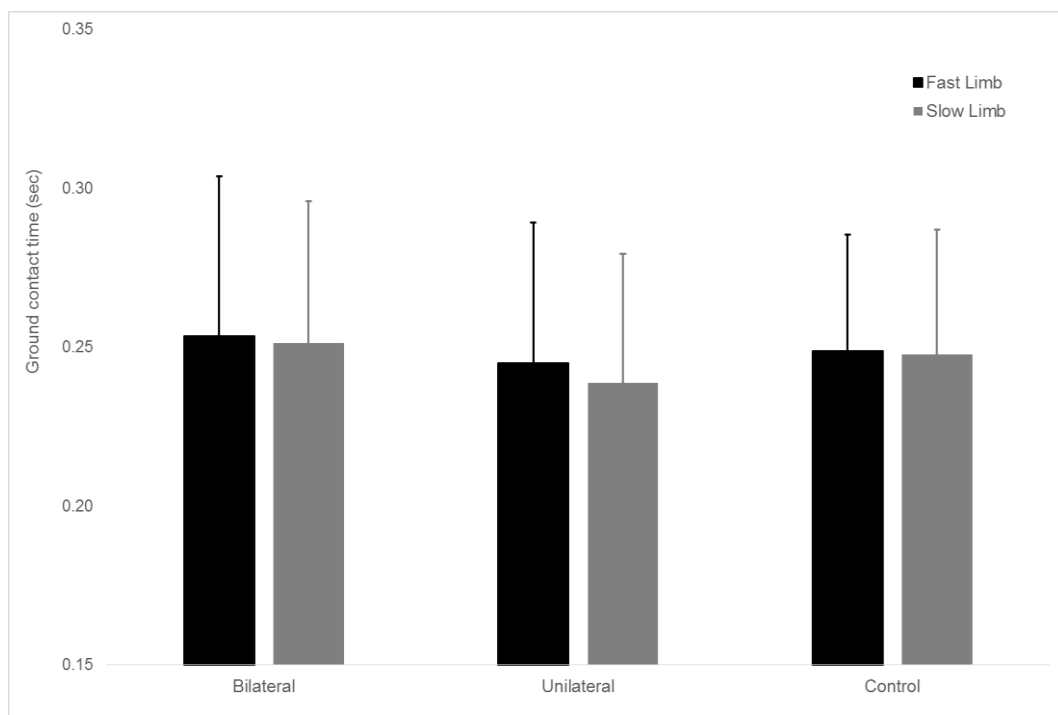
Figure 6.7 - Participants' ground contact times during the change of direction speed test for the fast and slow limbs following each of the three interventions.

Differences in ground contact times were not observed for the fast ($F_{(2,18)}$ = 0.75; P = 0.49) or slow ($F_{(2,18)}$ = 1.46; P = 0.26) limbs (Figure 6.7). Moderate effect sizes reported that ground contact time symmetry angle was lower following BILATERAL (d = -0.69) and UNILATERAL (d = -0.64) than following CONTROL, but these differences were not significant ($F_{(2,18)}$ = 2.19; P = 0.14).

6.4.2 Stiffness

Table 6.2 - Post-intervention vertical, ankle and knee stiffness, and the associated symmetry angles and percentage changes, following the three interventions.

Variable	Bilateral	Unilateral	Control
Vertical stiffness			
Stiffness ($N.m^{-1}.kg^{-1}$)	14.4 ± 4.8 *	14.8 ± 4.7 *	13.0 ± 4.3
Change in stiffness (%)	22.2 ± 29.7	26.0 ± 33.7	12.8 ± 22.1
Symmetry angle (%)	4.0 ± 4.3	5.3 ± 3.7	5.3 ± 4.0
Change in symmetry angle (%)	-0.7 ± 5.7	1.0 ± 6.3	0.2 ± 7.5
Ankle stiffness			
Stiffness ($N.m^{-1}.rad^{-1}$)	535.1 ± 137.6	550.5 ± 131.5	518.7 ± 91.1
Change in stiffness (%)	9.9 ± 1.3	8.6 ± 1.6	8.4 ± 1.5
Symmetry angle (%)	3.2 ± 3.0	3.1 ± 3.6	3.5 ± 2.5
Change in symmetry angle (%)	0.9 ± 4.9	2.7 ± 5.0	-0.8 ± 8.4
Knee stiffness			
Stiffness ($N.m^{-1}.rad^{-1}$)	2565.2 ± 714.3	2547.2 ± 590.6	2200.8 ± 359.0
Change in stiffness (%)	20.1 ± 23.5 *	15.3 ± 22.1	0.1 ± 19.2
Symmetry angle (%)	7.0 ± 5.4	4.0 ± 3.0	4.5 ± 3.4
Change in symmetry angle (%)	0.9 ± 7.2	-2.7 ± 7.9	5.0 ± 10.0
* indicates significantly different from control ($P < 0.05$).			
Key: change = change from pre- to post-intervention.			

Pre- to post-intervention

There was a main effect of the intervention, such that there was a significant increase in vertical ($F_{(1,9)}$ = 6.53; P = 0.031) and ankle ($F_{(1,9)}$ = 6.38; P = 0.032) stiffness, but not knee ($F_{(1,9)}$ = 2.80; P = 0.13) stiffness, from pre- to post-intervention. There was no significant interaction effect between time (pre- to post-intervention) and intervention for vertical ($F_{(2,18)}$ = 2.58; P = 0.104) and ankle ($F_{(2,18)}$ = 0.39; P = 0.684) stiffness, but there was a significant time by intervention

169

interaction effect for knee stiffness ($F_{(2,18)}$ = 5.38; P = 0.015) indicating that the change in knee stiffness was not uniform across all three conditions (Table 6.2).

The percentage change in vertical ($F_{(2,18)}$ = 2.36; P = 0.12) and ankle ($F_{(2,18)}$ = 0.04; P = 0.96) stiffness was not significantly different between conditions (Table 6.2). The percentage change in knee stiffness ($F_{(2,18)}$ = 5.85; P = 0.011) from pre- to post-intervention was significantly different between conditions. The change in knee stiffness was greater following BILATERAL versus CONTROL (P = 0.012; d = 0.86) but not UNILATERAL (P = 0.90; d = 0.21); there was no difference between UNILATERAL and CONTROL although the effect size was moderate (P = 0.06; d = 0.65).

Post-intervention

Post-intervention vertical stiffness was significantly different between conditions ($F_{(2,18)}$ = 5.16; P = 0.017) (Table 6.2). Vertical stiffness was greater following BILATERAL (11%; P = 0.019; d = 0.31) and UNILATERAL (14%; P = 0.049; d = 0.39) versus CONTROL; there was no difference between BILATERAL and UNILATERAL (-2.6%; P = 0.94; d = -0.08).

Post-intervention ankle ($F_{(2,18)}$ = 0.41; P = 0.67) and knee ($F_{(2,18)}$ = 3.04; P = 0.073) stiffness were not significantly different between conditions. A small effect size suggested greater ankle stiffness (6.1%; d = 0.26) and knee stiffness (15.7%; d = 0.58) following UNILATERAL versus CONTROL. A moderate effect size suggested greater knee stiffness (16.6%; d = 0.61) following BILATERAL versus CONTROL.

Asymmetry

Post-intervention symmetry angles for vertical ($F_{(2,18)}$ = 0.32; P = 0.73), ankle ($F_{(2,18)}$ = 0.14; P = 0.87) and knee ($F_{(2,18)}$ = 1.90; P = 0.18) stiffness were not significantly

170

different between conditions (Table 6.2). Likewise, the percentage change in vertical ($F_{(2,18)} = 0.15$; $P = 0.87$), ankle ($F_{(2,18)} = 0.60$; $P = 0.56$) and knee ($F_{(2,18)} = 1.60$; $P = 0.28$) stiffness was not significantly different between conditions.

6.4.3 Jump height and reactive strength index

Table 6.3 - Post-intervention drop jump height and reactive strength index, and the associated symmetry angles and percentage changes, following the three interventions.

Variable	Bilateral	Unilateral	Control
Drop jump height			
Jump height (m)	0.09 ± 0.04	0.09 ± 0.04	0.09 ± 0.05
Change in jump height (%)	17.9 ± 22.9	30.2 ± 32.2	10.8 ± 11.7
Symmetry angle (%)	6.1 ± 4.7	6.2 ± 3.6	7.1 ± 5.3
Change in symmetry angle (%)	-3.7 ± 5.0	1.5 ± 9.9	-4.1 ± 8.2
Reactive strength index			
RSI (flight time : contact time)	1.03 ± 0.25	1.03 ± 0.26	0.94 ± 0.29
Change in RSI (%)	16.1 ± 18.8	22.4 ± 17.7	7.1 ± 11.9
Symmetry angle (%)	3.9 ± 3.0	3.6 ± 2.5	3.9 ± 2.2
Change in symmetry angle (%)	0.0 ± 4.1	1.3 ± 6.5	-1.4 ± 5.0
Key: change = change from pre- to post-intervention, RSI = reactive strength index.			

Pre- to post-intervention

There was no significant change in drop jump height ($F_{(1,9)} = 0.62$; $P = 0.55$) or reactive strength index ($F_{(1,9)} = 2.18$; $P = 0.14$) from pre- to post-intervention. There was no interaction effect between time and condition for drop jump height ($F_{(2,18)} = 0.53$; $P = 0.598$), but there was for reactive strength index ($F_{(2,18)} = 3.59$; $P = 0.049$). The percentage change in drop jump height ($F_{(2,18)} = 0.17$; $P = 0.18$) or reactive strength index ($F_{(2,18)} = 0.04$; $P = 0.31$) was not significantly different between conditions.

Post-intervention

Post-intervention reactive strength index was significantly different between conditions ($F_{(2,18)}$ = 4.21; P = 0.032) (Table 6.3), although post-hoc comparisons did not reveal significant pair-wise differences. Post-intervention drop jump height was not significantly different between conditions ($F_{(2,18)}$ = 0.72; P = 0.50).

Asymmetry

Post-intervention symmetry angles for drop jump height ($F_{(2,18)}$ = 0.34; P = 0.72) and reactive strength index ($F_{(2,18)}$ = 0.05; P = 0.95) stiffness were not significantly different. Likewise, the percentage change in drop jump height ($F_{(2,18)}$ = 1.51; P = 0.25) and reactive strength index ($F_{(2,18)}$ = 0.52; P = 0.60) was not significantly different between conditions.

6.5 Discussion

The primary aim of Study 4 was to establish if acute exercise interventions designed to augment vertical stiffness influenced CODS. It was hypothesised that both the bilateral and unilateral preparation strategies would significantly improve CODS test performance versus a control strategy and that improvements would be greater following the unilateral intervention. Effect size analysis reported that both BILATERAL and UNILATERAL improved CODS performance versus CONTROL, but this difference was only significant for UNILATERAL. As such, these hypotheses cannot be wholly accepted.

The secondary aim of Study 4 was to establish if the effects of the interventions on CODS was linked to the modulation of vertical stiffness and vertical stiffness asymmetries. It was hypothesised that both BILATERAL and UNILATERAL would increase vertical stiffness versus CONTROL, but that the UNILATERAL would reduce vertical stiffness asymmetry to a greater extent. The first of these hypotheses may be accepted as vertical stiffness was greater following both BILATERAL and UNILATERAL in comparison to control. The second of these hypotheses is rejected as vertical stiffness symmetry angle was not different between interventions.

Following UNILATERAL, CODS test performance was 1.7% ($d = 1.08$) quicker versus CONTROL and 1.0% ($d = 0.59$) quicker versus BILATERAL. The effect of pre-conditioning interventions versus traditional dynamic warm-up practices on CODS has been evaluated previously in a selection of investigations. Reactive agility has been improved by 4.7% ($d = 1.2$) following heavy leg press exercise (Zois et al., 2011) in amateur soccer players. Badminton specific CODS has been improved by 5.0% ($d = 0.83$) following a weight vest loaded warm-up by Maloney

et al. (2014b) in professional badminton players. Nava (2015) also noted significant improvements in T-test performance following weight vest loaded warm-up in collegiate athletes, although the presentation of their results did not permit the calculation of percentages and effect size. Whilst Sole et al. (2013) did not report significant improvements (2.3%; $d = 0.18$; $P = 0.07$) in 10 m shuttle test performance following heavy back squats in collegiate tennis and basketball players, 70% of participants recorded faster times than following a dynamic warm-up. The magnitude of CODS improvement observed in the current study is therefore less than has previously been reported in the literature, although differences in the CODS tests employed make it difficult to draw direct comparisons.

The aforementioned studies which have reported CODS enhancements following pre-conditioning interventions have not attempted to examine the mechanisms by which these enhancements occur. The post-activation potentiation phenomenon is typically discussed within these investigations, as too is the purported physiological and neural underpinning of the post-activation potentiation response. However, it is also important to consider the potential role of acute modulations in stiffness (Maloney et al., 2014a). In Study 3 it was reported that vertical stiffness was the strongest predictor of CODS in the regression model and that faster performers in the CODS test exhibited greater vertical stiffness. This supports the deterministic model of CODS proposed in this thesis (Figure 6.1) and the hypothesis that increasing vertical stiffness will improve CODS. In comparison to CONTROL, post-intervention vertical stiffness was 11% ($d = 0.31$) greater following BILATERAL and 14% ($d = 0.39$) greater following UNILATERAL. The increase in vertical stiffness could explain why performances were quicker following the two stiffness interventions and is to be discussed later on in this section.

The increases in stiffness (BILATERAL: 11% and UNILATERAL: 14%) observed in the current study are comparable to the respective increases of 11% ($P < 0.05$) and 16% (d: 0.52; $P = 0.013$) observed by Comyns et al. (2007) and Moir et al. (2011) following heavy back squat interventions versus a post-warm-up baseline. However, Barnes et al. (2015) reported a greater increase of 20% (d: 0.76; 90%CI: 4%) following a weight vest loaded warm up versus a control warm-up, an intervention with greater similarity to the interventions performed in the current study. Comparisons with the Barnes et al. (2015) investigation are also more appropriate given that they are the only investigators, to this author's knowledge, to attempt to link performance enhancements to specific biomechanical variables, albeit within linear running. Barnes et al. (2015) reported an enhancement in performance (peak running speed) of 2.9% (90%CI: 0.8%), noting a 'very-high' correlation between the change in performance and the change in vertical stiffness ($r = 0.88$; 90% confidence intervals: 0.66-0.96). The current study reports a statistically significant relationship between increased stiffness and CODS, although this correlation ($r = 0.31$) is notably weaker than that of Barnes et al. (2015).

Study 3 demonstrated that shorter ground contact times were associated with faster CODS performances, in agreement with previous investigations (Sasaki et al., 2011; Marshall et al., 2014). Increased stiffness would be expected to facilitate shorter ground contact times, as has been discussed previously (Section 2.11), and could explain how greater stiffness may contribute to the enhancement of CODS. Whilst the shortest ground contact times were observed following UNILATERAL and the longest following CONTROL (Figure 6.7), mirroring what was observed for CODS performance time, this relationship was not statistically significant and the effect sizes were small ($d < 0.2$). The likely reason for the lack

of a relationship within the current study is that augmentations in ground contact time were small and inter-participant variation was large. For example, the difference in average ground contact time between UNILATERAL and CONTROL was -1.6%, and the standard deviation was ~18% of the mean. It should also be noted that limb or joint stiffness was not determined during the CODS test within this thesis. Future investigations should seek to examine direct measures of stiffness during the changes of direction.

Differences in CODS performance between interventions within the current study were not linked to symmetry angles or to changes (pre- to post-intervention) in symmetry angles. Study 3 had established that asymmetry in drop jump height was associated with slower CODS and that asymmetries in ankle stiffness, although not vertical stiffness, were greater in slower performers. This was in agreement with previous literature which had linked asymmetries in force-power qualities to impaired athletic performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), discussed in detail in Section 2.7. The magnitudes of asymmetry reported in the current study are similar to those reported in Study 3. It may therefore be inferred that asymmetries (drop jump height and ankle stiffness) show potential to differentiate CODS performance between individuals but that acute changes in these variables are not linked to changes in CODS within an individual. However, the current study demonstrates that changes in symmetry angles for all jump-derived variables were highly variable; in all but one instance the standard deviation was at least double the mean difference. Future investigations may wish to consider whether the magnitude of pre-intervention asymmetry could affect this response.

Although the enhancement in CODS performance was not linked to changes in the symmetry angle between 'fast' and 'slow' limb performances, statistical analyses

suggest that the effect of the interventions could be different for the respective limbs. The current study reported that performances for the slow limb were significantly faster following UNILATERAL than following CONTROL but a similar relationship was not observed for the fast limb. Given that the performance improvement was the same for both limbs (1.7%) and a greater effect size was observed for the fast limb ($d = 1.12$) than for the slow limb ($d = 0.86$), this is perhaps an example of a type I error and consequential of a relatively small sample size (n = 10). Nonetheless, this is an area that future research may wish to explore.

6.6 Conclusion

Study 4 reports that a unilateral pre-conditioning intervention designed to augment vertical stiffness improved CODS performance relative to a control intervention. The improvements in CODS performance observed following the unilateral intervention were reported in conjunction with greater post-intervention vertical stiffness. Asymmetries in jump and stiffness variables were not modulated following the pre-conditioning interventions and do not appear related to the enhancements in performance.

Chapter 7 - Summary of Findings and Practical Implications

7.1 Original contribution to knowledge

This thesis seeks to highlight the following original contributions to knowledge:

- This thesis demonstrated the reliability and validity of a novel method by which to assess vertical stiffness - the unilateral drop jump.

- This thesis demonstrated that vertical stiffness during unilateral drop jumping was associated with change of direction speed (CODS) performance. This highlights the potential applicability of the unilateral drop jump within athletic testing protocols.

- This thesis demonstrated that a novel unilateral 'stiffness' intervention augmented vertical stiffness and CODS performance beyond bilateral and control interventions. This highlights that the potential applicability of unilateral stiffness interventions in the pre-performance preparation of athletes.

7.2 Reflection on aims

This thesis aimed to answer three questions:

1. What is the most reliable and ecologically valid method to assess vertical stiffness in athletes required to perform changes of direction?
2. Do vertical stiffness and vertical stiffness asymmetries influence CODS?
3. Can acute 'stiffness' interventions positively influence CODS and, if so, are augmentations linked to the modulation of vertical stiffness and/or vertical stiffness asymmetries?

This thesis found that:

1. The unilateral drop jump was a more reliable and ecologically valid method to assess vertical stiffness in athletes required to perform changes of direction than bilateral hopping or bilateral drop jumping.
2. Stiffness asymmetries did not influence CODS, however, vertical stiffness and asymmetry in drop jump height negatively affected CODS as separate entities.
3. Acute stiffness interventions augmented CODS performance and vertical stiffness, but did not influence asymmetries. CODS performance was not directly related to the modulation of vertical stiffness.

   In addition, unilateral stiffness interventions were the most effective in augmenting both CODS performance and vertical stiffness.

7.3 Summary of studies

A total of five studies were conducted in order to answer the questions posed by this thesis.

7.3.1 Pilot study

The reliability of Achilles tendon stiffness derived from isometric dynamometry and ultrasonography

The aim of the pilot study was to assess the inter-session reliability of Achilles tendon stiffness obtained through ultrasonography. Despite the widespread use of ultrasonography to assess tendon properties, there has been a large degree of variability in the figures reported between investigations. Were the reliability of this method found to be acceptable during single-joint, quasi-isometric activity it would allow exploration of the reliability of these techniques during more complex and dynamic movements.

The pilot study reported that Achilles tendon stiffness demonstrated poor reliability (coefficient of variation (CV): > 10%, ICC: < 0.80) over four testing sessions in participants previously unfamiliar with the testing protocol. The lowest inter-session CV, of 27%, was found between testing sessions 3 and 4.

Given the high variability associated with ultrasonography measurements demonstrated in the pilot study, the use of ultrasonography was not incorporated in subsequent studies in this thesis.

The reliability of vertical stiffness during bilateral hopping, bilateral drop jumping and unilateral drop jumping

The aim of Study 1 was to assess the inter-session reliability of vertical stiffness obtained through bilateral hopping, bilateral drop jumping and unilateral drop jumping. Bilateral hopping is the most widely used method by which to assess vertical stiffness but drop jumping tasks may demonstrate higher validity if seeking to explore relationships with high-intensity athletic performance.

Study 1 reported CVs for vertical stiffness of ~14% for bilateral hopping, ~12% for bilateral drop jumping and ~7% for unilateral drop jumping following a single familiarisation session.

These results suggested that unilateral drop jumping provides a more reliable measure of vertical stiffness when compared to bilateral drop jumping or bilateral hopping; this was the only task to report CVs < 10%. The most valid task by which to assess vertical stiffness asymmetries for an individual athlete now needed to be considered; this was evaluated in Study 2.

A comparison of methods to determine vertical stiffness asymmetries

The aim of Study 2 was to establish the most valid performance task by which to assess the stiffness of the lower limb in subsequent investigations. Previous research has suggested that asymmetries may be differently expressed in cyclic versus acyclic (Flanagan & Harrison, 2007) and bilateral versus unilateral (Benjanuvatra et al., 2013) performance tasks. Determining the most valid task will provide athletes, coaches and applied practitioners with the most appropriate assessment tool to assess stiffness.

Study 2 reported that significant vertical stiffness asymmetries were observed within all three tasks; as such, all three tasks could be used as a diagnostic tool to directly assess and quantify vertical stiffness asymmetry. However, vertical stiffness ($P = 0.033$) and vertical stiffness symmetry angle ($P = 0.006$) were significantly different between methods. Vertical stiffness was significantly lower in the compliant limb versus the stiff limb ($P < 0.001$) with a significant interaction effect between limb and performance task ($P = 0.013$). Asymmetry percentages between compliant and stiff limbs were 5.6% ($P < 0.001$; d: 0.22), 23.3% ($P = 0.001$; $d = 0.86$) and 12.4% ($P = 0.001$; $d = 0.39$) for the bilateral hopping, bilateral drop jumping and unilateral drop jumping methods respectively.

The results of Study 2 demonstrated that asymmetry in vertical stiffness is expressed differently in cyclic versus acyclic and bilateral versus unilateral performance tasks. As this thesis sought to examine the relationships between stiffness and CODS - acyclic and unilateral in nature - the unilateral drop jump was subsequently used as the performance task by which to assess parameters of stiffness.

Do stiffness asymmetries predict change of direction speed?

The primary aim of Study 3 was to determine if bilateral asymmetry in vertical stiffness influenced CODS. Force-related and kinematic asymmetries have been linked to impaired performance (Bailey et al., 2013; Bazyler et al., 2014; Bell et al., 2014; Hart et al., 2014b; Bailey et al., 2015), but this has not been evaluated in regards to CODS. Were it to be determined that asymmetry influenced CODS, this would influence how interventions to improve CODS may be devised and structured.

The secondary aim of Study 3 was to evaluate the relative importance of the ankle, knee and hip in modulating vertical stiffness asymmetry. Previous research has demonstrated that ankle stiffness is likely to determine vertical stiffness (Farley et al., 1998; Farley & Morgenroth, 1999; Arampatzis et al., 2001b; Kuitunen et al., 2011; Kim et al., 2013) but has not examined this in relation to asymmetry. Understanding the determinants of asymmetry could influence the design of strategies intended to reduce asymmetry.

Study 3 reported that mean vertical stiffness and asymmetry in drop jump height explained 63% ($r^2 = 0.63$; $P = 0.001$) of CODS performance. Faster performers in the CODS demonstrated greater vertical stiffness ($P = 0.003$; $d = 1.76$), less asymmetry in jump height ($P = 0.026$; $d = -1.28$) and 'moderately' greater ankle stiffness ($P = 0.28$; $d = 0.62$). Ankle stiffness and reactive strength index symmetry angles explained 79% of the variance in vertical stiffness asymmetry angle ($r^2 = 0.79$; $P < 0.001$).

Whilst vertical stiffness asymmetry was not a predictor of performance, both vertical stiffness and asymmetry (drop jump height) were strongly associated with

CODS as separate entities. The unilateral drop jump test may therefore provide coaches and practitioners with a tool to not only assess an individual's stiffness profile, but also to quantify specific factors linked to CODS. Study 4 would seek to evaluate the effect of specific 'stiffness' pre-conditioning interventions on CODS with a particular focus around the ankle joint.

The acute effects of bilateral and unilateral stiffness interventions on change of direction speed

The primary aim of Study 4 was to determine if acute exercise interventions designed to augment vertical stiffness would improve CODS. It has previously been shown that pre-conditioning interventions can augment both vertical stiffness (Comyns et al., 2007; Moir et al., 2011; Barnes et al., 2015) and CODS (Zois et al., 2011; Maloney et al., 2014b; Nava, 2015), but not examined the relationship between these factors. Were it to be determined that such interventions impact performance, this could influence the performance preparation strategies of athletes. The literature had also demonstrated that unilateral training interventions (Fisher & Wallin, 2014) may carry greater benefits to CODS than bilateral interventions, but had not examined this effect acutely. For this reason, Study 4 examined the effects of bilateral and unilateral focused interventions.

The secondary aim of Study 4 was to establish if the effects of the intervention on CODS was linked to the modulation of vertical stiffness and vertical stiffness asymmetry. Previous research had shown that acute exercise interventions may reduce ground reaction force asymmetry (Hodges et al., 2011), but had not evaluated stiffness asymmetries.

CODS performance was significantly different between conditions ($P = 0.005$). Performances following the unilateral intervention were significantly faster than control (1.7%; $P = 0.011$; $d = -1.08$), but not significantly faster than the bilateral intervention (1.0% faster; $P = 0.14$; $d = -0.59$). Post-intervention vertical stiffness was also significantly different between conditions ($P = 0.017$). Versus control, vertical stiffness was 14% greater ($P = 0.049$; $d = 0.39$) following the unilateral

intervention and 11% greater ($P = 0.019$; $d = 0.31$) following the bilateral intervention; there was no difference between unilateral and bilateral interventions (2.6%; $P = 0.94$; $d = -0.08$). Post-intervention symmetry angles for vertical ($P = 0.73$) and ankle ($P = 0.87$) stiffness were not significantly different between conditions.

Study 4 reported that a unilateral pre-conditioning intervention designed to augment vertical stiffness improved CODS performance relative to a control intervention and was also associated with greater post-intervention vertical stiffness. However, performance improvements were not related to parameters of stiffness asymmetry.

7.4 Impact of the thesis

7.4.1 Publications

Partial findings from Study 1 have been published in the following peer-reviewed manuscript:

Maloney SJ, Fletcher IM and Richards J. (2015). Reliability of unilateral vertical leg stiffness measures assessed during bilateral hopping. *Journal of Applied Biomechanics* **31**(5): 285-291.

Partial findings from Study 1 have also been submitted for publication in the following manuscript:

Maloney SJ, Fletcher IM and Richards J. Reliability of vertical leg stiffness during bilateral and unilateral drop jumping. *Journal of Sports Sciences.* Under review.

The findings of Study 2 have been published in the following peer-reviewed manuscript:

Maloney SJ, Fletcher IM and Richards J. A comparison of methods to determine bilateral asymmetries in vertical stiffness. *Journal of Sports Sciences* **34**(9): 829-835.

The findings of Study 3 have been published in two separate manuscripts:

Maloney SJ, Richards J, Nixon DJN, Harvey LJ and Fletcher IM. Do stiffness and asymmetries predict change of direction performance? *Journal of Sports Sciences.* 30th April 2016 [epub ahead of print]. [doi: 10.1080/02640414.2016.1179775].

Maloney SJ, Richards J, Nixon DJN, Harvey LJ and Fletcher IM. Determinants of vertical stiffness asymmetries in drop jumping. *Scandinavian Journal of Science and Medicine in Sports.* 30th March 2016 [epub ahead of print]. [doi: 10.1111/sms.12682]

The findings of Study 3 were also presented in a poster at the 2015 national conference of the United Kingdom Strength & Conditioning Association:

Maloney SJ, Richards J, Nixon DJN, Harvey LJ and Fletcher IM. (2015, August). *Do stiffness and asymmetries predict change of direction performance?* Poster presented at the 2015 United Kingdom Strength & Conditioning Association National Conference, Kenilworth, United Kingdom.

7.4.2 Dissemination of findings to the wider audience

Following publication of the manuscript allied to Study 2, the author of this thesis was invited to discuss the study on a popular sports science podcast:

Franklyn-Miller, A. (Producer). (2015, 8th August). *Measuring Leg Stiffness and Asymmetry with Sean Maloney* [audio podcast]. Retrieved from https://soundcloud.com/drandyfranklynmiller/.

The methodologies and findings of Studies 1 - 2 have also been discussed in the following online blog articles:

Maloney, S. (2013, 20th October). *Stiffness 1.01* [web log post]. Retrieved from http://www.maloneyperformance.com/Blog/?p=1213.

Maloney, S. (2013, 3rd December). *Measuring Stiffness - The Principles* [web log post]. Retrieved from http://www.maloneyperformance.com/Blog/?p=1246.

Maloney, S. (2015, 27th December). *Assessing Stiffness in Athletes* [web log post]. Retrieved from http://www.maloneyperformance.com/Blog/?p=1550.

7.5 Implications of the thesis

7.5.1 Implications for the assessment of athletes

Study 2 demonstrated that the expression of vertical stiffness and vertical stiffness asymmetry differs depending on the type of performance task utilised. Careful consideration must therefore be given to the most appropriate task for an individual or group of athletes. It is therefore proposed that:

1. For athletes predominantly engaged in cyclic, submaximal activities bilateral hopping provides the assessment task with the greatest correspondence to performance.
2. For athletes required to perform bilateral, vertical jumps bilateral drop jumping would be the preferred task.
3. For athletes performing changes of direction off a single limb unilateral drop jumping carries the greatest degree of validity.

However, Study 1 demonstrated that the unilateral drop jump was the most reliable test (CV: ~7%). Bilateral hopping and bilateral drop jumping were associated with CVs > 10%. Researchers and practitioners should seek to establish the reliability of their chosen method within their specific population before deciding on the most appropriate assessment of vertical stiffness.

7.5.2 Implications for the preparation of athletes

Chronic preparation (training)

Study 3 demonstrated that vertical stiffness and drop jump height asymmetry were the strongest determinants of CODS. In addition, ankle stiffness was also likely to differentiate faster and slower performers within the sampled cohort. Athletes, coaches and applied practitioners should seek to develop vertical and ankle stiffness, whilst also minimising drop jump performance asymmetry, in instances where CODS is important to performance.

Although performance enhancement was the focus of this thesis, it is important to acknowledge that changes in stiffness parameters and related asymmetries is likely to influence injury incidence. It has been purported that high levels of stiffness, whilst advantageous to performance, may predispose an athlete to an increased risk of injury (Butler et al., 2003; Pearson & McMahon, 2012). The review article by Butler et al. (2003) summarises that high levels of stiffness may increase the risk of bony injuries such as knee osteoarthritis and stress fractures (no specific location), a likely consequence of increased loading rates. There is evidence to support a link between stiffness and stress fractures. For example, Milner et al. (2006) observed greater knee, but not ankle, stiffness in female endurance runners with a history of tibial stress fractures. There is currently no evidence to support the role of stiffness in knee osteoarthritis in humans; Kujala et al. (1995) concluded that repetitive non-traumatic loading was unlikely to confer greater risk. Lorimer and Hume (2016) have also linked increased leg stiffness, although decreased ankle stiffness, with an increased incidence of Achilles tendon injury in endurance runners.

However, the Butler et al. (2003) review also suggests that low levels of stiffness have been associated with an increased incidence of (non-specific) soft tissue injuries. Williams et al. (2001) observed that the incidence of general knee pain, patellar tendinopathy and posterior tibialis tendinopathy was higher in low-arched (and therefore lower leg stiffness) endurance runners. Reduced stiffness may also explain the increased incidence of anterior cruciate ligament injury in female athletes (Pearson and McMahon, 2012). Padua et al. (2006) reported that female athletes demonstrated less vertical stiffness than male athletes. A more compliant leg spring is likely to be associated with greater anterior translation of the tibia and increased internal rotation of the femur at ground contact (Pearson and McMahon, 2012).

It is perhaps appropriate to suggest that that there will be a 'desirable' stiffness profile for an individual dependent on their sport, position and athletic profile. Factors that could influence the body/surface interface, such as type of playing surface, weather conditions and choice of footwear, may also modulate this relationship on an intra-individual basis. The desirable stiffness profile would consider the magnitude of stiffness that is required for them to perform in an effective manner versus the increased demand this places upon the body. For this reason, the monitoring of vertical stiffness and related asymmetries may also be warranted from an injury prevention perspective. As asymmetries in vertical stiffness appear to infer an increased risk of muscular injury in Australian Rules footballers (Pruyn et al., 2012), a potential consequence of an imbalance in loading and loading rates, the monitoring of stiffness asymmetries may be more important than the overall level of stiffness.

<u>Acute preparation (warm-up)</u>

Study 4 demonstrated that a unilateral 'stiffness' pre-conditioning strategy was more effective than bilateral or control (additional CODS practice) strategies. For athletes preparing to engage in sports where CODS is an important determinant of performance, it is therefore recommended that preparation strategies include unilateral exercises designed to augment vertical and ankle stiffness. Examples utilised in this thesis included pogo hops and drop jumps.

7.6 Limitations of the thesis

7.6.1 Participant population

The population sampled in the current study were recreationally active males recruited from a university campus. Inclusion criteria stated that participants must be undertaking a minimum of 2.5 hours of physical activity per week, but did not stipulate that all participants were engaged in competitive sport, in order to ensure that a large enough sample size was achieved to meet *a priori* power analysis requirements. Future research should seek to explore the findings of this thesis in competitive athletes who are likely to have a greater training age, strength and CODS skill. It has been established that asymmetries are likely to be smaller in stronger individuals (Bazyler et al., 2014) and more skilled CODS performers may also be better able to initiate technical adjustments in response to asymmetries (Lockie et al., 2014).

7.6.2 Equipment

Ultrasonography

In the pilot study, the medial gastrocnemius - Achilles tendon complex was imaged using an ultrasound scanner (Vivid 7, GE Healthcare, Horton, Norway) capable of sampling at a rate of just 16.8 Hz. As discussed in Section 3.2.4, this could explain why poor reliability of elongation measures was observed. Elsewhere in the literature sampling rates of 25 - 50 Hz are commonly utilised (Kubo et al., 2001; Magnusson et al., 2001; Kubo et al., 2002; Burgess et al., 2009; Kongsgaard et al., 2011). It is reasonable to suggest that the reliability of Achilles tendon elongation

measures is unlikely to achieve improved reliability unless higher sampling rates can be utilised.

Motion capture

As drop jumping is a task performed in the sagittal plane, the assessment of ankle, knee and hip kinematics using two-dimensional motion capture would therefore seem appropriate. Indeed, this technique has been widely used within vertical stiffness investigations using drop jumping and hopping (Farley & Morgenroth, 1999; Arampatzis et al., 2001a; Arampatzis et al., 2001b; Hobara et al., 2009; Kuitunen et al., 2011). However, changes of direction are performed in sagittal, frontal and transverse planes of motion and a two-dimensional motion analysis is clearly inappropriate.

As a three-dimensional motion analysis system was not available for use within the thesis, Studies 3 and 4 were unable to evaluate kinematic parameters during the CODS test. Were this data available, this would permit the calculation of stiffness measures directly during the cutting action. As established in Study 2, the expression of stiffness and subsequent asymmetries is task-dependant. Stiffness measures determined during cutting may demonstrate different relationships with CODS performance than those determined during a unilateral drop jump. In addition, a three-dimensional motion analysis would also demonstrate how different kinematic factors (i.e. pelvic lateral tilt and thorax rotation (Marshall et al., 2014)) influence and interact with stiffness variables and CODS performance.

<u>7.6.3 Change of direction speed test</u>

<u>Specificity of cutting angle</u>

This thesis employed a 90° double-cutting task as the measure of CODS performance; the specific set-up of the task was constrained by the space within the testing laboratory and position of the force plates. Whilst a 90° cut may be - particularly applicable within certain team-sports - for instance, attempting to side-step a defender within rugby union - it may not be appropriate to extrapolate the findings of the current thesis to other cutting angles without investigating these directly. Within most sports, players are required to perform cutting actions across a range of angles and it is therefore important to consider whether determinants of CODS - such as vertical stiffness - are common across all of these.

<u>Influence of linear velocity</u>

The CODS task employed within this thesis incorporated short bursts of linear acceleration and deceleration punctuated by two changes of direction. The respective influence of these factors to overall CODS performance was not separated. The short distance between cuts (3 m) would be anticipated to reduce the emphasis placed upon linear speed versus longer distances. Also, the specific nature of the cut (a sharp 90° power cut with no curved approach) would be expected to increase the emphasis placed upon the change of direction. However, the possibility that task performance was dependent upon participants' velocity between the changes of direction cannot be discounted. Consideration of factors such as approach velocity and exit velocity, together with the aforementioned three-dimensional motion capture, would be warranted in future investigations. The utilisation of additional pairs of timings gates in future investigations would help differentiate linear and turning components of the CODS test.

Declaration

I declare that this thesis is my own unaided work. It is being submitted for the degree of Doctor of Philosophy at the University of Bedfordshire.

It has not been submitted for any degree or examination in any other University.

Name of candidate: **Sean Maloney**

Signature:

Date: **10/02/2016**

Appendix A1 - Ethical Approval and Informed Consent

Ethical Approval Form

University of Bedfordshire

13 June 2013

Ethical scrutiny confirmation

Proposer: Sean Maloney

Proposal short   Functional asymmetry in lower limb stiffness
title:

Dear Proposer

Your proposal has now received ethical scrutiny from the Institute for Sport and Physical Activity Research Ethics panel.

I can confirm that this has now been approved, please find below your approval number:

Approval number: 2012SPA001

Please note that if it becomes necessary to make any substantive change to the research design, the sampling approach or the data collection methods a further application will be required. Please be advised that your research project may be subject to an ethical audit at any given time. If you require any further information please contact ispar@beds.ac.uk

You are now clear to proceed with data collection for this project.

Thank you very much for your patience in this matter

Regards

Dr Stephen Harvey (ISPAR Ethics Chair)

INVESTORS IN PEOPLE | Gold

POSITIVE ABOUT DISABLED PEOPLE

THE QUEEN'S AWARDS FOR ENTERPRISE INTERNATIONAL TRADE 2011

Informed Consent Form

INFORMED CONSENT FORM
TO BE COMPLETED BY PARTICIPANT

NAME: …………………………………………… (Participant)

I have read the Study Information Sheet concerning this research study and understand what it entails.

I declare that I am fit and healthy to participate in physical activity.

All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage.

I know that:

- My participation in the study is entirely voluntary and I am free to withdraw from the study at any time without disadvantage or prejudice.

- As part of the study I will be asked to:

    o Complete a series of jumping and running tasks which may include: single and double leg depth jumps from a maximal drop height of 50cm, maximal velocity sprinting up to 60m, and maximal velocity changes of direction

    o Undergo non-invasive ultrasound scanning of the upper and lower legs both at rest and during some of these exercises tasks

    o Undergo non-invasive EMG scanning of the upper and lower legs

- I am aware of any risks that may be involved with the project and that all information and data collected will be held securely at the University indefinitely.

- The results of the study may be published but my anonymity will be preserved.

Signed: ………………………………… (Participant)   Date: ……………

Contact: Sean.Maloney@beds.ac.uk

Appendix A2 - Inverse Dynamics

Linear kinetics

Acceleration, velocity and centre of mass displacement at time intervals of 0.001 sec were determined from the vertical force trace using the biomechanical principles described by Blazevich (2007) and Hall (2012), detailed in the following formulae.

Acceleration

Instantaneous acceleration (m.s^{-2}) at each time interval was calculated from instantaneous force and body weight (both in N) as shown in Equation 1.

$$A_i = \frac{(Fi - BW)}{(BW / 9.81)} \qquad (1)$$

Where: A_i = instantaneous acceleration, F_i = instantaneous force and BW = body weight.

Velocity

Instantaneous velocity (m.s^{-1}) at each time interval was calculated from velocity at the previous time interval, acceleration at the previous time interval and the time interval as shown in Equation 2.

$$V_i = V_p + \left(A_p * \left(\Delta t\right)\right) \qquad (2)$$

Where: V_i = instantaneous velocity, V_p = previous velocity, A_p = previous acceleration and Δt = time interval.

Velocity at the first time interval (0.001 sec) previous velocity was determined as shown in Equation 3 (Hobara et al., 2013). A velocity of -1.88 m.s^{-1} is equivalent to the estimated velocity of a mass falling from a height of 0.18 m.

$$V_0 = -0.5 * 9.81 * t_a \qquad (3)$$

Where: V_0 = initial velocity, t_a = aerial time.

<u>Centre of mass displacement</u>

Centre of mass displacement (m) at each time interval during the initial ground contact phase was calculated from displacement at the previous time interval, velocity at the previous time interval and the time interval as shown in Equation 4.

$$D_i = D_p + \left(V_p * \left(\Delta t \right) \right) \qquad (4)$$

Where: D_i = instantaneous displacement, D_p = previous displacement, V_p = previous velocity and Δt = time interval.

Angular kinetics

Ankle moment

The sum of moments at the ankle (N.m) was calculated as shown in Equation 5.

$$M_a = (I * \alpha) + \left(\sum F_x * A_x\right) + \left(\sum F_z * A_z\right)$$ (5)

Where: M_a = ankle moment, I = moment of inertia, α = angular acceleration, ΣF_x = sum of horizontal forces, A_x = horizontal moment arm, ΣF_z = sum of vertical forces and A_z = vertical moment arm.

Knee moment

The sum of moments at the knee (N.m) was calculated as shown in Equation 6.

$$M_k = (I * \alpha) + \left(\sum F_x * A_x\right) + \left(\sum F_z * A_z\right)$$ (6)

Where: M_k = knee moment, I = moment of inertia, α = angular acceleration, ΣF_x = sum of horizontal forces, A_x = horizontal moment arm, ΣF_z = sum of vertical forces and A_z = vertical moment arm.

Hip moment

The sum of moments at the hip (N.m) was calculated as shown in Equation 7.

$$M_H = (I * \alpha) + \left(\sum F_x * A_x\right) + \left(\sum F_z * A_z\right)$$ (7)

Where: M_H = hip moment, I = moment of inertia, α = angular acceleration, ΣF_x = sum of horizontal forces, A_x = horizontal moment arm, ΣF_z = sum of vertical forces and A_z = vertical moment arm.

Leg stiffness

Leg stiffness may be calculated as shown in Equation 8 (McMahon and Cheng, 1990)

$$k_{leg} = F_{max}/ \Delta L \tag{8}$$

Where: k_{leg} = leg stiffness, F_{max} = maximum vertical force, ΔL = change in leg length.

The change in leg length used in Equation 8 is calculated as shown in Equation 9 (McMahon and Cheng, 1990).

$$\Delta L = \Delta y + L_0(1 - \cos) \text{ and } \theta = \sin^{-1}(ut_c / 2L_0) \tag{9}$$

Where: Δy = maximum displacement to the centre of mass, L_0 = standing leg length, θ = half angle of the arc swept by the leg, u = horizontal velocity, t_c = contact time.

References

Alexander RM, Ker RF. The architecture of leg muscles. In: Winters JM, Woo S-Y, eds. *Multiple muscle systems: biomechanics and movement organization*. New York: Springer-Verlag, 1990: 568-577.

Andrzejewski M, Chmura J, Pluta B, Strzelczyk R, Kasprzak A. Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research.* 2013: 27: 2134-2140.

Arampatzis A, Brüggemann GP, Klapsing GM. Leg stiffness and mechanical energetic processes during jumping on a sprung surface. *Medicine & Science in Sport & Exercise.* 2001a: 33: 923-931.

Arampatzis A, Morey-Klapsing G, Karamanidis K, DeMonte G, Stafilidis S, Brüggemann GP. Differences between measured and resultant joint moments during isometric contractions at the ankle joint. *Journal of Biomechanics.* 2005a: 38: 885-892.

Arampatzis A, Peper A, Bierbaum S, Albracht K. Plasticity of human Achilles tendon mechanical and morphological properties in response to cyclic strain. *Journal of Biomechanics.* 2010: 43: 3073-3079.

Arampatzis A, Schade F, Walsh M, Brüggemann GP. Influence of leg stiffness and its effect on myodynamic jumping performance. *Journal of Electromyography and Kinesiology.* 2001b: 11: 355-364.

Arampatzis A, Stafilidis S, DeMonte G, Karamanidis K, Morey-Klapsing G, Brüggemann GP. Strain and elongation of the human gastrocnemius tendon and aponeurosis during maximal plantarflexion effort. *Journal of Biomechanics.* 2005b: 38: 833-841.

Bachman G, Heise GD, Bressel E. The symmetry of the human leg spring: spring coefficients between right and left legs during running. In: Smith G, ed. *Proceedings of the 23rd Annual Meeting of the American Society of Biomechanics.* Pittsburgh, Philadelphia: American Society of Biomechanics, 1999.

Bailey C, Sato K, Alexander R, Chiang C-Y, Stone MH. Isometric force production symmetry and jumping performance in collegiate athletes. *Journal of Trainology.* 2013: 2: 1-5.

Bailey CA, Sato K, Burnett A, Stone MH. Force production asymmetry in male and female athletes of differing strength levels. *International Journal of Sports Physiology and Performance.* 2015: 10: 504-508.

Barnes KR, Hopkins WG, McGuigan MP, Kilding AE. Warm-up with a weighted vest improves running performance via leg stiffness and running economy. *Journal of Science and Medicine in Sport.* 2015: 18: 103-108.

Bazyler CD, Bailey CA, Chiang C-Y, Sato K, Stone MH. The effects of strength training on isometric force production symmetry in recreationally trained males. *Journal of Trainology.* 2014: 3: 6-10.

Beck TW. The importance of a priori sample size estimation in strength and conditioning research. *Journal of Strength and Conditioning Research.* 2013: 27: 2323-2337.

Becker HP, Rosenbaum D, Kriese T, Gerngroß H, Claes L. Gait asymmetry following successful surgical treatment of ankle fractures in young adults. *Clinical Orthopaedics and Related Research.* 1995: 311: 262-269.

Bell DR, Sanfilippo JL, Binkley N, Heiderscheit BC. Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *Journal of Strength and Conditioning Research.* 2014: 28: 884-891.

Benjanuvatra N, Lay BS, Alderson JA, Blanksby BA. Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. *Journal of Strength and Conditioning Research.* 2013: 27: 2700-2707.

Bishop D. Warm up II: Performance changes following active warm up and how to structure the warm up. *Sports Medicine.* 2003: 33: 483-498.

Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet.* 1986: 327: 307-310.

Blazevich AJ. Position, Velocity and Acceleration. In: Blazevich AJ, ed. *Sports Biomechanics: The Basics: Optimising Human Performance.* London, England: A & C Black Publishers Ltd, 2007:1-14.

Blickhan R. The spring-mass model for running and hopping. *Journal of Biomechanics.* 1989: 22: 1217-1227.

Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science and Medicine.* 2007: 6: 63-70.

Bobbert MF, Casius LJR. Is the effect of a countermovement on hump height due to active state development? *Medicine & Science in Sport & Exercise.* 2005: 37: 440-446.

Bobbert MF, Huijing PA, Van Ingen Schenau GJ. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine & Science in Sport & Exercise.* 1987: 19: 332-338.

Bourdin M, Rambaud O, Dorel S, Lacour JR, Moyen B, Rahmani A. Throwing performance is associated with muscular power. *International Journal of Sports Medicine.* 2010: 31: 505-510.

Brauner T, Sterzing T, Wulf M, Horstmann T. Leg stiffness: Comparison between unilateral and bilateral hopping tasks. *Human Movement Science.* 2014: 33: 263–272.

Bret C, Rahmani A, Dufour AB, Messonnier L, Lacour JR. Leg strength and stiffness as ability factors in 100 m sprint running. *Journal of Sports Medicine and Physical Fitness.* 2002: 42: 274-281.

Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Medicine.* 2008: 38: 1045-1063.

Burgess KE, Pearson SJ, Onambélé GL. Menstrual cycle variations in oestradiol and progesterone have no impact on in vivo medial gastrocnemius tendon mechanical properties. *Clinical Biomechanics.* 2009: 24: 504-509.

Butler RJ, Crowell III HP, Davis IM. Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics.* 2003: 18: 511-517.

Cavagna GA. Force platforms as ergometers. *Journal of Applied Physiology.* 1975: 39: 174-179.

Cavagna GA. The landing–take-off asymmetry in human running. *Journal of Experimental Biology.* 2006: 209: 4051-4060.

Cavagna GA, Saibene FP, Margaria R. Mechanical work in running. *Journal of Applied Physiology.* 1964: 19: 249-256.

Chaouachi A, Manzi V, Chaalali A, Wong DP, Chamari K, Castagna C. Determinants analysis of change-of-direction ability in elite soccer players. *Journal of Strength and Conditioning Research.* 2012: 26: 2667-2676.

Chelly SM, Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Medicine & Science in Sport & Exercise.* 2001: 33: 326-333.

Chow JW, Knudson DV. Use of deterministic models in sports and exercise biomechanics research. *Sports Biomechanics.* 2011: 10: 219-233.

Clarys JP, Cabri J. Electromyography and the study of sports movements: A review. *Journal of Sports Sciences*. 1993: 11: 379-448.

Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. New Jersey: Lawrence Erlbaum 1998.

Coleman DR, Cannavan D, Horne S, Blazevich AJ. Leg stiffness in human running: Comparison of estimates derived from previously published models to direct kinematic-kinetic measures. *Journal of Biomechanics*. 2012: 45: 1987–1991.

Comyns TM, Harrison AJ, Hennessy L, Jensen RL. Identifying the optimal resistive load for complex training in male rugby players. *Sports Biomechanics*. 2007: 6: 59-70.

Condello G, Kernozek TW, Tessitore A, Foster C. Biomechanical analysis of a change of direction task in collegiate soccer players. *International Journal of Sports Physiology and Performance*. 2016: 11: 96-101.

Cormie P, McGuigan MR, Newton RU. Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sport & Exercise*. 2010: 42: 1731-1744.

Delaney JA, Scott TJ, Ballard DA, Duthie GM, Hickmans JA, Lockie RG, Dascombe BJ. Contributing factors to change-of-direction ability in professional rugby league players. *Journal of Strength and Conditioning Research*. 2015: 29: 2688-2696.

Dempster WT. *Space requirements of the seated operator*. Ohio: Wright-Patterson Air Force Base 1955.

DeWeese BH, Nimphius S. Program design and technique for speed and agility training. In: Haff GG, Triplett NT, eds. *Essentials of Strength Training and Conditioning*. 4th Edition ed. Champaign, IL: Human Kinetics, 2016:521-558.

Divert C, Baur H, Mornieux G, Mayer F, Belli A. Stiffness adaptations in shod running. *Journal of Applied Biomechanics*. 2005: 21: 311-321.

Farley CT, Blickhan R, Saito J, Taylor CR. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *Journal of Applied Physiology*. 1991: 71: 2127-2132.

Farley CT, Glasheen J, McMahon TA. Running springs: speed and animal size. *The Journal of Experimental Biology*. 1993: 185: 71-86.

Farley CT, Houdijk HHP, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *Journal of Applied Physiology*. 1998: 85: 1044-1055.

Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *Journal of Biomechanics*. 1999: 32: 267-273.

Ferris DP, Farley CT. Interaction of leg stiffness and surface stiffness during human hopping. *Journal of Applied Physiology*. 1997: 82: 15-22.

Ferris DP, Liang K, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. *Journal of Biomechanics*. 1999: 32: 787-794.

Feldmann CR, Weiss LW, Schilling BK, Whitehead PN. Association of drop vertical jump displacement with select performance variables. *Journal of Strength and Conditioning Researc*h. 2012: 26: 1215-1225.

Fisher J, Wallin M. Unilateral versus bilateral resistance and plyometric training for change of direction speed. Journal of Athletic Enhancement. 2014: 3: 1-5.

Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength & Conditioning Journal*. 2008: 30: 32-38.

Flanagan EP, Harrison AJ. Muscle dynamics differences between legs in healthy adults. *Journal of Strength and Conditioning Research*. 2007: 21: 67-72.

Freriks B, Hermens HJ, Disselhorst-Klug C, Rau G. The Recommendations for Sensors and Sensor Placement Procedures for Surface ElectroMyoGraphy. In: Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G, eds. *SENIAM 8: European Recommendations for Surface ElectroMyoGraphy*: Roessingh Research and Development b.v., 1999:13-55.

Fukashiro S, Hay DC, Nagano A. Biomechanical behavior of muscle-tendon complex during dynamic human movements. *Journal of Applied Biomechanics.* 2006: 22: 131-147.

Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. In vivo behaviour of human muscle tendon during walking. *Proceedings of the Royal Society of London B: Biological Sciences.* 2001: 268: 229-233.

Gabbett TJ. Sprinting patterns of National Rugby League competition. *Journal of Strength and Conditioning Research.* 2012: 26: 121-130.

Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews.* 2001: 81: 1725-1789.

Gilbert G, Lees A. Changes in the force development characteristics of muscle following repeated maximum force and power exercise. *Ergonomics.* 2005: 48: 1576-1584.

Glaister BC, Orendurff MS, Schoen JA, Bernatz GC, Klute GK. Ground reaction forces and impulses during a transient turning maneuver. *Journal of Biomechanics.* 2008: 41: 3090-3093.

Golik-Peric D, Drapsin M, Obradovic B, Drid P. Short-term isokinetic training versus isotonic training: effects on asymmetry in strength of thigh muscles. *Journal of Human Kinetics.* 2011: 30: 29-35.

Gouwanda D, Senanayake SM. Identifying gait asymmetry using gyroscopes--a cross-correlation and Normalized Symmetry Index approach. *Journal of Biomechanics.* 2011: 44: 972-978.

Gullich A, Schmidtbleicher D. MVC-induced short-term potentiation of explosive force. New Studies in Athletics. 1996: 11: 67-81.

Hall SJ. Linear Kinematics of Human Movement. In: Hall SJ, ed. *Basic Biomechanics.* 6th Edition ed. New York, USA: McGraw Hill, 2012:319-354.

Harrison AJ, Keane SP, Coglan J. Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes. *Journal of Strength and Conditioning Research.* 2004: 18: 473-479.

Hart NH, Lockie RG, Spiteri T. Detecting deficits in change of direction performance using the pre-planned, multi-directional AFL agility test. *Journal of Strength and Conditioning Research.* 2014a.

Hart NH, Nimphius S, Spiteri T, Newton RU. Leg strength and lean mass symmetry influences kicking performance in Austrailian football. *Journal of Sports Science and Medicine.* 2014b: 13: 157-165.

Heise GD, Bachman G. Leg spring model properties of children. In: Smith G, ed. *Proceedings of the 24th Annual Meeting of the American Society of Biomechanics.* Pittsburgh, Philadelphia: American Society of Biomechanics, 2000.

Henry GJ, Dawson B, Lay BS, Young WB. Relationships between reactive agility movement time and unilateral vertical, horizontal and lateral jumps. *Journal of Strength and Conditioning Research.* 2013.

Hewit JK, Cronin JB, Hume PA. Kinematic factors affecting fast and slow straight and change-of-direction acceleration times. *Journal of Strength and Conditioning Research.* 2013: 27: 69-75.

Hobara H, Inoue K, Kanosue K. Effect of hopping frequency on bilateral differences in leg stiffness. *Journal of Applied Biomechanics*. 2013: 29: 55-60.

Hobara H, Inoue K, Kobayashi Y, Ogata T. A comparison of computation methods for leg stiffness during hopping. *Journal of Applied Biomechanics*. 2014: 30: 154-159.

Hobara H, Inoue K, Omuro K, Muraoka T, Kanosue K. Determinant of leg stiffness during hopping is frequency-dependent. *European Journal of Applied Physiology*. 2011: 111: 2195-2201.

Hobara H, Kanosue K, Suzuki S. Changes in muscle activity with increase in leg stiffness during hopping. *Neuroscience Letters*. 2007: 418: 55-59.

Hobara H, Kimura K, Omuro K, Gomi K, Muraoka T, Iso S, Kanosue K. Determinants of difference in leg stiffness between endurance- and power-trained athletes. *Journal of Biomechanics*. 2008: 41: 506-514.

Hobara H, Kimura K, Omuro K, Gomi K, Muraoka T, Sakamoto M, Kanosue K. Differences in lower extremity stiffness between endurance-trained athletes and untrained subjects. *Journal of Science and Medicine in Sport*. 2010: 13: 106-111.

Hobara H, Kobayashi Y, Kato E, Ogata T. Differences in spring-mass characteristics between one- and two-legged hopping. *Journal of Applied Biomechanics*. 2013: 29: 785-789.

Hobara H, Muraoka T, Omuro K, Gomi K, Sakamoto M, Inoue K, Kanosue K. Knee stiffness is a major determinant of leg stiffness during maximal hopping. *Journal of Biomechanics*. 2009: 42: 1768-1771.

Hodges SJ, Patrick RJ, Reiser II RF. Effects of fatigue on bilateral ground reaction force asymmetries during the squat exercise. *Journal of Strength and Conditioning Research*. 2011: 25: 3107-3117.

Hoffman JR, Ratamess NA, Klatt M, Faigenbaum AD, Kang J. Do bilateral power deficits influence direction-specific movement patterns? *Research in Sports Medicine*. 2007: 15: 125-132.

Hopkins WG. Measures of reliability in sports medicine and science. *Sports Medicine*. 2000: 30: 1-15.

Hopkins WG. A spreadsheet for analysis of straightforward controlled trials. *Sportscience*, 2003.

Hopkins WG. Precision of measurement. *A New View of Statistics*, 2011.

Horita T, Komi PV, Nicol C, Kyröläinen H. Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: implications to performance. *European Journal of Applied Physiology*. 2002: 88: 76-84.

Houghton L, Dawson B, Rubenson J. Achilles tendon mechanical properties after both prolonged continuous running and prolonged intermittent shuttle running in cricket batting. *Journal of Applied Biomechanics*. 2013: 29: 453-462.

Impellizzeri FM, Rampinini E, Maffiuletti N, Marcora SM. A vertical jump force test for assessing bilateral strength asymmetry in athlete. *Medicine & Science in Sport & Exercise*. 2007: 39: 2044-2050.

Jarvis MM, Graham-Smith P, Comfort P. A methodological approach to quantifying plyometric intensity. *Journal of Strength and Conditioning Research*. 2016: 9: 2522-2532.

Joseph CW, Bradshaw EJ, Kemp J, Clark RA. The interday reliability of ankle, knee, leg, and vertical musculoskeletal stiffness during hopping and overground running. *Journal of Applied Biomechanics*. 2013: 29: 386-394.

Joseph MF, Lillie KR, Bergeron DJ, Denegar CR. Measuring Achilles tendon mechanical properties: A reliable, noninvasive method. *Journal of Strength and Conditioning Research*. 2012: 26: 2017-2020.

Keogh JWL, Weber CL, Dalton CT. Evaluation of anthropometric, physiological, and skill related tests for talent identification in female field hockey. *Canadian Journal of Applied Physiology*. 2003: 28: 397-409.

Kilduff LP, Bevan HR, Kingsley MIC, Owen NJ, Bennett MA, Bunce PJ, Hore AM, Maw JR, Cunningham DJ. Postactivation potentiation in professional rugby players: Optimal recovery. *Journal of Strength and Conditioning Research*. 2007: 21: 1134-1138.

Kilduff LP, Owen N, Bevan H, Bennett M, Kingsley MIC, Cunningham D. Influence of recovery time on post-activation potentiation in professional rugby players. *Journal of Sports Sciences*. 2008: 26: 795-802.

Kim W, João F, Tan J, Mota P, Vleck V, Aguiar L, Veloso A. The natural shock absorption of the leg spring. Journal of Biomechanics. 2013: 46: 129-136.

Komi PV. Stretch-shortening cycle. In: Komi PV, ed. *Strength and Power in Sport*. 2nd Edition ed. Oxford: Blackwell Science, 2003:184-202.

Kongsgaard M, Nielsen CH, Hegnsvad S, Aagaard P, Magnusson SP. Mechanical properties of the human Achilles tendon, in vivo. *Clinical Biomechanics*. 2011: 26: 772-777.

Kubo K. In vivo elastic properties of human tendon structures in lower limb. *International Journal of Sport and Health Science*. 2005: 3: 143-151.

Kubo K, Kanehisa H, Fukanaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *Journal of Physiology*. 2002: 538: 219-226.

Kubo K, Kanehisa H, Kawakami Y, Fukanaga T. Influence of static stretching on viscoelastic properties of human tendon structures in vivo. *Journal of Applied Physiology*. 2001: 90: 520-527.

Kubo K, Kawakami Y, Fukanaga T. Influence of elastic properties of tendon structures on jump performance in humans. *Journal of Applied Physiology*. 1999: 87: 2090-2096.

Kubo K, Morimoto M, Komuro T, Tsunoda N, Kanehisa H, Fukanaga T. Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint. *European Journal of Applied Physiology*. 2007: 99: 235-243.

Kuitunen S, Komi PV, Kyröläinen H. Knee and ankle joint stiffness in sprint running. *Medicine & Science in Sport & Exercis*e. 2002: 34: 166-173.

Kuitunen S, Ogiso K, Komi PV. Leg and joint stiffness in human hopping. *Scandinavian Journal of Medicine and Science in Sports*. 2011: 21: e157-e167.

Kujala UM, Kettunen J, Paananen H, Aalto T, Battié MC, Impivaara O, Videman T, Sarna S. Knee osteoarthritis in former runners, soccer players, weight lifters, and shooters. *Arthritis and Rheumatology*. 1995: 38: 539-546.

Kunimasa Y, Sano K, Oda T, Nicol C, Komi PV, Locatelli E, Ito A, Ishikawa M. Specific muscle–tendon architecture in elite Kenyan distance runners. *Scandinavian Journal of Medicine and Science in* Sports. 2014: 24: e269-e274.

Kvist M. Achilles tendon injuries in athletes. *Sports Medicine*. 1994: 18: 173-201.

Latash ML, Zatsiorsky VM. Joint stiffness: Myth or reality? *Human Movement Science*. 1993: 12: 653-692.

Lindstedt SL, LaStayo PC, Reich TE. When active muscles lengthen: properties and consequences of eccentric contractions. *News in Physiological Sciences*. 2001: 16: 256-261.

Linthorne NP. Analysis of standing vertical jumps using a force platform. *American Journal of Physics*. 2001: 69: 1198-1204.

Lorimer AV, Hume PA. Stiffness as a risk factor for achilles tendon injury in running athletes. *Sports Medicine*. 2016. 18 May 2016 [epub ahead of print]. [doi: 10.1007/s40279-016-0526-9].

Lloyd RS, Oliver JL, Hughes MG, Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *Journal of Sports Sciences*. 2009: 27: 1565-1573.

Lockie RG, Callaghan SJ, Berry SP, Cooke ER, Jordan CA, Luczo TM, Jeffriess MD. Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *Journal of Strength and Conditioning Research*. 2014: 28: 3557-3566.

Lockie RG, Shultz AB, Jeffriess MD, Callaghan SJ. The relationship between bilateral differences of knee flexor and extensor isokinetic strength and multi-directional speed. *Isokinetics and Exercise Science*. 2012: 20: 211-219.

Maganaris CN, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. *Journal of Biomechanics*. 2002: 35: 1639-1646.

Magnusson SP, Aagaard P, Rosager S, Dyhre-Poulsen P, Kjaer M. Load-displacement properties of the human triceps surae aponeurosis in vivo. *Journal of Physiology*. 2001: 531: 277-288.

Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour and adaptation, in vivo. *The Journal of Physiology*. 2008: 586: 71-81.

Mahieu NN, McNair P, De Muynck M, Stevens V, Blanckaert I, Smits N, E W. Effect of static and ballistic stretching on the muscle-tendon unit properties. *Medicine & Science in Sport & Exercise*. 2007: 39: 494-501.

Mahieu NN, Witvrouw E, Stevens V, Willems T, Vanderstraeten G, Cambier D. Test-retest reliability of measuring the passive stiffness of the Achilles tendon using ultrasonography. *Isokinetics and Exercise Science*. 2004: 12: 185-191.

Mahlfeld K, Franke J, Awiszus F. Postcontraction changes of muscle architecture in human quadriceps muscle. *Muscle & Nerve*. 2004: 29: 597-600.

Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review of the literature and practical applications. *Sports Medicine*. 2014a: 44: 1347-1359.

Maloney SJ, Turner AN, Miller S. Acute effects of a loaded warm-up protocol on change of direction speed in professional badminton players. *Journal of Applied Biomechanics*. 2014b: 30: 637-642.

Mann TN, Lamberts RP, Lambert MI. High responders and low responders: factors associated with individual variation in response to standardized training. *Sports Medicine*. 2014: 44: 1113-1124.

Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey ÉC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *Journal of Strength and Conditioning Research*. 2014: 28: 2845-2851.

Marshall BM, Moran KA. Which drop jump technique is most effective at enhancing countermovement jump ability, "countermovement" drop jump or "bounce" drop jump? *Journal of Sports Sciences*. 2013: 31: 1368-1374.

McGill SM, Andersen JT, Horne AD. Predicting performance and injury resilience from movement quality and fitness scores in a basketball team over 2 years. *Journal of Strength and Conditioning Research*. 2012: 26: 1731-1739.

McGowan CJ, Pyne DB, Thompsen KG, Rattray B. Warm-up strategies for sport and exercise: mechanisms and applications. *Sports Medicine.* 2015: 45: 1523-1546.

McLachlan KA, Murphy AJ, Watsford ML, Rees S. The interday reliability of leg and ankle musculotendinous stiffness measures. *Journal of Applied Biomechanics.* 2006: 22: 206-304.

McMahon TA, Cheng GC. The mechanics of running: how does stiffness couple with speed? *Journal of Biomechanics.* 1990: 23: 65-78.

Meir R, Newton R, Curtis E, Fardell M, Butler B. Physical fitness qualities of professional rugby league football players: Determination of positional differences. *Journal of Strength and Conditioning Research.* 2001: 15: 450-458.

Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Medicine and Science in Sports and Exercise.* 2006: 38: 323-328.

Moir GL, Dale JR, Dietrich WW. The acute effects of heavy back squats on mechanical variables during a series of bilateral hops. *Journal of Strength and Conditioning Research.* 2009: 23: 1118-1124.

Moir GL, Mergy D, Witmer CA, Davis SE. The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. *Journal of Strength and Conditioning Research.* 2011: 25: 1486-1491.

Moresi MP, Bradshaw EJ, Greene DA, Naughton GA. The impact of data reduction on the intra-trial reliability of a typical measure of lower limb musculoskeletal stiffness. *Journal of Sports Sciences.* 2015: 33: 180-191.

Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. *Journal of Applied Biomechanics.* 2005: 21: 167-180.

Morin JB, Jeannin T, Chevallier B, Belli A. Spring-mass model characteristics during sprint running: Correlation with performance and fatigue-induced changes. *International Journal of Sports Medicine.* 2006: 27: 158-165.

Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *Journal of Physiology.* 2008: 586: 97-106.

Muramatsu T, Muraoka T, Kawakami Y, Fukanaga T. Superficial aponeurosis of human gastrocnemius is elongated during contraction: implications for modeling muscle-tendon unit. *Journal of Biomechanics.* 2002: 35: 217-223.

Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Hirano Y, Fukunaga T. Mechanical properties of tendon and aponeurosis of human gastrocnemius muscle in vivo. *Journal of Applied Physiology.* 2001: 90: 1671-1678.

Muraoka T, Muramatsu T, Takeshita D, Kawakami Y, Fukunaga T. Length change of human gastrocnemius aponeurosis and tendon during passive joint motion. *Cells Tissues Organs.* 2002: 171: 260-268.

Nava KM. The acute effects of different warm-up techniques on power output, agility, and flexibility in athletes: University of Texas at Brownsville, 2015.

Newton RU, Dugan E. Application of strength diagnosis. *Strength & Conditioning Journal.* 2002: 24: 50-59.

Ortiz A, Olson S, Libby CL, Kwon Y-H, Trudelle-Jackson E. Kinematic and kinetic reliability of two jumping and landing physical performance tasks in young adult women. *North American Journal of Sports Therapy.* 2007: 2: 104-112.

Padua DA, Arnold BL, Carcia CR, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *Journal of Motor Behaviour.* 2005: 37: 111-126.

Pearson SJ, McMahon J. Lower limb mechanical properties: determining factors and implications for performance. *Sports Medicine.* 2012: 42: 929-940.

Perttunen JR, Anttila E, Sodergard J, Merikanto J, Komi PV. Gait asymmetry in patients with limb length discrepancy. *Scandinavian Journal of Medicine and Science in Sports.* 2004: 14: 49-54.

Pruyn EC, Watsford M, Murphy A. The relationship between lower-body stiffness and dynamic performance. *Applied Physiology, Nutrition, and Metabolism.* 2014: 39: 1144-1150.

Pruyn EC, Watsford ML, Murphy AJ, Pine MJ, Spurrs RW, Cameron ML, Johnston RJ. Relationship between leg stiffness and lower body injuries in professional Australian football. *Journal of Sports Sciences.* 2012: 30: 71-78.

Read MM, Cisar C. The influence of varied rest interval lengths on depth jump performance. *Journal of Strength and Conditioning Research.* 2001: 15: 279-283.

Reilly T, Williams AM, Nevill A, Franks A. A multidisciplinary approach to talent identification in soccer. *Journal of Sports Sciences.* 2000: 18: 695-702.

Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of Manipulative Physiological Therapy.* 1987: 10: 172-176.

Rosager S, Aagaard P, Dyhre-Poulsen P, Neergaard K, Kjaer M, Magnusson SP. Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scandinavian Journal of Medicine and Science in Sports.* 2002: 12: 90-98.

Sasaki S, Nagano Y, Kaneko S, Takakuni S, Fukubayashi T. The relationship between performance and trunk movement during change of direction. *Journal of Sports Science and Medicine.* 2011: 10: 112-118.

Sato K, Heise GD. Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *Journal of Strength and Conditioning Research.* 2012: 26: 342-349.

Schmidtbleicher D. Training for power events. In: Komi PV, ed. *Strength and Power in Sport.* Oxford: Blackwell Scientific Publications, 1992:381-395.

Seifert L, Button C, Davids K. Key properties of expert movement systems in sport: An ecological dynamics perspective. *Sports Medicine.* 2013: 43: 167-178.

Serpell BG, Ball NB, Scarvell JM, Smith PN. A review of models of vertical, leg, and knee stiffness in adults for running, jumping or hopping tasks. *Journal of Sports Sciences.* 2012: 30: 1347-1363.

Seyfarth A, Blickhan R, Van Leeuwen JL. Optimum take-off techniques and muscle design for long jump. *Journal of Experimental Biology.* 2000: 203: 741-750.

Sheppard JM, Young WB. Agility literature review: classifications, training and testing. *Journal of Sports Sciences.* 2006: 24: 919-932.

Shimokochi Y, Ide D, Kokubu M, Nakaoji T. Relationships among performance of lateral cutting maneuver from lateral sliding and hip extension and abduction motions, ground reaction force, and body center of mass height. *Journal of Strength and Conditioning Research.* 2013: 27: 1851-1860.

Shorter KA, Polk JD, Rosengren KS, Hsiao-Wrecksler ET. A new approach to detecting asymmetry in gait. *Clinical Biomechanics.* 2008: 23: 459-467.

Simon AM, Ferris DP. Lower limb force production and bilateral force asymmetries are based on sense of effort. *Experimental Brain Research.* 2008: 187: 129-138.

Sole CJ, Moir GL, Davis SE, Witmer CA. Mechanical analysis of the acute effects of a heavy resistance exercise warm-up on agility performance in court-sport athletes. *Journal of Human Kinetics.* 2013: 39: 147-156.

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. *European Journal of Sport Science*. 2013: 13: 642-652.

Spiteri T, Newton RU, Binetti M, Hart NH, Sheppard JM, Nimphius S. Mechanical determinants of faster change of direction and agility performance in female basketball athletes. *Journal of Strength and Conditioning Research*. 2015: 29: 2205-2214.

Stålbom M, Holm DJ, Cronin JB, Keogh JWL. Reliability of kinematics and kinetics associated with horizontal single leg drop jump assessment. A brief report. *Journal of Sports Science and Medicine*. 2007: 6: 261-264.

Sturgess S, Newton RU. Design and implementation of a specific strength program for badminton. Strength & Conditioning Journal. 2008: 30: 34-41.

Sugiyama T, Kameda M, Kageyama M, Kiba K, Kanehisa H, Maeda A. Asymmetry between the dominant and non-dominant legs in the kinematics of the lower extremities during a running single leg jump in collegiate basketball players. *Journal of Sports Science and Medicine*. 2014: 13.

Sweeney HL, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrae striated muscle: regulation and function. *American Journal of Physiology - Cell Physiology*. 1993: 264: C1085-C1095.

Theis N, Mohagheghi AA, Korff T. Method and strain rate dependence of Achilles tendon stiffness. *Journal of Electromyography and Kinesiology*. 2012: 22: 947-953.

Turner AN, Jeffreys I. The stretch-shortening cycle: proposed mechanisms and methods for enhancement. *Strength & Conditioning Journal*. 2010: 32: 87-99.

Vagenas G, Hoshizaki B. Functional asymmetries and lateral dominance in the lower limbs of distance runners. *International Journal of Sport Biomechanics*. 1991: 7: 311-329.

Walshe AD, Wilson GJ. The influence of musculotendinous stiffness on drop jump performance. *Canadian Journal of Applied Physiology*. 1997: 22: 117-132.

Watsford ML, Murphy AJ, McLachlan KA, Bryant AL, Cameron ML, Crossley KM, Makdissi M. A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. *American Journal of Sports Medicine*. 2010: 38: 2058-2064.

Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*. 2005: 19: 231-240.

Williams DS, McClay IS, Hamill J. Arch structure and injury patterns in runners. *Clinical Biomechanics*. 2001: 16: 341-347.

Wilson GJ, Murphy AJ, Pryor JF. Musculotendinous stiffness: Its relationship to eccentric, isometric, and concentric performance. *Journal of Applied Physiology*. 1994: 76: 2714-2719.

Winter DA. Kinematics. *Biomechanics and Motor Control of Human Movement*. 4th ed. New Jersey: John Wiley & Sons, Inc., 2009a: 45-81.

Winter DA. Kinetics: forces and moments of force. *Biomechanics and Motor Control of Human Movement*. 4th ed. New Jersey: John Wiley & Sons, Inc., 2009b: 107-138.

Witmer CA, Davis SE, Moir GL. The acute effects of back squats on vertical jump performance in men and women. *Journal of Sports Science and Medicine*. 2010: 9: 206-213.

Young W, Farrow D. A review of agility: Practical applications for strength and conditioning. *Strength & Conditioning Journal*. 2006: 28: 24-29.

Young W, James R, Montgomery I. Is muscle power related to running speed with changes of direction? *Journal of Sports Medicine and Physical Fitness.* 2002: 42: 282-288.

Young WB, Miller IR, Talpey SW. Physical qualities predict change-of-direction speed but not defensive agility in Australian rules football. *Journal of Strength and Conditioning Research.* 2015: 29: 206-212.

Zhao H, Ren Y, Wu Y-N, Liu SQ, Zhang L-Q. Ultrasonic evaluations of Achilles tendon mechanical properties poststroke. *Journal of Applied Physiology.* 2009: 106: 843-849.

Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: A novel, robust method of quantifying asymmetry. *Gait & Posture.* 2008: 27: 622-627.

Zois J, Bishop DJ, Ball K, Aughey RJ. High-intensity warm-ups elicit superior improvements to a current soccer warm-up routine. *Journal of Science and Medicine in Sport.* 2011: 14: 522-528.