An investigation of the biological variability of the Triple-Joint Flexion Test in adolescent male athletes using 2-D video analysis

Matiu John Taingahue

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Abstract

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Background: Movement screening has become standard practice in a range of sports injury settings, however, few standardised protocols have undergone rigorous testing, and the biological variability in athletes’ performance has seldom been investigated or discussed in the movement screening literature.

Aim: to investigate the intra-athlete within- and between-session variability of the Triple-Joint Flexion Test (TJFT) in adolescent, development-level, court and field sport athletes.

Design: video-based, repeated-measures.

Methods: Two-dimensional video rating and kinematic analyses were performed on simultaneous front and side views of 17 uninjured, male, adolescent athletes (mean ± SD age = 16.9 ± 0.9 years) performing 6 repetitions of the TJFT; and 14 athletes who repeated the TJFT 24h later. Two digital cameras (Panasonic HC-V520M) and video analysis software (PnO Data Solutions, CA, United States) were used to capture, synchronise and analyse the images. Intraclass correlation coefficients (ICC) and typical errors (TE) were used to assess within- and between-day reliability of all variables. Friedman’s and Wilcoxon signed-rank tests were used to check for systematic changes in rating score within- and between-sessions.

Results: The within-session reliability of rating scores (TE 1.5 to 0.7 pts, ICC 0.14 to 0.87) and frontal plane kinematic variables (TE 15 to 3°, ICC -0.11 to 0.88) ranged from ‘poor’ to ‘excellent’ for the individual movement tests (TE 0.7 to 1.5 pts, and 3 to 15°, ICC 0.14 to 0.87, and -0.11 to 0.88), but the within-session reliability of the sagittal plane flexion angles was ‘good’ to ‘excellent’ for all movement tests (TE 1 to 7°, ICC 0.60 to 0.97). The between-session reliability of rating scores (TE 0.8 to 0.5 pts, ICC 0.62 to 0.98) and kinematic variables (TE 8 to 1°, ICC 0.30 to 0.88) were predominantly ‘good’ to ‘excellent’ for all tests. No significant systematic changes were observed in rating score within- or between-sessions for any of the tests.

Conclusions: These results suggest the TJFT could be clinically useful for monitoring lower limb function in adolescent athletes. The need for further investigation of movement variability associated with performance, scoring and interpretation of movement screening tests is also highlighted.

Keywords: Reliability, Biological variability, Lower limb, Movement screening, Triple-joint flexion
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Chapter 1: Introduction

Sport is a popular means of balancing the sedentary nature of our modern lifestyle, and although participation is encouraged by most health professionals (Kohl et al., 2012), musculoskeletal injuries are common (Verhagen, Bolling, & Finch, 2015). Lower limb injuries are most prevalent in competitive sport, especially in court and field sports (Fong, Hong, Chan, Yung, & Chan, 2007), and most injury reduction strategies target preventable injuries, such as those associated with overuse. Adolescent athletes have arguably the most to gain from injury reduction interventions because they have a high prevalence of overuse injuries (DiFiori et al., 2014), and the highest participation rates in court and field sports (Sport & Recreation New Zealand [SPARC], 2008). In addition, minimising overuse injuries and developing fundamental movement skills are central components of most long term athlete development models (Balyi, Way, & Higgs, 2013; Giles, 2010). The focus on injury prevention in adolescent athletes is further supported by the general consensus that previous injury is the strongest predisposing factor for future musculoskeletal injury (Hägglund, Waldén, & Ekstrand, 2013; Bahr & Holme, 2003). There is considerable debate among sports injury practitioners as to what modifiable factors predispose athletes to injury, and consequently, what factors should be assessed in injury reduction interventions. Despite this debate, it is generally accepted that traditional assessments of isolated structures are no longer adequate, and movement dysfunction assessments (collectively termed ‘movement screening’) based on visual analysis of functional tasks have become common (McCall et al., 2014; Mottram & Comerford, 2008).

Movement dysfunction is associated with most common lower limb injuries and there is growing evidence that it also increases the risk of injury (Felson et al., 2013; Chuter & Janse de Jonge, 2012; Powers, 2010; McKeon & Hertel, 2008; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007a; Plisky, Rauh, Kaminski, & Underwood, 2006; Hewett et al., 2005). This combination of findings provides a rationale for using movement screening to help guide injury reduction and management strategies, and to some extent, justify its widespread use. Although movement screening has become standard-practice in a range of settings and can substantially impact clinical decision-making, it should be acknowledged that few standardised protocols have undergone rigorous testing and its limitations for clinical use are not well understood (Kivlan & Martin, 2012). In order for movement screening protocols to have clinical utility, they need to be reliable, valid, and effective. Movement screening tests are often clinically-developed and practically-oriented for the monitoring of athlete development, rehabilitation and injury risk over time (Gamble, 2013). It is difficult to investigate the validity of movement screening for predicting injury because of practical and ethical difficulties with identifying dysfunction, and then tracking athletes to record injuries, without disclosing the
dysfunction or intervening to correct it. It is understandable therefore, that most of the existing research has focussed on reliability of visually analysed movement screening tests.

The reliability of visually analysed movement tests is influenced by the biological variability of the athlete and the rater, but few researchers have investigated intra-athlete variability in movement screening. Video rating has been successfully used in previous studies to specifically investigate the intra- and inter-rater reliability of movement screening tests by excluding the intra-athlete variability (McKeown, Taylor-McKeown, Woods, & Ball, 2014; Shultz, Anderson, Matheson, Marcello, & Besier, 2013; Whatman, Hing, & Hume, 2012a). Although excluding intra-athlete variability could be useful for investigating visual rating methods and criteria, an understanding of expected variability in athletes’ performance of movement tests is also required in order to refine the testing protocol and interpret the results within a clinical context. Intra-athlete, within-session variability has seldom been reported in movement screening literature and the potential effect it can have on ratings, clinical interventions, and injury risk has seldom been discussed. Because the rating of most movement screening protocols is based on several repetitions of each test, the lack of investigation of intra-athlete, within-session variability in performance and subsequent understanding of how a rating should be made to represent that performance, is surprising.

In essence, most of the movement screening research to date has focussed on rater reliability, and there has generally been insufficient investigation of intra-athlete variability associated with movement tests, protocols, and criteria used to make ratings. When interpreting results of reliability studies to inform the clinical use of movement screening, it is important to consider all sources of variability and the manner in which ratings were made. In the development of a movement screening protocol, individually investigating both the variability associated with athlete’s performance, and the rating process, provides an opportunity to specifically adapt parts of the protocol that most impact reliability and improve clinical utility of results. A two-part study using video analysis and then live video rating of the same subject group could potentially be the best way to conduct an initial investigation of a movement screening protocol.

The movement screening protocol being investigated in this study is the Triple-Joint Flexion Test (TJFT). The TJFT is a movement screening protocol based on the visual analysis of three commonly used lower limb tests: the double leg squat (DL), single leg squat (left = SLL and right = SLR), and a single leg landing from a 50cm horizontal hop, termed the ‘hop and stick’ (left = HSL and right = HSR). These movement tests were selected to challenge mobility and neuromuscular control in three fundamental lower limb movements, which are kinematically similar, but the loading characteristics of each test progressively increase demand for dynamic stability. The rating method and criteria are similar for each movement test (see Appendix 1) and were designed to address multiple clinical
needs: (1) to permit the comparison of right/left differences; (2) to provide clinically useful information for guiding intervention; (3) to maximise the potential for reliable results; (4) to minimise the requirement for expensive or technical equipment; and (5) to simplify screening large groups of athletes as typically occurs in pre-season situations. The TJFT protocol was clinically developed and has undergone considerable practical testing and modification in a range of sporting environments (see Appendix 2), but has not been formally investigated to date.

This study was therefore the initial exploratory step in investigating the reliability of the TJFT. The study aim was to investigate the biological variability associated with performance of the TJFT in a group of development-level, adolescent, court and field sport athletes. The specific objectives were:

1. to assess the intra-athlete within-session reliability of (a) the rating scores of each of the movement tests; and (b) the 2-dimensional frontal and sagittal plane kinematics during each of the movement tests; and
2. to assess the intra-athlete, between-session reliability of (a) the rating scores of each of the movement tests; and (b) the 2-dimensional frontal and sagittal plane kinematics during each of the movement tests.
Chapter 2: Literature Review

2.1. Injuries in physical activity and sport

2.1.1. Sport is popular and encouraged for health and disease prevention

Non-communicable diseases, primarily cancer, diabetes, cardiovascular and chronic lung disease, account for the majority of all deaths worldwide and the four major behavioural risk factors for development of these diseases are: the harmful use of alcohol, an unhealthy diet, tobacco use, and a lack of physical activity (World Health Organisation, 2010). The positive impact of physical activity on health is so widely supported that several leading medical practitioners and scientists have advocated that the “exercise vital sign” described by Sallis (2011), should be recorded as a routine part of all consultations in the same manner other vital signs such as blood pressure are measured and recorded (Khan et al., 2012). With the importance of physical activity contrasting against the sedentary nature of our modern lifestyles (Kohl et al., 2012) there is an increasing awareness of how important regular physical activity is for health. Referral by medical practitioners for exercise prescription as primary prevention or secondary management is now a relatively well accepted and utilised intervention in the publically funded healthcare systems of Sweden and New Zealand (Leijon, Bendtsen, Nilsen, Ekberg, & Ståhle, 2008; Patel, Schofield, Kolt, & Keogh, 2011). Participation in sport and recreation activities is a popular and widely-encouraged means of accumulating physical activity with government funded agencies in many countries established to promote this. In New Zealand, 79% of people aged 16 or over participate in sport or recreation activities at least once per week, with walking (64.1%), gardening (43.2%), swimming (34.8%), equipment-based exercise (26.5%) and cycling (22.7%) most popular (SPARC, 2008).

2.1.2. An increased risk of musculoskeletal injury is associated with sports participation

The physical, psychological and social benefits of sports participation are widely documented, however, a trade-off exists between these benefits and the increased risk of musculoskeletal injury that is associated with sports training and competition (Marshall & Guskiewicz, 2003; Verhagen et al., 2015). Between 1997 and 1999 the rate of sports related injuries requiring treatment in the United States exceeded that of transport-related injuries, 1 out of every 5 injury episodes in people aged 5 to 24-years were sports related, and although the consequences of sports related injuries were generally mild, 20 to 28% of people lost at least one day of work or school as a result (Conn, Annest, &
Gilchrist, 2003). It has been reported that at least one third of Americans between the ages of 5 and 24-years seeks medical attention each year for sports related injuries with an estimated yearly cost of US$1.8 billion to treat these injuries (Adirim and Cheng, 2003). Injury may lead to discontinuity of training, drop out, decreased performance, residual symptoms, and also predisposes future joint degeneration and disability (Maffuli, Longo, Gougoulias, Caine, & Denaro, 2011). So, although sport and recreation activities are a popular and effective means of getting people involved in, and continuing physical activity practices, decreasing the risk of musculoskeletal injury is important to ensure an optimal cost:benefit ratio.

2.1.3. Competitive sport is easier to study and lower limb injuries are common

The repetitive nature, performance focus, and systematic injury monitoring in competitive sport are conducive to research, making it easier to study musculoskeletal injuries associated with competitive sport, than in recreational sport. Increased exposure to competition has also been reported to be an independent risk factor for sports injury (Ekstrand, Hägglund, & Waldén, 2011; Nilstad, Andersen, Bahr, Holme, & Steffen, 2014). In a systematic review of epidemiological studies on sports injuries from 1977 to 2005, Fong, et al. (2007) reported that the knee was the most commonly injured site followed by the ankle, and that these injuries were especially prevalent in multi-directional, court and field sports. In competitive sport the requirement for high levels of performance needs to be carefully balanced with the athletes ability to tolerate the demands of that performance. Although it is generally accepted that little can be done to prevent injuries resulting from acute trauma, injury management and reduction strategies that target preventable injuries, such as those associated with overuse, have become integral components of sports performance.

2.1.4. Adolescent development-level athletes are potentially the optimal group for injury reduction studies

Overuse injuries develop when the micro-trauma of repeated submaximal loading exceeds the ability of a musculoskeletal structure to adapt and tolerate that load (DiFiori, 2010). Abrupt changes in training load, periods of rapid growth, previous injury, and faulty biomechanics are considered to be predisposing factors for overuse injuries of the lower limb (Wilder and Sethi, 2004), especially in youth (6 to 18-years) athletes (Hawkins & Metheny, 2001; DiFiori et al., 2014). Although the prevalence varies between 30 and 70% by sport, conservative estimates suggest that overuse injuries account for approximately half of all injuries in youth sport (DiFiori et al., 2014). In New Zealand, participation rates above 10% in dynamic, multi-directional sports are only evident in those under 25 years old, with basketball (22.7%), rugby (19.7%), touch (19.2%), and tennis (17.6%) the most
popular among the 16 to 24 year old group (SPARC, 2008). In competitive sport the transition from youth to senior competition is known as the ‘development-level’ and athletes at this level will often be exposed to more specialised training and participate to some degree in both youth and senior sport. Development-level, adolescent athletes could potentially be the optimal group to study with respect to injury reduction, for several reasons: (1) avoiding an initial injury decreases the risk of subsequent injury; (2) their exposure to competition can be easily controlled and monitored; (3) they are commonly involved in dynamic, multidirectional sports and are undergoing rapid physical development; and (4) changes in training load and potentially avoidable overuse injuries are common.

2.1.5. Summary - Injuries in physical activity and sport

The sedentary nature of modern lifestyles has made sport and recreational activities increasingly important determinants of health, but there is a trade-off between the potential benefits of these activities and the increased risk of musculoskeletal injury. In order to gain an understanding of these injuries and investigate potential strategies for injury reduction, it is easier to study competitive sport than recreational sport. Lower limb injuries are the most common musculoskeletal injuries in competitive sport and development-level, adolescent athletes could potentially be an optimal group to study, because of their participation rates, exposure to competition and training, and high incidence of lower-limb overuse injuries.

2.2. The aetiology of injury in competitive sport

There is good evidence for the interplay of biological, psychological, and social factors in the aetiology, prognosis, and management of injury (Pincus et al., 2013), however, this review will focus on the biological factors associated with injuries in competitive sport. In general there appears to be more literature on lower limb sports injuries than upper limb, or any other body region. The research emphasis on lower limb injury is possibly due to the higher prevalence of lower limb injury (Fong et al., 2007), and negative impact on sports participation (Maffuli et al, 2011). Given the context of the present study, lower limb injury will be the focus of the remainder of the review.

2.2.1. Physical risk factors for lower limb sports injury

With the exception of increased exposure to competition, previous injury, and older age (Murphy, Connolly, & Beynon, 2003; Hägglund et al., 2013), there is considerable debate in the scientific
literature as to the individual physical factors that predispose sports injury and a multifactorial approach to analysis is required (Bahr and Krosshaug, 2005). In a review of methodological approaches for investigating injury risk in sport, Bahr and Holme (2003) described a dynamic model, adapted from that proposed by Meeuwisse (1994), which accounts for the multifactorial nature of injury and the sequence of events that led to the injury. In describing the practical application of the model, the authors emphasised the complex interaction of multiple risk factors and events that lead to injury and that although non-modifiable risk factors were of interest, the potentially modifiable intrinsic and extrinsic risk factors are considered the most important to identify and study. So, in the absence of evidence to suggest otherwise, there are potentially multiple physical factors that interact to increase the risk of lower limb sports injury, and from a practical standpoint, it seems justified to attempt to identify the modifiable factors that are most likely to increase risk.

2.2.2. Lack of consensus as to which modifiable physical risk factors predispose injury

In one of the first extensive reviews of literature on risk factors for lower extremity injury, Murphy et al. (2003) identified several modifiable, physical risk factors, but concluded that there was insufficient consensus to confirm that any of them predisposed athletes to subsequent lower extremity injury. Although this review is now dated, similar findings have been reported recently in more targeted studies (Hägglund et al., 2013; van Beijsterveldt, van de Port, Vereijken, & Back, 2013). Murphy et al. (2003) suggested that the lack of consensus between studies might result from varying definitions of injury and risk, dissimilar baseline risks across sports, different experimental protocols and different timing and frequency of data acquisition. These are common difficulties when comparing studies on risk factors for injury because few studies have used standardised models for collecting, analysing or presenting data that permit comparison (Hägglund, Waldén, Bahr, & Ekstrand, 2005; Hopkins, Marshall, Quarrie, & Hume, 2007). Closer analysis of the studies reviewed by Murphy et al (2003) does however, suggest a tendency for increased risk to be associated with increased postural sway, anatomical malalignment, muscle strength imbalances, and decreased aerobic fitness, but no increased risk associated with decreased range of movement (ROM).

2.2.3. Is range of movement a modifiable risk factor for lower limb injury?

Range of movement assessment is commonly included in pre-participation and pre-season injury risk assessments and stretching to increase range of movement has traditionally been a standard part of injury prevention programs. In a systematic review of the literature on the impact of stretching and flexibility on injury risk, Thacker, Gilchrist, Stroup, and Kimsey (2004) found that there was good evidence stretching increased range of movement, at least short term, and that extremes of
hypomobility and hypermobility increased the risk of injury, however, stretching had no significant impact on injury risk or a reduction in total injuries. The authors concluded that although stretching might be necessary in specific cases of extreme hypomobility or sports that require extreme ranges of movement for performance, the evidence suggests it has little or no impact on injury risk. Based on a prospective study of elite soccer players, Witvrouw, Danneels, Asselman, D’Have, and Cambier. (2003) suggested that decreased pre-season hamstring flexibility did increase the risk of hamstring injury in soccer, but this has not been confirmed in recent systematic reviews because of considerable conflicting evidence in the primary studies (van Beijsterveldt, 2013; Freckleton & Pizzari, 2013). The association between injury risk and extreme hypomobility or hypermobility (Thacker et al., 2004), have been supported by more recent systematic reviews on risk factors for knee and ankle injury. de Noronha, Refshauge, Herbert, and Kilbreath. (2006) reported that ankle hypomobility (≤ 34° ankle dorsiflexion), postural sway and possibly proprioception were modifiable physical risk factors that predicted ankle sprain. de Noronha et al. (2006) also commented that high quality studies on the predictors of ankle sprain were scarce and although decreased dorsiflexion range was the best predictor at that time, an interaction of factors was more likely the key to prediction of ankle injury. Pacey, Nicholson, Adams, Munn, and Munns (2010), concluded that sports participants with generalized hypermobility had significantly increased risk of knee injury (OR 4.69, 95%CI 1.33 to 16.52, p = 0.02) but not ankle injury while playing contact sports when compared with non-hypermobile peers.

2.2.4. Traditional focus on range of movement and isolated structures insufficient for prevention or rehabilitation

The general lack of evidence to support the traditionally accepted association between injury risk and range of movement, excluding extreme hypo- and hypermobility, may in part be explained by the body’s apparent ability to compensate for a loss in range of movement at one or more moving segments by developing compensatory movement at adjacent segments. This clinically observed compensation has been described as ‘relative stiffness’ and ‘relative flexibility’ by Sahrmann (2002) and contributes heavily to the rationale behind many assessment and treatment techniques in manual and physical therapy today (Starrett & Cordoza, 2013; Mottram & Comerford, 2008; Cook, Burton, & Hoogenboom, 2006). A general trend away from measuring isolated joints and muscle actions in single anatomical planes and acknowledging that the risk of injury is the result of an interaction of multiple factors, has led to more interest in so called ‘functional’, whole system models in which movement dysfunction is the central focus (Key, Cliff, Condie, & Harley, 2008). The fact that previous injury is one of the most consistent and reliable predictors of subsequent injury provides further support for this shift away from isolated measures. The strength of previous injury as a
predictor of re-injury, has lead to the view that existing clinical outcomes of asymptomatic function, normal range of joint movement (isolated testing) and normal muscle strength (isolated testing) are insufficient rehabilitation end points (Motttram & Comerford, 2008). These endpoints could be replaced with assessments of movement control in functional tasks involving multiple muscle interactions on multiple joints (Comerford, 2006; Roussel et al., 2012) and such assessment has emerged in widespread clinical use.

2.2.5. Summary - The aetiology of injury in competitive sport

It is well established that previous injury, increased age, and increased exposure to competition are predisposing factors for lower limb injury in sport, but there is lack of consensus in the literature as to the individual physical risk factors that are modifiable. This lack of consensus is possibly due to the complex and potentially multifactorial nature of sports injury, as well as the inability to compare studies because of a lack of standardised experimental protocols and data collection methods. So, in the absence of evidence to suggest otherwise, it seems plausible that musculoskeletal sports injuries result from an event or series of events in which the demand on musculoskeletal structures exceeds their ability to tolerate those demands, for whatever reason, at that time. With the exception of extreme hyper- and hypomobility, it is questionable whether the traditional focus on ROM as a risk factor for injury is justifiable. There also appears to be a general trend away from the clinical assessment of isolated structures and an increased focus on movement control and joint alignment in functional tasks that involve multi-joint, multi-plane motion.

2.3. Deficits in movement control and dynamic joint malalignment (movement dysfunction) are commonly associated with lower limb injury.

The increased focus on assessing functional tasks, as opposed to isolated structures, has led to increased sports injury research on movement dysfunction, and there is now growing evidence that deficits in movement control and dynamic malalignment are associated with increased risk and progression of lower limb injury. The term ‘movement dysfunction’ is commonly used in sport without an operational definition of what it is and how it was assessed (Reiman & Manske, 2011), but for the purposes of this review, movement dysfunction refers to deficits in movement control and/or dynamic joint malalignment during multi-joint, multi-plane, functional tasks. In the sports injury literature, the knee has been studied more extensively than any other lower limb joint and its anatomical structure and hinge-like function make it less capable of multiplanar motion than the hip or ankle. Given the breadth of research, high prevalence of knee injury (Fong et al., 2007), and
potential impact multi-directional movement could have on knee injury (Powers, 2010), the following section is primarily focussed on common injuries to the knee. More general associations between movement dysfunction and injury to the other lower limb joints are drawn, based on less extensive review, and finally a review of the contradictory evidence is presented.

2.3.1. Movement dysfunction and common knee injuries

2.3.1.1. Knee ligament injury generally

Based on two parallel studies of n=277 collegiate athletes with no previous history of knee injury, it was reported that athletes with decreased neuromuscular control of the trunk had an increased risk of knee injury (Zazulak et al., 2007a; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007b). Trunk displacement was measured in response to sudden force release tasks in an apparatus that restrained pelvic and lower limb movement but allowed the upper body to move freely and trunk proprioception was measured using trunk repositioning tasks with an apparatus that produced motion of the lumbar spine in the transverse plane. Knee injuries were subsequently monitored during a 3-year follow up period and all ligament injuries were confirmed by magnetic resonance imaging (MRI). Increased trunk displacement in the frontal plane was the strongest single predictor of knee injury especially in females who sustained ligament injuries. A history of low back pain was also reported to be a predictor of knee injury, especially in males, and the combination of factors related to lumbo-pelvic control (history of low back pain, all trunk displacements and trunk repositioning measures) was reported to predict knee injury with 83% sensitivity and 63% specificity. Although Zazulak et al (2007a) did not report a likelihood ratio, this combination of factors appears to increase the likelihood of knee injury (positive likelihood ratio [+LR] calculated as 2.2), albeit moderately (Attia, 2003). In combination, these findings emphasise the multifactorial nature of non-contact knee injury and support the idea that movement control deficits are associated with an increased risk of lower limb injury.

2.3.1.2. Anterior cruciate ligament injury

There has been considerable research on anterior cruciate ligament (ACL) injury in soccer, possibly due to the amount of time lost from competition (Gotlob & Baker, 2000) and the subsequent increased risk of secondary injuries and osteoarthritis (Lohmander, Englund, Dahl, & Roos, 2007). Based on an extensive review of the literature, Alentorn-Geli et al. (2009) defined the most probable mechanisms of ACL injury in soccer, and identified modifiable physical risk factors including: decreased hamstring to quadriceps strength and recruitment ratio, poor neuromuscular control of the trunk and hip, lateral trunk displacement and hip adduction with increased knee valgus, and increased internal
rotation of the femur with external rotation of the tibia. Although these findings were applied to soccer, the research reviewed was not limited to soccer and the risk factors proposed can therefore be generalised to other dynamic, multi-directional sports. With the exception of a decreased hamstring to quadriceps ratio, the other risk factors indentified by Alentorn-Geli et al. (2009) could all potentially present as dynamic knee valgus malalignment. The most commonly accepted modifiable risk factor for ACL injury is dynamic knee valgus malalignment, possibly due to an association with other identified risk factors, but also with the injury mechanism and an increased incidence in female athletes.

In a large study of n=1718 athletes who presented with ACL injury to an orthopedic sports medicine clinic in Japan between 1988 and 2008, Kobayashi et al. (2010) reported that females accounted for 70% of the non-contact injuries and knee valgus or “knee in, toe out” was described as the dynamic alignment at the time of injury in 49.5% of all injuries. Although the mechanism of injury was not directly observed, this figure is conservative given that 34% of athletes were unclear as to the dynamic alignment they had at the time of injury. Based on linear regression analysis instrumented measures of increased dynamic knee valgus during a drop-landing task in a biomechanics laboratory have also been reported to predict ($r^2 = 0.88$; +LR = 2.9 calculated based on reported specificity and sensitivity) ACL injury in female soccer, basketball and volleyball athletes, and provide further support for an association between dynamic knee valgus malalignment and ACL injury (Hewett et al., 2005). In a video analysis study in which injury mechanisms were directly observed in the sagittal plane, Sheehan Sipprell, and Boden (2012) reported that landing with the centre of mass far posterior to the base of support was also a defining feature of the injury mechanism in unilateral landing manoeuvres that resulted in ACL injury. With reference to the study by Zazulak et al. (2007b), Sheehan et al., (2012) suggested that poor trunk control could increase the risk of ACL injury as it may lead to athletes landing in a compromised, posterior loaded position and also decrease their ability to correct it.

In summary, a lack of movement control in landing has been most commonly associated with the ACL injury mechanism and landing mechanics are common features of ACL injury studies. There is considerable evidence that dynamic knee valgus malalignment is a feature of the injury mechanism and it appears to be generally accepted as a risk factor for ACL injury. Although dynamic knee valgus malalignment has been shown to be associated with an increased risk of ACL injury, it is questionable whether or not the magnitude of the increased risk (+LR = 2.2) is sufficient to consider it as a strong independent risk factor. There are a range of other identified risk factors for ACL injury that could potentially present as dynamic knee valgus malalignment, and based on the combination of these findings, it seems justified that it is the most commonly accepted. In general, the research on
ACL and knee ligament injury provides considerable support for an association between movement dysfunction and lower limb injury.

### 2.3.1.3. Knee osteoarthritis

Knee joint malalignment is widely accepted to be a feature of knee osteoarthritis (OA), however, due to previous injury being so commonly involved in the development of OA it is difficult to determine whether valgus malalignment also predisposes the development of OA. Based on a systematic review of radiographic studies that investigated the relationship between knee malalignment and the progression or development of OA, Tanamas et al. (2009) concluded that although anatomical knee malalignment could be considered an independent risk factor for the progression of knee OA, there was insufficient evidence to confirm it was also a predisposing factor for development of knee OA. In a large recent study that involved the secondary analysis of radiographic images of n=11,006 knees from two large longitudinal studies (the Multicenter Osteoarthritis Study and the Osteoarthritis Initiative), Felson et al. (2013) suggested that knee valgus malalignment was a potent cause of lateral compartment knee OA, alongside previous cartilage and lateral meniscus damage. In another more recent systematic review, Lim et al. (2013) also concluded that there was strong evidence mechanical knee alignment was a risk factor for the development of bone marrow lesions, an established precursor and contributing factor to the progression of OA. It seems that there is conclusive evidence that joint malalignment predisposes the progression of knee OA and joint degeneration. Although there is not sufficient consensus in the existing literature for definitive conclusions about knee malalignment, there is also growing evidence that malalignment is at least a strong candidate risk factor for the development of knee OA. This combination of findings contributes to a hypothesis that dynamic malalignment appears to be associated with the development and progression of lower limb injury.

### 2.3.1.4. Patellofemoral pain syndrome

Patellofemoral joint pain and dysfunction has historically been attributed to abnormal patella tracking and associated with increased quadriceps angle (Q angle) or knee valgus (Messier, Davis, Curl, Lowery, & Pack, 1991). Cadaver studies have provided additional mechanistic support for this association in that increasing Q-angle has been shown to increase patellofemoral contact pressure (Huberti & Hayes, 1984). More than twice as many females experience patellofemoral pain as males, and females with patellofemoral pain syndrome (PFPS) have been reported to exhibit significantly increased knee valgus in the single leg squat test when compared to matched controls without PFPS (Boling et al., 2009; Willson & Davis, 2008). The interchangeable use of “Q-angle” and “knee valgus” in the literature to incorrectly describe both anatomical alignment and dynamic alignment has
led to confusion and complicated analysis of the potential role knee valgus plays in PFPS. In a recent systematic review of risk factors for PFPS, Lankhorst, Bierma-Zeinstra, and Van Middelkoop (2012) concluded that an increased anatomical Q-angle did not increase the risk of developing PFPS. Decreased knee extensor strength and increased hip adduction and/or internal rotation during loaded weight bearing activities were reported to be associated with PFPS, and emphasise the importance of dynamic alignment and movement control as possible contributing factors. In another systematic review that specifically focussed on hip characteristics associated with PFPS, Meira and Brumitt (2011) reported similar findings to Lankhorst et al. (2012), that patients with PFPS exhibited increased internal hip rotation during weight-bearing activities and weakness in hip abduction and external rotation.

Muscle weakness at the hip and knee has commonly been associated with PFPS and strengthening the postero-lateral hip muscles of patients with PFPS has been shown to decrease pain and increase function (Witvrouw et al, 2014). Although many practitioners assume therefore, that decreased hip strength is a risk factor for the development of PFPS, there appears to be no direct evidence to support this assumption (Rathlef, Rathleff, Crossley, & Barton, 2014). It seems important to recognise that in this case, decreased hip strength could in fact be a consequence of knee pain and not necessarily part of the aetiology. From a biomechanical perspective, movement dysfunction at the hip could influence PFPS by adversely impacting tibiofemoral and patellofemoral mechanics in multiple planes (Powers, 2010). The altered lower extremity kinematics associated with PFPS have in fact been shown to be unaffected by increasing hip abductor and knee extensor strength if not accompanied by targeted movement retraining (Ferber, Kendall & Farr, 2011; Willy & Davis, 2011). Electromyography studies have also demonstrated that movement dysfunction at the hip is associated with PFPS. Based on a systematic review of studies investigating the association between gluteal electromyography and PFPS, Barton, Lack, Malliaras, and Morrissey (2013) concluded that there was moderate-strong evidence that gluteus medius activation was delayed and of shorter duration in individuals with PFPS during stair negotiation. In addition to stair climbing, Barton et al., (2013) reported there was some evidence that individuals with PFPS also had delayed and shorter duration gluteus medius activation during running and increased gluteus maximus activation during stair descent. Based on the existing evidence it appears that although improvements in lower limb strength are important for rehabilitation of patients with PFPS, an increased focus on neuromuscular control and dynamic alignment in functional weight-bearing movements is justified and could potentially also reduce the risk of developing PFPS.
2.3.2. Movement dysfunction and ankle and foot injuries

Poor postural control has long been associated with ankle and foot instability (Freeman, 1965). Often described as ‘postural sway’, instrumented measures of the inability to maintain stability in single leg stance, have been shown in prospective cohort studies to significantly increase the risk (Odds Ratio [OR] 1.2 to 6.7) of ankle injury (Tropp, Ekstrand, & Gillquist, 1984a; McGuine, Greene, Best, & Leversen, 2000; Wang, Chen, Shiang, Jan, & Lin, 2006). Based on a systematic review of studies that used an instrumented stable force plate to assess postural control, McKeon and Hertel (2008) report a consensus of agreement in the literature that poor postural control was associated with an increased risk of ankle sprain. They also concluded there was strong evidence postural control deficits were present in both the injured and uninjured limb following acute ankle sprain and that these deficits were most apparent when compared to uninjured controls or uninjured baseline measurements. These findings provide support for an early theory first proposed by Tropp, Ekstrand, and Gillquist (1984b), that central and peripheral deficits occur following ankle injury. Although these instrumented tests of postural control provide useful clinical information, few sports or physical activities typically involve static balance. It could therefore be argued that postural control assessments involving dynamic balance tasks might be more specific to the requirements of sport.

2.3.3. Movement dysfunction and lower limb injury in general

Poor neuromuscular control of the lumbo-pelvic-hip complex, often referred to as ‘core stability’ (Kibler, Press, & Sciascia, 2006), and functional weakness in hip abduction and external rotation have been commonly implicated in the development of several lower limb injuries including anterior cruciate ligament (ACL) injury and overuse injuries affecting the foot and ankle, knee and hip (Chuter & Janse de Jonge, 2012). In a prospective cohort (n=140) of basketball and track athletes that were monitored for back and lower limb injuries over two seasons, Leetun, Ireland, Willson, Ballantyne, & Davis (2004) reported that the athletes who sustained injuries had significantly lower hip abduction and external rotation strength compared to those that did not sustain injury. In a systematic review of functional performance tests of the hip, Kivlan and Martin (2012) concluded there was a consensus of evidence that poor performance in the deep squat, single leg balance, single leg squat, and star excursion balance tests were associated with the presence of hip dysfunction in the form of gluteal tendonopathy or femoroacetabular impingment. The star excursion balance test (SEBT) first described by Gray (1995) is a widely-used, non-instrumented postural control task that has been reported to be reliable and valid for identifying dynamic balance deficits in patients with a variety of lower extremity conditions (Gribble, Hertel, & Plisky, 2012). In a large prospective study of n=235 high school basketball players Plisky et al., (2006) reported that players with dynamic
balance deficits were also more likely to suffer a lower limb injury during the season. Players with a right/left anterior reach difference of greater than 4cm on the SEBT, were found to be 2.5 times (OR 2.7, 95%CI 1.4 to 5.3) more likely to suffer a lower limb injury than those with less than 4cm difference. These findings provide support for the hypothesis that dynamic balance deficits might predispose lower limb injury, however, although all players were injury-free at the time of testing and the authors reported that they controlled for previous injury in the analysis, it is unclear how these data were analysed and whether the reported increased risk is associated with new injury, re-injury or a combination of both and needs to be considered when interpreting the results.

2.3.4. Movement dysfunction not associated with lower limb injury

Poor neuromuscular control and dynamic malalignment of the lower limb appear to be associated with a range of lower limb injuries and there is growing evidence that they could also be risk factors for new injury. There are, of course, studies that have reported no association and in a small number of cases, increased neuromuscular control has been associated with increased injury risk. In the laboratory setting biomechanical measures of neuromuscular control associated with dynamic knee valgus during a drop vertical jump (DVJ) have been shown to be predictive of ACL injury (calculated as +LR = 2.9 based on reported specificity and sensitivity) in female athletes (Hewett et al., 2005). The landing error scoring system (LESS) has been reported to be valid and reliable for evaluating landing biomechanics associated with the DVJ test and proposed as a clinically useful, non-instrumented screening tool for identifying athletes at increased risk of ACL injury (Padua et al., 2009). However, in a large prospective study of n=5,047 high school and college athletes over 3 years, Smith et al. (2012) reported there was no relationship (OR 1.14, 95%CI 0.88 to 1.48, p = 0.32) between the risk of suffering an ACL injury and LESS score. This finding was unexpected and conflicting with previous research, and given the number of athletes studied and long follow-up period, the findings challenge the view that poor neuromuscular control and dynamic knee valgus malalignment are risk factors for ACL injury. The authors suggested that in light of previous research and a post-hoc power analysis, the results may have been influenced by the small total number of injuries observed (n=28), and the older age-group of the athletes (females 18±1.74 yrs, males 18.48±2.47 yrs) or lack of poor performances (LESS range 1 to 11 out of 17) compared to the sample in which the LESS was developed. In addition, the time between screening and injury was 224 ± 150 days and although the control participants were matched closely in an attempt to standardize the possible change in LESS score during this time, individual changes in movement control over such a long period of time can not be excluded. Notwithstanding these limitations, Smith et al. (2012) findings do not support the establishment of movement dysfunction as a risk factor for lower limb injury or the use of the LESS for predicting ACL injury. The limitations identified do, however,
highlight some of the practical difficulties in identifying physical risk factors for sports injury and mean that an association between movement dysfunction and ACL injury risk can not be ruled out based on these findings.

2.3.5. Movement dysfunction negatively associated with lower limb injury

In a recent prospective, season-long study of elite female football players, Nilstad et al. (2014) reported that no association was observed between new lower limb injuries and dynamic balance, measured with the SEBT. The best predictor of new lower limb injuries in general was a greater body mass index (OR 1.51, 95%CI 1.21 to 1.90, p = 0.001) but although the difference between those that sustained an injury and those that didn't was significant, it was very small (22.6 ± 1.7 vs 21.8 ± 1.7). An increased risk of foot and ankle injury was reported to be associated with previous knee injury (OR 3.57, 95%CI 1.27 to 9.99, p = 0.02) and, surprisingly, decreased dynamic knee valgus in a drop-jump landing (OR 0.64, 95%CI 0.41 to 1.00, p = 0.04). The mean difference in knee valgus angle was 2.3° and the authors acknowledged that possible measurement error made the clinical relevance of such a small difference questionable. Although this unexpected finding has potentially little clinical relevance, it is similar to the earlier findings of Östenberg and Roos (2000) and Söderman, Alfredson, Pietila, and Werner (2001) who reported that female football players who performed better in a functional performance task and a single legged postural sway task respectively, also had an increased risk of new lower limb injuries. These unexpected findings are in direct conflict with the majority of current research on risk factors for lower limb injury and demonstrate that numerous factors can influence injury risk as well as performance in functional tests of neuromuscular control and dynamic balance. Interestingly, all three of these studies involved Scandinavian female football players and in this athlete group, players with high levels of skill have been reported to have significantly higher incidences of injury per 1000 playing hours than players with low skill levels (Soligard, Grindem, Bahr, & Andersen, 2010). A potential contributing factor to these unexpected and seemingly novel findings could therefore be that an increased role in influential on-field situations and important competition events might also result in highly skilled players being involved in more high risk injury situations per playing hour than the players with lower skill levels. Although this explanation is speculative and based primarily on anecdotal evidence, it does highlight a potential source of error that is seldom discussed or investigated in sports injury research.
2.3.6. Summary - Deficits in movement control and dynamic joint malalignment (movement dysfunction) are commonly associated with lower limb injury.

Movement dysfunction has been associated with most common lower limb injuries, and although there is insufficient evidence, it is possible that it also predisposes injury. Given that the aetiology of injury is complex and appears to be multi-factorial and specific to the individual involved (Bahr & Holme, 2003; Bahr & Krosshaug, 2005), it is unlikely that conclusive evidence will be found for individual, physical risk factors that independently ‘cause’ lower limb injury. There is conclusive evidence, however, that movement dysfunction, expressed as dynamic knee malalignment, is an independent risk factor for the progression of knee joint degeneration (Tanamas et al., 2009; Lim et al., 2013). The practical difficulties of conducting controlled, appropriately powered, injury risk studies (Smith et al., 2012) and an inability to compare studies because of a lack of standardised protocols and reporting methods (Hägglund et al., 2005; Hopkins et al., 2007) also increases the difficulty to determine injury risk. So, in the absence of better options, the inclusion of movement dysfunction as an intervention target in most current injury reduction and rehabilitation programs seems justified based on the existing evidence.

2.4. Injury risk management in sport

Athletes involved in competitive sport regularly undergo a variety of physical assessments, including tests of physical capacity and specific skills, monitoring of physiological status, medical imaging, and clinical examinations. In all cases the major goal of assessment is to inform or guide intervention and monitor change. In an attempt to minimise injuries and improve the efficiency of performance preparation, injury monitoring, periodization of training loads, ‘prehabilitation’ and rehabilitation have all become important components of athletic preparation. Sporting organisations have also been encouraged to implement risk management processes using a combination of these monitoring, assessment and intervention practices as part of a general model for best practice in sport (Fuller & Drawer, 2004; Fuller, 2007).

2.4.1. The identification of movement dysfunction

Anecdotally, the drive to be more efficient and individually focussed in athletic preparation has led to more specific assessment of performance and identification of individualised intervention needs. Although there is considerable debate among sports injury practitioners as to what the specific targets for intervention should be, movement dysfunction is a common theme in most injury management
and prevention programmes. The measurement of function can be broadly categorized into three major forms: impairment measures, self-report measures and physical performance measures (Reimann & Manske, 2011). In a recent systematic review of lower limb physical performance tests commonly used to assess knee function, Hegedus, McDonough, Bleakley, Cook, and Baxter (2014) found limited or conflicting evidence to support their reliability, validity and clinical applicability for injury management and it was unknown whether any of the tests reviewed could predict injury in athletes. A lack of standardised terminology and protocols were also highlighted as problematic given the wide range of practitioners that use these tests. Hegedus et al. (2014) concluded that clinical conclusions based on the results of these tests should be made with caution until more research had been conducted in this area. Interestingly, the tests that were included in the final analysis of the review by Hegedus et al (2014), were all hopping tasks in which quantitative performance was measured and movement quality or movement control were not assessed. Physical performance measures that include movement control assessment, collectively termed movement screening, have been advocated to improve injury risk assessment (Comerford, 2006) and are now commonly used to identify movement dysfunction, guide injury prevention strategies and monitor progress during rehabilitation (Mottram & Comerford, 2008).

2.4.2. Lower limb movement screening: Common features and descriptions of common terminology and measurements

The rationale for using movement screening to help guide preventative intervention is based on an association between movement dysfunction and injury and the underlying premise that, correcting uncontrolled or dysfunctional movement might decrease injury risk. The fundamental movement patterns of squatting, lunging, hopping, jumping, landing and gait, all require combined ankle, knee and hip flexion and extension, commonly referred to as ‘triple-joint flexion’. It seems justified therefore, that most lower limb movement screening tests are based on the analysis of triple-joint flexion tasks and the identification of postural sway, dynamic malalignment, movement control deficits, and right/left differences. Although movement screening tests generally appear to utilise clinical rating criteria, some of the more commonly assessed features of lower limb movement tests, such as dynamic knee valgus, lumbo-pelvic stability and lateral trunk motion, have also been investigated with objective methods. The following sub-sections provide brief descriptions of how these three features are measured clinically using 2-dimensional (2-D) video analysis, the reliability of these measurements, and the relationship between 2-D and 3-dimensional (3-D) measurements.
2.4.2.1. Dynamic knee valgus

The frontal plane projection angle (FPPA), first proposed by Willson, Ireland, and Davis (2006), is commonly used clinically to assess dynamic knee valgus in triple-joint flexion tasks using 2-D video analysis. The specific marker placements and angle readings have varied slightly in the literature (Willson et al., 2006; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug et 2010; Munro, Herrington, & Carolan, 2012; Dingenen, Malfait, Vanreunterghem, Verschueren, & Staes, 2014), but FPPA is essentially the angle subtended between a line from the anterior superior iliac spine (ASIS) to the middle of the ipsilateral tibiofemoral joint and a second line from the same point on the tibiofemoral joint to the middle of the ipsilateral ankle mortise. Although FPPA does not describe the complex combination of multi-planar movements that contribute to dynamic knee valgus, it has been ‘moderately’ correlated with 3-D knee abduction angle, knee external rotation (r = 0.48, p = 0.002) and hip adduction (r = 0.32, p = 0.044) (McLean et al., 2005; Willson and Davis, 2008).

2.4.2.2. Lumbo-pelvic stability

The dynamic control of the position, alignment and combined motion of the trunk, pelvis, and thigh, described as lumbo-pelvic stability is perceived clinically as an essential component of injury prevention (Perrot, Pizzari, Opar, & Cook, 2012). Because of the complex nature of lumbo-pelvic stability (Kibler et al., 2006) and lack of valid and reliable clinical tests (Chmielewski et al. (2007)), assessment of lumbo-pelvic stability during triple-joint flexion tasks is often based on overall impressions of movement quality and deviations in the frontal or sagittal plane. Based on a Delphi-like discussion method involving five expert physiotherapists, Perrot et al. (2012) proposed a set of theoretical rating criteria for assessing lumbo-pelvic stability during triple-joint flexion tasks. A loss of lumbar lordosis, deviation from an upright trunk position, and a discernable change in pelvic tilt in either the frontal or sagittal plane were all suggested as rating criteria for poor lumbo-pelvic stability. Montgomery, Boocock, and Hing. (2010) reported that when the trunk is inclined to 45°, similar to the typical position of a mid-range squat (Schoenfeld, 2010), excursions from a neutral lordosis significantly decreased rotational ROM in functional tasks. Assessment of lateral pelvic tilt (LPT), using 2-D video analysis, has been reported to have excellent between session reliability (ICC ≥ 0.98, CI not reported) and a very large association (r = 0.71, 90% confidence limits 0.56 to 0.81) with 3-D lateral pelvic tilt during a single leg small knee bend (Whatman, Hume, & Hing, 2012b). The LPT angle was measured in this study between a horizontal line from the ASIS of the stance leg and a line between the ipsilateral and contralateral ASIS.
2.4.2.3. Lateral trunk motion

Dingenen et al. (2014) reported that the reliability of using 2-D video analysis to measure the lateral trunk motion (LTM) angle during single leg triple-joint flexion tasks was excellent within- (ICC range between 0.99 and 1.00, 95%CI 0.95 to 1.00; SEM 0.3 to 0.5°, CI not reported) and between-testers (ICC range between 0.98 and 0.99, 95%CI 0.86 to 1.00; SEM 0.4 to 0.6°, CI not reported). The LTM angle was measured between a vertical line from the ASIS of the stance leg and a line between the ipsilateral ASIS and the manubrium sterni. In addition, significant negative correlations were reported between peak external knee abduction moment in the single leg drop-vertical jump and the combination of LTM and FPPA (dominant leg $r = -0.36$, 95%CI -0.66 to -0.07, $p = 0.017$; non-dominant leg $r = -0.32$, 95%CI -0.62 to -0.03, $p = 0.034$), but not FPPA or LTM separately.

2.4.3. Visual analysis of movement dysfunction

The high equipment cost, set-up time, expertise required, and questionable transferability of findings outside of the laboratory make the use of instrumented movement measurement systems prohibitive for most clinical environments. Visual analysis, on the other hand, is a basic component of most clinical practitioners’ examination, to varying degrees influences their intervention decisions, and if reliable, is a useful clinical assessment and monitoring tool (von Porat, Holmström, & Roos, 2008). In one of the earlier movement screening studies to specifically compare overall and segmental visual rating methods, Chmielewski et al. (2007) reported that neither method produced high rater agreement and although the rating process and criteria reflected current practice at that time, the need for explicit rating criteria, detailed instructions, and anatomical reference points were indicated. Interestingly, only the segmental method produced intra- and inter-rater reliability that was better than chance agreement, which further supports the authors’ recommendation for more specific guidelines. These suggestions were supported by the findings of Ekegren, Miller, Celebrini, Eng, and Macintyre (2009), who reported high intra- and inter-rater reliability (Kappa 0.75 to 0.85, 95%CI 0.58 to 1.00) for visual ratings of dynamic knee valgus in jump landings, using explicitly defined rating criteria. The authors attributed the high reliability observed to the standardised and detailed instruction given to raters, the use of easily identifiable anatomical landmarks, and the dichotomous nature of the rating method. Although the visual rating method was reported to have adequate specificity (60 to 72%) for identifying individuals who were deemed to be at high risk of ACL injury using 3-D video analysis, it lacked sufficient sensitivity (67 to 87%). The lower limit of the sensitivity range reported, meant that up to a third of truly high risk individuals were not identified. The authors suggested that although this visual analysis technique provided reliable ratings of dynamic knee valgus, it lacked sufficient
sensitivity to be the sole screening test for ACL injury risk, and a range of tests should therefore be included in ACL injury screening protocols.

In a random sample of university athletes that were visually rated by experienced athletic therapists, using standardized, specific criteria, Kennedy, Burrows, and Parent (2010) also concluded that dichotomous classification of performance was a reliable rating method for the single leg squat. Counting the number of acceptable repetitions performed before postural control faults were evident was also reported to have good inter- and intra-rater reliability, however, identification of the major limiting factor in performance had poor inter- and intra-rater reliability. Unfortunately, the testing procedures, rating methods and analyses used in this study were not described completely, and the results are therefore difficult to compare with other research. So although the findings appear to provide general support for those reviewed previously, it is difficult to substantiate the authors’ conclusions. This study does however, highlight the possibility of rating performance by counting acceptable repetitions, which has seldom been discussed in the movement screening literature and potentially incorporates elements of performance consistency and fatigue that could impact injury risk.

2.4.4. Summary- Injury risk management in sport

Risk management processes for sports injury emphasise the need for increased monitoring and assessment in order to guide intervention. In an attempt to improve traditional assessments of injury risk and more effectively guide intervention strategies, movement screening has become common. Because of the practical and economical constraints of instrumented measurement, most lower limb movement screening tests are based on visually analyzed ratings of movement dysfunction during triple-joint flexion tasks. Some of the common features of lower limb movement screening tests, FPPA, lumbo-pelvic stability and LTM, have also been assessed clinically using 2-D video analysis to increase the objectivity and reliability of the rating process. In order to be useful monitoring tools, visually analysed ratings need to be reliable, especially when multiple practitioners are involved, and have the clinical utility to inform subsequent interventions. Not unexpectedly, a standardised rating process with specific rating criteria appears to improve the reliability of visual ratings and it has been suggested that a range of tests to identify different characteristics associated with injury risk could potentially improve the clinical utility of the results.
2.5. Two sources of biological variability in movement screening – the performance of the athlete and the rater.

All visually analysed movement-screening tests have two major sources of biological variability, the athlete’s performance and the rater’s analysis. It has been demonstrated that when viewing conditions are similar, there is no significant difference between live and video ratings of the same performance (McKeown et al., 2014; Shultz et al., 2013; Ekegren et al, 2009), and this suggests that these two sources of variability can be individually analysed. The majority of reliability studies have focussed on the rater, and any variability in the athlete’s performance has either been excluded from the analysis using video, or included in the total reliability assessment, without the possibility to interpret the findings with reference to the expected movement variability of the tests. In order to provide a more complete analysis of the overall reliability and clinical utility of a visually analysed movement screening protocol, investigation of the variability in the athlete’s movement performance, and that of the rater’s analysis (McKeown et al. 2014), using clips of the same performances, appears to be required. Although live clinical ratings include both sources of biological variability, individual investigation could improve the comparisons between studies, practical interpretation of results, and identification of highly variable features that require adjustment, especially in the development stages of new protocols.

2.5.1. Movement variability and visual ratings

During most movement screening protocols the athlete is required to perform several repetitions of a test movement in order for a rating to be made, often based on views from at least two perspectives. Anecdotal evidence suggests that there is often considerable variation in the performance of these repetitions, but the potential difficulties this creates in assigning a representative live rating appears not to have been investigated in the movement screening literature. Emerging research in the fields of neurologic physical therapy and motor control suggests that, contrary to traditional motor control theories, variability in the performance of movement tasks is in fact associated with highly skilled performance and a decreased risk of injury (Seifert et al., 2014; Wagner, Pfusterschmied, Klous, von Duvillard, & Müller, 2012; Harbourne & Stergiou, 2009; Stergiou, Harbourne, & Cavanaugh, 2006). The findings of Brown, Bowser, and Simpson (2012), provide support for the suggestion that a lack of movement variability is associated with injury, in that recreational athletes with chronic ankle instability were found to demonstrate significantly less movement variability at the hip and knee during single leg jump landings, when compared to healthy controls. Some movement screening protocols, like the Functional Movement Screen (Cook et al., 2006) for example, require ratings to be based on the ‘best repetition’ of each movement. Although this method of rating removes the potential difficulty of describing the range of performances, it is doubtful the assigned rating is indicative of the
athlete’s normal movement function, or even the same repetition, given that more than one viewing position is often required to make a rating. Kennedy et al. (2010) suggested counting the number of acceptable repetitions to be a reliable measure for rating single leg squat performance, however, an incomplete description of the methods and analyses they used to determine this does not permit interpretation or replication of an otherwise plausible approach. Although it is beyond the scope of this review to attempt to determine what optimal movement variability is and how it might be assessed, it seems justified to expect some variability in the rep-to-rep performance of movement tests, and that a complete lack of variability could potentially be associated with injury.

2.5.2. Variability associated with the athlete’s performance

2.5.2.1. Three-dimensional analysis

With the exception of a few biomechanical studies, the within- and between-session variability in the athletes’ performance of the test movements has seldom been investigated in the movement screening literature, possibly due to the cost and expertise associated with 3-D kinematic analysis. Ford, Myer, and Hewett (2007) reported that the reliability of young athletes’ lower extremity peak angular rotations during landing from a drop vertical jump were excellent within-session (ICC 0.90, 95%CI 0.86 to 0.95) and good to excellent between-sessions (ICC 0.77, 95%CI 0.72 to 0.82). Milner, Westlake, and Tate, (2011) also reported good to excellent within-session (ICC 0.63 to 0.88, CI not reported) and between-session (ICC 0.69 to 0.96, CI not reported) reliability for peak knee angles and moments during a stop jump landing. When compared with the findings of Ford et al (2007) for the drop jump, the slightly lower within-session reliability was attributed to larger intra-subject variability in the stop jump due to the less constrained nature of the task.

2.5.2.2. Two-dimensional analysis

Two-dimensional (2-D) video analysis is more commonly used in the clinical setting and although it is not a substitute for 3-D analysis, it has also been used to investigate the variability associated with the athlete’s performance in some movement screening tests. Using 2-D video analysis, Munro et al. (2012) reported that the within-session reliability of the FPPA during single leg squats, drop jumps and single leg landings was excellent for men (ICC 0.79 to 0.86, 95%CI 0.65 to 0.92) and fair-excellent for women (ICC 0.59 to 0.88, 95%CI 0.31 to 0.93). The between-session reliability of the FPPA during the same movement tests was also reported to be excellent for men (ICC 0.80 to 0.89, 95%CI 0.70 to 0.93) and good-excellent for women (ICC 0.72 to 0.91, 95%CI 0.56 to 0.95). Closer analysis of the methods in this study revealed that the within-session measures were in fact based on two sessions, 1-hr apart and were therefore a within-day measure that did not include analysis of the
rep-to-rep variation. In essence, the reported reliability statistics were both indications of between-session reliability with 1-hr or 1-week between tests. In an earlier study, Levinger, Gilleard, and Coleman (2007) used femoral frontal angle and femoral deviation instead of FPPA to quantify dynamic knee valgus from 2-D video analysis of single leg squats. It was reported that in healthy subjects the reliability of femoral frontal angle was excellent within-session (ICC 0.88, CI not reported) and good between-sessions (ICC 0.74, SEM = 1.7°, CI’s not reported) and the reliability of femoral deviation was also excellent within-session (ICC 0.76, CI not reported) but only fair between-sessions (ICC 0.46, SEM 0.75cm, CI’s not reported).

2.5.3. A two-part study that separately investigates both sources of biological variability

2.5.3.1. Three-dimensional intra-athlete variability of movement tests within- and between-sessions

There appears to be only one series of studies in the movement screening literature that has investigated variability of athlete’s performance using 3-D motion analysis (Whatman, Hing, & Hume, 2011) and then the reliability of rater’s analysis using video rating (Whatman et al., 2012a) for the same lower limb screening tests. The lower limb kinematics of 25 uninjured participants jogging and performing three repetitions of each of the five lower extremity functional tests (small knee bend, single leg small knee bend, lunge, hop lunge, step down) on their dominant kicking leg were quantified using peak 3-D angles. Ten participants returned 1 to 2 days later and repeated an identical analysis. The reliability of all angle measurements during all five tests were excellent within-session (ICC range between 0.92 and 1.00; lowest ICC 90% CI ~ ±0.14) except lateral trunk flexion, which was good-excellent (ICC 0.79 to 0.93) and good-excellent between-sessions (ICC range between 0.61 and 0.99; lowest ICC 90% CI ~ ± 0.47, highest ICC 90% CI ~ ± 0.02) except lateral trunk flexion, which was fair-excellent (ICC 0.46 to 0.84). The typical errors for all angle measures ranged from 0.2 to 1.8° (90%CI ~ x/÷ 1.20) within-session and with the exception of hip flexion (TE = 2.8 to 5.4°; 90%CI ~ x/÷ 1.47), ranged from 0 to 3.7° (90%CI ~ x/÷ 1.47) between-sessions. Based on these results the authors concluded that in uninjured participants, the reliability of movement performance in these five functional tests was good to excellent and they should be clinically useful for the assessment of lower limb movement control.

2.5.3.2. Inter- and intra-rater reliability of visually assessing the movement tests

In the follow-up video-based study, involving n=44 physiotherapists, Whatman et al. (2012a) investigated the reliability of visually rating the four small knee bend tests (step down test removed) analysed in the previous study. The visual assessment procedure and rating sheet used were largely
based on the findings of Chmielewski et al. (2007) and Ekegren et al. (2009). Of specific interest was the influence of variations in clinical experience (inexperienced, novice and experienced), rating method (segmental versus overall), and classification of ratings (dichotomous versus ordinal). Estimates of true intra- and inter-rater agreement were determined using the first order agreement coefficient (AC1) proposed by Gwet (2008) with magnitudes interpreted in a similar manner to kappa coefficients on the scale proposed by Landis and Koch (1977). The mean intra-rater reliability for all groups was reported to range from slight to almost perfect (AC1 0.01 to 0.96) and the mean inter-rater reliability was fair to good (AC1 0.22 to 0.71). For all levels of experience, intra- and inter-rater reliability were better for dichotomous ratings than ordinal ratings, and no significant differences in intra- or inter-rater reliability were observed between the segmental or overall rating method. Using a magnitude-based inferences approach (Hopkins et al., 2009), Whatman et al. (2012a) reported that the intra-rater reliability of the experienced physiotherapists was also reported to be ‘likely’ to ‘very-likely’ (probability 0.84 to 0.99) higher than the inexperienced and novice physiotherapists. The more favorable, unsupervised, individual viewing condition with which the experienced physiotherapists made their ratings compared to the other two groups supervised, group viewing in a lecture theatre, may have influenced this finding. The viewing conditions during the video rating in this study were also not the same as they are during live rating, because ratings were made from frontal view video, with marked anatomical landmarks, and repeat viewing was permitted. Unfortunately, this discrepancy makes it unlikely that the findings are representative of the variability that could be expected to be associated with the rater and rating process of this movement screening protocol in a live-clinical situation.

2.5.4. Summary - Two sources of biological variability in movement screening – the performance of the athlete and the rater

Movement screening tests employing visual analysis have two sources of biological variability, the athlete and the rater, but the intra-athlete variability has seldom been investigated. Based on the movement variability research, it seems plausible to expect some variability in the rep-to-rep performances of an athlete, and a lack of variability could, in fact, be potentially associated with injury. The combination of findings from 3-D (Ford et al, 2007; Whatman et al., 2011; Milner et al., 2011) and 2-D analysis (Munro et al., 2012; Levinger et al., 2007) of common lower limb movement screening tests could be interpreted to suggest that there is little intra-athlete, within- and between-session variability in these movement tests. It is important to consider that most findings were based on isolated peak joint angles and therefore, do not take into account variations in timing, or relationships between multiple joints, which are common components of movement screening. In addition, the variation in levels of reliability reported between studies, could often be attributed to
slight differences in the movement test, measurement variable, or participant, and emphasise the need to specifically assess the intra-athlete variability of movement screening tests within the screening protocol and subject group they will be used. Although there were some limitations in the rating study (Whatman et al., 2012a), the established stability of the movement screening tests in the initial study (Whatman et al., 2011), meant that the intra- and inter-rater reliability findings could be interpreted with reference to the expected movement variability of the tests and more definitive conclusions drawn. The findings of Whatman et al. (2012a) rating study, were similar to those of Ekegren et al. (2009) and Kennedy et al. (2010), and provide further support for the suggestions made by Chmielewski et al. (2007) with respect to visual rating methods. Based on the combination of findings from all of these studies it seems that the reliability of visually rating lower limb movement control is similar for segmental and overall rating methods and that explicitly defined rating criteria and dichotomously classified ratings improve the reliability of ratings. In general there is a paucity of movement screening research in the area of movement variability, especially within-session, and given the substantial effect this can have on the outcome of screening processes and subsequent clinical intervention, the lack of discussion as to what a rating should represent is surprising.

2.6. Reliability and clinical utility of existing movement screening protocols

Movement screening has only recently become common practice and despite its widespread use and the impact it can have on management decisions, there are currently a lack of standardised, industry-accepted protocols that have undergone rigorous testing. The limited number of high quality studies and lack of standardisation in movement tests, rating methods, and testing protocols also make it difficult to compare studies and draw conclusions about their reliability and clinical utility. In order for movement screening to effectively guide clinical decision-making, the testing protocols and rating systems need to be reliable, valid, and provide sufficient information that similar conclusions can be made about the same case by a range of practitioners.

2.6.1. Recently developed protocols

Several of the standardised protocols currently used in sport were developed in response to a clinical need and therefore lack sufficient continued research to substantiate or follow-on from the initial findings associated with their development. The Movement Compensation Screen (Gilligan, personal communication, February 11, 2015) is part of several strength and conditioning courses in the United Kingdom and Ireland including the National Certificate in Strength and Conditioning, yet there appears to be a lack of published research that supports this. High Performance Sport New Zealand
(HPSNZ) have recently included the Movement Competency Screen, developed by Kritz (2012), in their athlete development program. This protocol was reported to be reliable at the time of development and the plausibility of using components of the protocol to guide progression in strength and conditioning training have also been suggested (Kritz, Cronin, J., & Hume 2009a; 2009b; 2010), however, there appears to be a lack of subsequent peer-reviewed evidence to support its use (Gamble, 2013).

In Australia, McKeown et al. (2014) recently developed the Athletic Ability Assessment (AAA), a 13 test battery specifically developed for athlete profiling and assessing changes in functional movement ability that are not normally included in physical fitness and performance testing. Each test of the battery is scored segmentally on a 3-point ordinal scale with a maximum score of 9 per test and 117 overall. The intra-tester reliability was reported to be excellent (ICC 0.97, 90% CI 0.92 to 0.99) for the overall score and ranged from moderate to excellent (ICC 0.53 to 0.9, CI’s not reported) for the individual test scores. The inter-tester reliability was also reported to be excellent (ICC 0.96, 90% CI 0.94 to 0.98) for the overall score but ranged from fair to substantial (Kappa 0.33 to 0.77, CI’s not reported) for the individual test scores. The authors also described that like many other reliability studies, the biological variability associated with the athlete’s performance had been removed from the rating process by the use of video, and therefore further research was required to investigate the within-subject variability associated with the testing protocol. The unilateral lower-limb and lateral bracing tests produced the least reliable ratings and given that these tests are also more technically challenging, the within-subject variability might also be greater, which could contribute to even less reliable ratings for these tests. It appears therefore, that the AAA may offer a starting point for the development of a clinically useful movement screen for athletes, however the high number of tests, low reliability of the unilateral lower limb tests, and unknown within-subject variability associated with the tests, mean that considerable further investigation is required.

2.6.2. Commercially available, standardised protocols

2.6.2.1. The Functional Movement Screen (FMS)

The Functional Movement Screen (FMS) developed by Cook et al. (2006) is the most commonly used movement screening protocol in professional football (McCall et al., 2014) and possibly all competitive sport. It was one of the first commercially available protocols and has undergone considerable investigation in the published literature since its release. The FMS comprises seven movement tests that are visually analysed by a rater and the athlete’s best performance in each test is assigned an ordinal rating (0 to 3), according to explicit criteria. In this way, individual rating scores
for each test are generated as well as an overall or total rating score. The inter- and intra-rater reliability of overall score in the FMS have been reported to be moderate to excellent in most studies (Schneiders, Davidsson, Hörman, & Sullivan, 2011; Teyhen et al., 2012; Onate et al., 2012; Gribble, Brigle, Pietrosimone, Pfile, & Webster, 2013a; Smith, Chimera, Wright, & Warren, 2013). In an earlier study with similar findings, Minick et al. (2010) also reported that the inter-rater reliability of the individual test scores was substantial to excellent for all tests. Shultz et al. (2013) recently reported however, that the inter-rater reliability of the FMS was poor, and although the reliability of the individual test scores have been reported to be moderate to excellent in general, there is considerable variation and the two unilateral lower limb tests have been reported to have poor to moderate inter- and intra-rater reliability (Onate et al., 2012; Smith et al., 2013; and Teyhen et al., 2012). Closer analysis of all of these studies reveals that there were sufficient differences in the number of raters and athletes, experience and training of raters, method of rating (live vs. video), and statistical analysis methods to explain the variation in findings. In general however, it seems reasonable to suggest that the inter- and intra-rater reliability of the overall FMS score are good and with exception of the unilateral lower limb tests, the individual test scores also have moderate to good reliability.

Frohm, Heijne, Kowalski, Svensson, and Myklebust (2012) also reported high inter- and intra-rater reliability (ICC 0.75 and 0.8 respectively, CI not reported) for the total scores of a 9-test movement screening protocol that includes 7 of the FMS tests. Although the instructions and scoring were adapted from those used in the original FMS, the inter-rater reliability also ranged from moderate to good (ICC ranged between 0.63 and 0.81, CI’s not reported) for the individual test scores except the single leg squat (ICC 0.53, CI not reported) and rotational stability (ICC 0.30, CI not reported) tests. Given that individual test scores, as opposed to the overall score, will probably guide intervention, the reliability of the individual scores is probably more clinically relevant than the overall score. Although the FMS appears to be a reliable general movement screening protocol, it could be argued that reliable tests of unilateral lower limb movement control are more important for gait dominant athletes due to the dominance of unilateral lower limb movements in most sports and the prevalence of lower limb injury. It appears therefore, that similar to the AAA, the unilateral lower limb tests in the FMS may require some adjustment and further investigation in order to improve the clinical utility of the protocol for use with athletes.

2.6.2.2. The Star Excursion Balance Tests (SEBT) and Y-Balance Test (YBT)

In a systematic review of studies involving a wide range of subjects, Gribble et al. (2012) reported that the SEBT appeared to be a reliable measure of unilateral lower limb movement control, as mentioned earlier in this literature review. The general consensus in the currently available literature
is that the test-retest and inter-rater reliability of the SEBT are good to excellent (Hertel et al., 2000; Stockert & Barakatt, 2005; Munro & Herrington, 2010; Gribble, Kelly, Refshauge, & Hiller, 2013b). No studies were found that reported poor test-retest reliability and only Kinzey and Armstrong (1998) and Shaikh and Walunjkar (2014) reported that some of the measured directions displayed moderate test-retest reliability. It was commonly reported that learning effects were evident in performance of the SEBT and adequate practice trials (>4 to 5) were required for performance to stabilise (Kinzey & Armstrong, 1998; Hertel, Miller, & Denegar, 2000; and Munro & Herrington, 2010). The presence of learning effects and need for several trials to be performed in order to ensure a stable performance is common in quantitative performance tests and it is important to consider that performance in the SEBT is determined by right and left reach distances, and does not include visual analysis of movement quality or movement control like most other movement screening tests. In order to improve the reliability and clinical utility of the SEBT, further investigation has led to the development of the commercially available, Y-balance test (YBT) described by Plisky et al. (2009). The YBT utilises apparatus that simplifies the measurement of reach distance in three (anterior, posteromedial and posterolateral) of the eight SEBT directions and appears to be increasingly popular in the clinical setting for diagnosis, screening and rehabilitation (Coughlan et al., 2010). Good to excellent inter- and intra-rater reliability have been reported for all directions of the YBT (Plisky et al., 2009; Shaffer et al., 2013). It appears therefore, that when sufficient practice trials are completed, both the SEBT and YBT provide reliable measures of unilateral lower limb performance and permit right/left comparisons.

Unlike other movement screening tests that are based on visual analysis of movement quality or movement control, quantitative measurement determines performance in the SEBT and YBT. Because of their similarity, performance in the SEBT and YBT are often compared interchangeably, however, Coughlan et al. (2010) reported that uninjured male athletes reached significantly further in the anterior direction of the SEBT when compared with the YBT. “Differing postural control strategies” between the tests were suggested to have most-likely influenced the anterior reach differences. In a recent study of participants with chronic ankle instability, de la Motte, Arnold, and Ross (2014) reported that although no differences in reach distance were observed between injured and uninjured participants on the SEBT, the injured participants used greater hip flexion, trunk rotation and pelvis rotation to achieve maximum anteromedial and medial reach. The authors suggested that abnormal movement patterns of the hip and trunk observed during the SEBT could be clinically relevant for the rehabilitation and prevention of chronic ankle instability. Given that differing postural control strategies appear to affect reach distance in the SEBT and YBT (Coughlan et al., 2010; de la Motte et al., 2014), it is possible that clinically relevant, movement control deficits and changes in performance could be masked by compensatory movements if qualitative analysis of the movement is not also considered.
2.6.3. Summary - Reliability and clinical utility of existing movement screening protocols

With the exception of the FMS (Cook et al., 2006), which is the most widely used screening protocol, few of the established movement screening protocols that are currently used in sport appear to be supported by repeated peer-reviewed evidence of reliability. The protocol described by Whatman et al. (2011) appears to be the only lower limb movement screening test for which the intra-athlete within- and between-session variability has been reported in the literature. Although learning effects were mentioned in the development of the protocol for the SEBT and that sufficient repetitions were required in order for performance to stabilise, there appears to be no discussion of either the impact movement variability or intra-athlete within-session variability might have on the rating of movement screening tests. McKeown et al. (2014) acknowledged that descriptions of inter- and intra-rater reliability reported for the AAA were based on video recordings that removed the variability associated with the athlete’s performance and that this should be assessed in future research into the AAA. A common finding for the multi-test protocols that have undergone reliability testing is that although the compound or total score was reported to have good to excellent inter- and intra-rater reliability, there was considerable variability in the rating scores of some of the individual tests. In general, the unilateral, lower limb, dynamic balance tests were those that had the lowest reliability of rating. Although this was not the case with the SEBT and YBT, it was reported that different postural control strategies could substantially impact on reach distances and that this could have implications for the identification of movement dysfunction or the monitoring of rehabilitation progress. Based on the existing evidence there is a need for more research on the reliability of movement screening protocols that will be used clinically for the evaluation of lower limb function, and in particular there is a lack of research on the intra-athlete within-session movement variability of multi-test movement screening protocols.

2.7. Overall summary of the existing literature to describe the rationale for movement screening and identify the area of research need

Sport and recreation activities are popular (SPARC, 2008) and are critical components in health and disease prevention (Kohl et al., 2012), but participation is also associated with an increased risk of musculoskeletal injury (Verhagen et al., 2015). In competitive sport, lower limb injuries are most prevalent (Fong et al., 2007) and adolescent, development-level athletes could be an ideal group to study within this field because of their high levels of participation in dynamic, multi-directional sports (SPARC, 2008) and high prevalence of potentially avoidable overuse injuries (DiFiori et al., 2014; Hawkins & Metheny, 2001). The aetiology of sports injury appears to be multifactorial and complex (Bahr and Krosshaug, 2005; Bahr & Holme, 2003) and although previous injury, increased age and
increased exposure to competition are generally accepted to increase injury risk (Hägglund et al., 2013; Murphy et al., 2003), there is a lack of consensus as to which modifiable physical factors predispose injury (van Beijsterveldt et al., 2013). Practical difficulties with studying injury risk (Smith et al., 2012) and a lack of standardised protocols and reporting methods have been suggested as potential reasons for this conflicting evidence (Hägglund et al., 2005; Hopkins et al., 2007).

There is currently insufficient evidence in the sports injury literature to conclude that movement dysfunction predisposes lower limb injury. The lack of support for traditional injury assessments that focus on ROM and isolated structures (van Beijsterveldt et al., 2013; Freckleton & Pizzari, 2013; Roussel et al., 2012), conclusive evidence that movement dysfunction predisposes the progression of knee joint degeneration (Lim et al., 2013; Tanamas et al., 2009), and the association of movement dysfunction with most common lower limb injuries, do however, provide a rationale for using movement screening, and justify its common use in sports injury risk management (Mottram & Comerford, 2008). In order to be a useful clinical tool, movement screening needs to be practical, reliable and specific enough to guide the next phase of intervention, especially in situations where multiple practitioners are involved.

Most lower limb movement screening tests are based on visual analysis of functional triple-joint flexion tasks. The reliability of visual ratings appears to be similar for segmental and overall rating methods, but dichotomous classifications with explicit criteria appear to result in higher reliability than generalised ordinal classifications (Whatman et al., 2012a; Kennedy et al., 2010; Ekegren et al., 2009; Chmielewski et al., 2007). Although the athlete’s performance and the rater’s analysis are both potential sources of biological variability in movement screening, the majority of research has focussed on the reliability of the rater and few researchers have investigated the intra-athlete within- and between-session variability. Based on anecdotal evidence and the emerging movement variability research (Seifert et al., 2014; Harbourne & Stergiou, 2009), it seems plausible to expect variability in the rep-to-rep performances of an athlete, and given the substantial effect it can have on the outcome of the screening process (McKeown et al., 2014), the paucity of research in this area and lack of acknowledged importance in the movement screening literature is surprising.

Of the established, multi-test, movement screens, intra-athlete variability has been investigated only in the small knee bend protocol described by Whatman et al. (2011), and the FMS (Cook et al., 2006) is the only protocol that is supported by repeated peer-reviewed evidence of reliability (Smith et al., 2013; Teyhen et al., 2012; Schneiders et al., 2011; Minick et al., 2010). A common feature in most multi-test screens appears to be ‘good’ to ‘excellent’ rater reliability for compound or total scores, but considerable variation in the reliability of the individual tests with unilateral dynamic balance tests often having the lowest reliability of rating (McKeown et al., 2014; Smith et al., 2013; Onate et al., 2013).
2012). If the intra-athlete variability of these tests was also known, it would be possible to determine where adjustment could be made in order to improve the reliability of the test, and the clinical implications of an observed change in the rating scores.

In summary, there appears to be a need for a series of studies that investigate the reliability and validity of a lower limb movement screening protocol that: 1) involves a range of fundamental movements, 2) includes overall and segmental rating methods, and 3) uses specifically defined, dichotomous rating criteria. Following clinical development and practical testing, the reliability investigation should include a combination of studies similar to those described by Whatman et al. (2011) and Whatman et al. (2012a) that investigate intra-athlete within- and between-session variability of the movement tests and then the inter- and intra-rater reliability. The remainder of this thesis reports an investigation that constitutes the first of a series of studies into a lower-limb movement screening protocol (TJFT) that has undergone clinical development and practical testing.
Chapter 3: Methods

3.1 Methodology

High speed, 3-D motion analysis permits valid and reliable assessment of joint motion and is considered the gold standard for movement analysis of lower limb movement tasks, especially when related to the knee and knee injuries (Ford, Myer, & Hewett, 2003; Myer, Ford, & Hewett, 2002; Chappell, Yu, Kirkendall, & Garrett, 2002). Because of its ease of use and relative low cost, 2-D video analysis is commonly used in clinical situations. In the assessment of functional triple-joint flexion tests, 2-D analysis of frontal plane knee motion has been reported to have good to excellent reliability (Munro et al., 2012) and to be moderately correlated with 3-D knee motion, but explains only 23 to 36% of the within-subject variance observed with 3-D analysis (McLean et al., 2005; Willson and Davis, 2008). Functional triple-joint flexion tasks require coordinated multiple joint motion, however, it appears single joint, single plane analysis is not capable of identifying potentially high risk compensatory movements that occur at adjacent joints or in other planes of motion (Ekegren et al., 2009; Mottram and Comerford, 2008). The TJFT rating criteria were based on common clinical analysis techniques and multiple joint motion in the frontal and sagittal planes are incorporated to account for possible compensatory motion within the constraints of visual analysis. In the absence of access to 3-D motion analysis, 2-D video analysis was used to minimise the intra-rater variability in rating the TJFT movement tests and provide a clinically relevant indication of the biological variability associated with an athlete’s test performance. In order to further describe the biological variability of the movement tests and permit some comparison with previous studies, 2-D video analysis was also used to measure a range of commonly used frontal and sagittal plane joint angles.

3.2. Research Design and Ethics

The intra-athlete, within- and between-session reliability of the TJFT was investigated using a video-based, repeated-measures design. The study was approved by the Unitec Research Ethics Committee (UREC 2013-1019). All participants received verbal and written information about the study and gave written informed consent prior to testing (See Appendix 3 for ethics documentation).
3.3. Participants

Male athletes were recruited using convenience sampling from a high school sports academy using posters and word of mouth. Reported differences between genders in lower limb anatomy, predisposition to injury, and factors that predict injury risk (Cowling and Steele, 2001; Ford et al., 2006; Zazulak et al., 2007; Gribble et al., 2012) were the main reasons for recruiting only male athletes. Twenty-three athletes expressed initial interest in participating and received detailed information about the study. In order to reflect a typical development-level sports training squad, athletes were eligible for inclusion if they: 1) were between the ages of 15 and 19 years; 2) currently competed in at least one dynamic, multi-direction team sport; and 4) could follow verbal instructions in English. Exclusion criteria were: 1) known disturbance of balance including dizziness, vertigo, a neurological or other disease known to alter balance, co-ordination or motor function; and 2) currently unable to fully participate in their normal sports team trainings due to a neuromusculoskeletal condition.

3.4. The TJFT protocol and system for assigning rating points

The TJFT consists of five movement tests – double leg squat (DL), single left leg squat (SLL), single right leg squat (SLR), left leg hop and stick (HSL), and right leg hop and stick (HSR). The TJFT protocol and rating criteria are presented in Appendix 1. Each movement test has a standard set-up and basic requirements that have to be met. If the requirements of a movement test are not met the athlete scores zero (0) points for that test and a rating of movement quality is not made. If the athlete does meet the requirements of a movement test they score one (1) point and their movement quality is rated according to five dichotomous criteria (3 frontal plane and 2 sagittal plane). One (1) point is scored for each of the criteria the athlete meets, which results in a total score of 1 to 6 points for each test, in which the requirements were met. The composite score for all five tests therefore, has a possible range of 0 to 30 points.
3.5. Data collection procedures

3.5.1. Video capture of movement testing

Testing and retesting consisted of two identical sessions, 24-h apart, to minimise the possibility for training effects and to standardise the test conditions as much as possible. In order to minimise the likelihood of learning or altered activity on performance, athletes were also asked not to practice the test movements or undertake any unaccustomed physical activity between sessions. At each session an explanation of the test procedure, a video presentation of a high scoring performance of each of the tests, and a live demonstration of all test movements took place. Height and weight of all participants were measured and the sports they currently competed in were recorded. The testing was carried out in a school gymnasium and in order to reflect a typical pre-season screening of a sports squad; the athletes were tested in small groups, in full view of all in the space.

A standardised triple-joint flexion warm-up consisting of nine single leg squats on each leg, in anterior, posterolateral and posteromedial directions, was performed by all athletes prior to testing. Seven raised reflective markers were attached to the midline thoracolumbar spine and bilateral pelvic landmarks, and 4 flat reflective markers were placed over the lateral aspects of both thighs according to the model described by Tully, Fotoohabadi, and Galea (2005) and replicated by Fotoohabadi, Tully, and Galea (2010). In addition, flat reflective markers were placed over the sternal notch, and bilaterally over the lateral malleoli, fibular heads and mid-patellae. All five movement tests were performed standing on a 1m x 1m mat marked with 100mm grid lines. For each test the athletes performed one practice repetition to familiarise themselves with the start position, ROM, and timing of the test and then six repetitions of the test with 10 seconds rest between repetitions undertaken. The movement tests were performed in the order they are described in the protocol (DL, SLL, SLR, HSL, HSR). Each test repetition was recorded for analysis using two 25 Hz, high definition digital video cameras (Panasonic HC-V520M) on tripods positioned anterior and lateral to the athlete. The cameras were positioned 4m from the front edge and side edge of the grid at a height of 800mm and directly fed to a computer using HDMI cables. Capture and live synchronisation of the anterior and lateral views was performed using video analysis software (PnO Data Solutions, CA, United States). Lateral views corresponding to the limb tested were recorded for all single leg tests and a left-only lateral view was recorded for the double leg squat.
3.5.2. Video analysis

Simultaneous, 2-D lateral and anterior views of all the recorded tests were analysed using the video analysis software by the principal researcher. The TJFT ratings and angle measurements were both made on the same still frame of each recorded test. Angle measurements were made on all recorded tests in which a stable position was achieved irrespective of whether the range of movement requirement was achieved.

3.5.2.1. Determination of which frame to analyse

In most 2-D video analysis of triple-joint flexion movements analysis of movement quality has been made at the point of maximum knee flexion (Herrington & Munro, 2010; Stensrud et al., 2011; Munro et al. 2012, Dingenen et al., 2014; Räisänen, Pasanen, & Parkkari, 2014). Given that part of the requirement of the TJFT is to hold a target squat depth for 3 secs in the DL and SL squat, the time at which maximum knee flexion did not change for 3 consecutive frames (0.12 s) was chosen for analysis. A preliminary analysis of a random sample of 20 recorded DL and SL tests, assessed on two occasions, 2 weeks apart, determined that the reliability of identifying this time point was ‘excellent’ (TE = 0.06 s, 95%CI 0.05 to 0.09 s; ICC = 1.00, 95%CI 0.99 to 1.00). However, due to the more dynamic nature of movement and lack of a specified knee flexion requirement in the hop landing tests, a stable maximum knee flexion position was considerably more difficult to identify. A similar analysis of 20 randomly selected HSL and HSR tests determined that although the reliability of identifying this time point was ‘good’, it could range from ‘poor’ to ‘excellent’ with an expected typical error that was also almost five times that for the DL and SL squat tests (TE = 0.29 s, 95%CI 0.22 to 0.42 s; ICC = 0.66, 95%CI 0.32 to 0.85) and was therefore not used to analyse the hop landing tests. Identifying initial ground contact from video of landing tasks is relatively simple and it has been reported that the time to stabilisation in single leg landing tasks is approximately 1.5 s for uninjured subjects (Ross, Guskiewicz, & Yu, 2005; Ross, Guskiewicz, Gross, & Yu, 2009). Reliability of identifying the time point at which the heel and big toe were first in contact with the floor in the same random sample of 20 hop landings was ‘excellent’ (TE = 0.01 s, 95%CI 0.01 to 0.01 s; ICC = 1.00, 95%CI 0.99 to 1.00) with identical times identified on all but two occasions. Analysis of the hop landings were therefore made 1 s after the heel and big toe were first in contact with the floor. This time point could be reliably identified, was prior to full stabilisation, and in most cases was within 8 frames (0.32 s) of a time point identified for maximum knee flexion using the previous method.

3.5.2.2. Procedure for rating the TJFT and reliability of rating using this procedure

The complete recordings of each test were viewed in real-time, slow motion and frame by frame as
many times as required to determine if the athlete met the requirements of the movement test. In all tests in which the criteria were met, the still frame to be analysed was identified and rated by the principal researcher according to the TJFT protocol described earlier. Another preliminary analysis of the random samples of the 20 squat and 20 hop tests described above, determined that the reliability of ratings the principal researcher made using this procedure was ‘excellent’ (TE = 0.31 pts, 95%CI 0.26 to 0.41 pts; ICC = 0.90, 95%CI 0.82 to 0.95). Similar to the preliminary analyses described earlier, a two week time interval between ratings and blinding to the initial rating scores was used to reduce his memory of the previous scores (Lucas, Macaskill, Irwig, & Bogduk, 2010).

3.5.2.3. Procedures for sagittal and frontal plane angle measurements

Ankle dorsiflexion was measured as the angle between a vertical line starting at the lateral malleolus marker and the line between the ipsilateral lateral malleolus and fibula head markers. Knee, hip and lumbar spine flexion angles were measured according to the procedures described by Tully et al. (2005), in which hip and lumbar spine angles are defined as zero when the line joining the ipsilateral posterior superior iliac spine and ASIS markers is perpendicular to the line that represents the thigh and lumbar spine respectively. Thoracic spine flexion was not measured due to difficulties with adhesion of the T1 marker. For all sagittal plane angles flexion was measured as a positive angle and larger angles represented more flexion. The FPPA and LTM were measured according to the procedure described by Dingenen et al. (2014). The FPPA angles were then subtracted from 180 degrees so that positive values reflected knee valgus and negative values reflected knee varus (Munro et al., 2012). Smaller LTM angles represented more LTM in the direction of the supporting leg and when the sternal notch was more lateral than the ipsilateral ASIS, the angle was negative.

Due to the extent of hip flexion, ASIS markers were not visible in some analysis frames and position was therefore estimated, based on the last visible frame and the subsequent movement of the pelvis. No measurement was made if pelvic movement was excessive or the ASIS marker was not visible in the 8 preceding frames (0.32 s). The deep hip and knee flexion position of the DL created considerable distortion in several frontal plane measurements of FPPA and LTM and the ASIS markers were seldom visible within a timeframe that made estimation possible. These measurements were therefore removed from further analysis of the DL. Lateral pelvic tilt was measured as the angle between the two ASIS markers and the horizontal, however, due to an inability to accurately see both ASIS markers in a large number of repetitions of all tests, LPT was also excluded from further analysis of the movement tests.
3.6. Data Analysis

An indication of the biological variability associated with performance of the TJFT was gained by calculating the intra-athlete within- and between-session reliability of the TJFT scores for each test, the angle measurements from each test, and the composite TJFT scores for the whole protocol. The group means and within-session reliabilities for each test were calculated for Day 1 and Day 2 using each athlete’s TJFT scores and angle measurements from each of the 6 repetitions of the test. The between-session reliabilities for each test were calculated using the mean TJFT scores and angle measurements from each test of each athlete that completed both testing sessions. The between session reliability of the TJFT composite score was also calculated using the sum of each athlete’s mean TJFT scores for each day. All within- and between-session reliabilities were calculated using the excel spreadsheet of Hopkins (2000a) and were expressed as TE’s and ICC’s with 95% CI’s (Hopkins 2000b; Hopkins, Marshall, Batterham, & Hanin, 2009). Readers are referred to Hopkins (2011) for a description of the calculations used in the spreadsheet and the rationale for their use. The ICC classifications of Cichetti (1994), which are similar to those described by Fleiss (1981) but separate the ‘fair to good’ category, were used to describe the magnitude of ICC values (less than 0.4 was ‘poor’, 0.4 to 0.59 was ‘fair’, 0.60 to 0.74 was ‘good’, and greater than 0.75 was ‘excellent’). The TE was interpreted as the expected variation in rating score or joint angle when one individual is tested on repeat occasions (Hopkins, 2000b). To investigate any within-session systematic change in rating scores, potentially indicative of a learning effect, a Friedman’s test was used to determine if there were differences between the rating scores of each repetition of each test. Where post-hoc analysis was required a Wilcoxon-signed rank test was used with the appropriate Bonferroni correction applied. Similarly, a Wilcoxon sign-ranked test with Bonferroni correction was also used to determine if there were any between-session systematic differences in the mean rating scores of each test. All non-parametric testing was undertaken with SPSS software v22.0 (IBM SPSS, Armonk, NY).
Chapter 4. Results

Seventeen athletes (mean age 16.9 ± 0.9 years, mean height 182 ± 5 cm, mean weight 77.4 ± 12.0 kg) currently competing in basketball, rugby, soccer, cricket, or hockey met the inclusion and exclusion criteria and completed the initial testing session. The mean composite score for the TJFT over both days of testing was 11.9 ± 5.1 pts and the mean rating scores were approximately 2 to 3 pts for each of the five movement tests (Table 1). The mean frontal plane angle measurements of the single leg tests are reported in Table 2 and the mean sagittal plane flexion angles of all tests are reported in Table 3. Frontal plane measurements were not analysed for the DL because of distortions in 2-D measurement and difficulty seeing the ASIS markers so the reliability measures for the FPPA and LTM refer only to the SL tests.

4.1 Intra-athlete rep-to-rep variation in performance of the TJFT movement tests

4.1.1 Within-session systematic change in performance

There were no significant systematic changes in rating score over the six repetitions for any of the movement tests ($\chi^2(5)$ ranged between 0.61 and 7.50, $p = 0.19$ to 0.99), except the SLR on Day 2, which was higher ($\chi^2(5) = 11.79$, $p = 0.038$). Post hoc Wilcoxon signed-rank tests with a Bonferroni corrected alpha level of 0.01 (0.05/5 tests) determined, however, that the identified difference between repetitions of the SLR on Day 2 was not significant ($Z$ ranged between -2.13 and -1.61, $p = 0.03$ to 0.11).

4.1.2 Within-session reliability of the TJFT rating scores

For Day 1 and Day 2 the reliability of the rep-to-rep rating scores were ‘excellent’ for the DL, ‘fair’ to ‘good’ for the SL and SLR, and ‘poor’ to ‘fair’ for the HSL and HSR (Table 1). The typical errors for the rep-to-rep rating scores were approximately 1 pt for the DL, SLL and SLR, and approximately 1.5 pts for the HSL and HSR (Table 1).

4.1.3. Within-session reliability of the frontal and sagittal plane angle measurements

The rep-to-rep reliability of the FPPA and LTM were ‘good’ to ‘excellent’ for the SLL and SLR with typical errors less than 8°, and predominantly ‘poor’ to ‘fair’ for the HSL and HSR with typical errors
ranging from 7 to 15° (Table 2). The reliability of the rep-to-rep sagittal plane flexion angles were ‘excellent’ for the DL, SLL and SLR and ‘good’ to ‘excellent’ for HSL and HSR with typical errors less than 5° for most angles and tests (Table 3).

Table 1. Within-session reliability of TJFT rating scores

<table>
<thead>
<tr>
<th>TJFT Test &amp; Session</th>
<th>n</th>
<th>Mean ± SD (pts)</th>
<th>TE (95%CI) (pts)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL 1</td>
<td>17</td>
<td>2.2 ± 1.9</td>
<td>0.8 (0.6 - 0.9)</td>
<td>0.87 (0.75 - 0.95)</td>
</tr>
<tr>
<td>DL 2</td>
<td>14</td>
<td>2.5 ± 1.7</td>
<td>0.7 (0.6 - 0.9)</td>
<td>0.85 (0.72 - 0.95)</td>
</tr>
<tr>
<td>SLL 1</td>
<td>17</td>
<td>2.3 ± 1.7</td>
<td>1.2 (1.0 - 1.5)</td>
<td>0.54 (0.31 - 0.77)</td>
</tr>
<tr>
<td>SLL 2</td>
<td>14</td>
<td>2.5 ± 1.8</td>
<td>1.0 (0.9 - 1.3)</td>
<td>0.69 (0.47 - 0.87)</td>
</tr>
<tr>
<td>SLR 1</td>
<td>17</td>
<td>1.8 ± 1.5</td>
<td>1.1 (0.9 - 1.3)</td>
<td>0.58 (0.35 - 0.80)</td>
</tr>
<tr>
<td>SLR 2</td>
<td>14</td>
<td>2.3 ± 1.6</td>
<td>1.0 (0.9 - 1.3)</td>
<td>0.60 (0.37 - 0.80)</td>
</tr>
<tr>
<td>HSL 1</td>
<td>17</td>
<td>2.3 ± 1.8</td>
<td>1.4 (1.2 - 1.7)</td>
<td>0.39 (0.18 - 0.65)</td>
</tr>
<tr>
<td>HSL 2</td>
<td>14</td>
<td>2.9 ± 1.8</td>
<td>1.4 (1.2 - 1.7)</td>
<td>0.43 (0.19 - 0.71)</td>
</tr>
<tr>
<td>HSR 1</td>
<td>17</td>
<td>2.3 ± 1.6</td>
<td>1.5 (1.3 - 1.8)</td>
<td>0.14 (-0.02 - 0.41)</td>
</tr>
<tr>
<td>HSR 2</td>
<td>14</td>
<td>2.9 ± 1.6</td>
<td>1.4 (1.2 - 1.8)</td>
<td>0.18 (-0.01 - 0.49)</td>
</tr>
</tbody>
</table>

Notes: DL = double leg squat; SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; TE = typical error; ICC = intraclass correlation coefficient; SD = standard deviation; CI = confidence interval; pts = rating points

Table 2. Within-session reliability of frontal plane angles during the TJFT tests

<table>
<thead>
<tr>
<th>TJFT Test &amp; Session</th>
<th>n</th>
<th>Mean ± SD (°)</th>
<th>TE (95%CI) (°)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLL FPPA 1</td>
<td>17</td>
<td>17 ± 11</td>
<td>5 (4 - 6)</td>
<td>0.80 (0.65 - 0.91)</td>
</tr>
<tr>
<td>FPPA 2</td>
<td>14</td>
<td>17 ± 11</td>
<td>6 (5 - 8)</td>
<td>0.69 (0.47 - 0.87)</td>
</tr>
<tr>
<td>LTM 1</td>
<td>17</td>
<td>18 ± 8</td>
<td>3 (3 - 4)</td>
<td>0.85 (0.73 - 0.94)</td>
</tr>
<tr>
<td>LTM 2</td>
<td>14</td>
<td>19 ± 9</td>
<td>3 (3 - 4)</td>
<td>0.88 (0.76 - 0.95)</td>
</tr>
<tr>
<td>SLR FPPA 1</td>
<td>17</td>
<td>17 ± 11</td>
<td>6 (5 - 7)</td>
<td>0.77 (0.60 - 0.90)</td>
</tr>
<tr>
<td>FPPA 2</td>
<td>14</td>
<td>19 ± 13</td>
<td>8 (6 - 10)</td>
<td>0.67 (0.44 - 0.86)</td>
</tr>
<tr>
<td>LTM 1</td>
<td>17</td>
<td>16 ± 7</td>
<td>3 (3 - 4)</td>
<td>0.84 (0.70 - 0.93)</td>
</tr>
<tr>
<td>LTM 2</td>
<td>14</td>
<td>18 ± 8</td>
<td>3 (2 - 4)</td>
<td>0.88 (0.76 - 0.95)</td>
</tr>
<tr>
<td>HSL FPPA 1</td>
<td>17</td>
<td>6 ± 10</td>
<td>8 (7 - 11)</td>
<td>0.43 (0.14 - 0.71)</td>
</tr>
<tr>
<td>FPPA 2</td>
<td>14</td>
<td>10 ± 10</td>
<td>9 (7 - 12)</td>
<td>0.23 (-0.02 - 0.56)</td>
</tr>
<tr>
<td>LTM 1</td>
<td>17</td>
<td>15 ± 11</td>
<td>11 (9 - 14)</td>
<td>0.09 (-0.15 - 0.43)</td>
</tr>
<tr>
<td>LTM 2</td>
<td>14</td>
<td>17 ± 13</td>
<td>7 (6 - 10)</td>
<td>0.69 (0.45 - 0.87)</td>
</tr>
<tr>
<td>HSR FPPA 1</td>
<td>17</td>
<td>8 ± 23</td>
<td>9 (7 - 12)</td>
<td>0.86 (0.72 - 0.94)</td>
</tr>
<tr>
<td>FPPA 2</td>
<td>14</td>
<td>12 ± 12</td>
<td>9 (8 - 12)</td>
<td>0.44 (0.17 - 0.72)</td>
</tr>
<tr>
<td>LTM 1</td>
<td>17</td>
<td>16 ± 14</td>
<td>15 (12 - 20)</td>
<td>-0.11 (-0.28 - 0.20)</td>
</tr>
<tr>
<td>LTM 2</td>
<td>14</td>
<td>19 ± 11</td>
<td>8 (6 - 10)</td>
<td>0.58 (0.32 - 0.81)</td>
</tr>
</tbody>
</table>

Notes: SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; FPPA = frontal plane projection angle; LTM = lateral trunk motion; SD = standard deviation; CI = confidence interval
### Table 3. Within-session reliability of sagittal plane flexion angles during the TJFT tests

<table>
<thead>
<tr>
<th>TJFT Test</th>
<th>Joint &amp; Session</th>
<th>n</th>
<th>Mean ± SD (°)</th>
<th>TE (95%CI) (°)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DL</strong></td>
<td>Ankle 1</td>
<td>16</td>
<td>29 ± 5</td>
<td>2 (1 - 2)</td>
<td>0.92 (0.83-0.97)</td>
</tr>
<tr>
<td></td>
<td>Ankle 2</td>
<td>14</td>
<td>30 ± 6</td>
<td>1 (1 - 1)</td>
<td>0.97 (0.93-0.99)</td>
</tr>
<tr>
<td></td>
<td>Knee 1</td>
<td>16</td>
<td>101 ± 11</td>
<td>3 (2 - 3)</td>
<td>0.95 (0.91-0.98)</td>
</tr>
<tr>
<td></td>
<td>Knee 2</td>
<td>14</td>
<td>106 ± 12</td>
<td>3 (2 - 3)</td>
<td>0.96 (0.92-0.99)</td>
</tr>
<tr>
<td></td>
<td>Hip 1</td>
<td>16</td>
<td>98 ± 8</td>
<td>3 (2 - 4)</td>
<td>0.90 (0.80-0.96)</td>
</tr>
<tr>
<td></td>
<td>Hip 2</td>
<td>14</td>
<td>101 ± 9</td>
<td>2 (2 - 3)</td>
<td>0.96 (0.91-0.98)</td>
</tr>
<tr>
<td></td>
<td>Lsp 1</td>
<td>16</td>
<td>36 ± 11</td>
<td>3 (3 - 4)</td>
<td>0.93 (0.86-0.97)</td>
</tr>
<tr>
<td></td>
<td>Lsp 2</td>
<td>14</td>
<td>34 ± 12</td>
<td>3 (3 - 4)</td>
<td>0.94 (0.88-0.98)</td>
</tr>
<tr>
<td><strong>SLL</strong></td>
<td>Ankle 1</td>
<td>17</td>
<td>34 ± 7</td>
<td>2 (2 - 3)</td>
<td>0.93 (0.86-0.97)</td>
</tr>
<tr>
<td></td>
<td>Ankle 2</td>
<td>14</td>
<td>34 ± 8</td>
<td>3 (3 - 4)</td>
<td>0.94 (0.87-0.98)</td>
</tr>
<tr>
<td></td>
<td>Knee 1</td>
<td>17</td>
<td>88 ± 9</td>
<td>3 (3 - 4)</td>
<td>0.89 (0.78-0.95)</td>
</tr>
<tr>
<td></td>
<td>Knee 2</td>
<td>14</td>
<td>89 ± 11</td>
<td>4 (3 - 5)</td>
<td>0.87 (0.75-0.95)</td>
</tr>
<tr>
<td></td>
<td>Hip 1</td>
<td>17</td>
<td>67 ± 9</td>
<td>4 (3 - 4)</td>
<td>0.86 (0.74-0.94)</td>
</tr>
<tr>
<td></td>
<td>Hip 2</td>
<td>14</td>
<td>71 ± 8</td>
<td>4 (3 - 4)</td>
<td>0.81 (0.64-0.92)</td>
</tr>
<tr>
<td></td>
<td>Lsp 1</td>
<td>17</td>
<td>30 ± 16</td>
<td>3 (3 - 4)</td>
<td>0.97 (0.93-0.99)</td>
</tr>
<tr>
<td></td>
<td>Lsp 2</td>
<td>14</td>
<td>26 ± 15</td>
<td>3 (3 - 4)</td>
<td>0.95 (0.91-0.98)</td>
</tr>
<tr>
<td><strong>SLR</strong></td>
<td>Ankle 1</td>
<td>17</td>
<td>35 ± 6</td>
<td>2 (2 - 2)</td>
<td>0.91 (0.82-0.96)</td>
</tr>
<tr>
<td></td>
<td>Ankle 2</td>
<td>14</td>
<td>34 ± 6</td>
<td>2 (1 - 2)</td>
<td>0.94 (0.87-0.98)</td>
</tr>
<tr>
<td></td>
<td>Knee 1</td>
<td>17</td>
<td>88 ± 10</td>
<td>4 (3 - 5)</td>
<td>0.87 (0.76-0.95)</td>
</tr>
<tr>
<td></td>
<td>Knee 2</td>
<td>14</td>
<td>91 ± 9</td>
<td>4 (3 - 5)</td>
<td>0.82 (0.66-0.93)</td>
</tr>
<tr>
<td></td>
<td>Hip 1</td>
<td>17</td>
<td>65 ± 10</td>
<td>4 (3 - 5)</td>
<td>0.83 (0.69-0.93)</td>
</tr>
<tr>
<td></td>
<td>Hip 2</td>
<td>14</td>
<td>71 ± 9</td>
<td>4 (3 - 5)</td>
<td>0.83 (0.68-0.93)</td>
</tr>
<tr>
<td></td>
<td>Lsp 1</td>
<td>17</td>
<td>25 ± 15</td>
<td>3 (2 - 3)</td>
<td>0.97 (0.95-0.99)</td>
</tr>
<tr>
<td></td>
<td>Lsp 2</td>
<td>14</td>
<td>27 ± 13</td>
<td>3 (2 - 3)</td>
<td>0.97 (0.93-0.99)</td>
</tr>
<tr>
<td><strong>HSL</strong></td>
<td>Ankle 1</td>
<td>17</td>
<td>31 ± 7</td>
<td>3 (3 - 5)</td>
<td>0.78 (0.58-0.90)</td>
</tr>
<tr>
<td></td>
<td>Ankle 2</td>
<td>14</td>
<td>33 ± 7</td>
<td>3 (2 - 3)</td>
<td>0.90 (0.79-0.96)</td>
</tr>
<tr>
<td></td>
<td>Knee 1</td>
<td>17</td>
<td>77 ± 12</td>
<td>5 (4 - 7)</td>
<td>0.82 (0.64-0.92)</td>
</tr>
<tr>
<td></td>
<td>Knee 2</td>
<td>14</td>
<td>83 ± 13</td>
<td>5 (4 - 7)</td>
<td>0.86 (0.73-0.95)</td>
</tr>
<tr>
<td></td>
<td>Hip 1</td>
<td>17</td>
<td>64 ± 9</td>
<td>4 (4 - 6)</td>
<td>0.80 (0.62-0.91)</td>
</tr>
<tr>
<td></td>
<td>Hip 2</td>
<td>14</td>
<td>69 ± 8</td>
<td>4 (3 - 5)</td>
<td>0.77 (0.56-0.91)</td>
</tr>
<tr>
<td></td>
<td>Lsp 1</td>
<td>17</td>
<td>23 ± 13</td>
<td>4 (4 - 6)</td>
<td>0.90 (0.79-0.96)</td>
</tr>
<tr>
<td></td>
<td>Lsp 2</td>
<td>14</td>
<td>27 ± 12</td>
<td>3 (3 - 4)</td>
<td>0.94 (0.87-0.98)</td>
</tr>
<tr>
<td><strong>HSR</strong></td>
<td>Ankle 1</td>
<td>17</td>
<td>33 ± 5</td>
<td>3 (3 - 4)</td>
<td>0.65 (0.39-0.84)</td>
</tr>
<tr>
<td></td>
<td>Ankle 2</td>
<td>14</td>
<td>33 ± 5</td>
<td>3 (2 - 4)</td>
<td>0.69 (0.45-0.87)</td>
</tr>
<tr>
<td></td>
<td>Knee 1</td>
<td>17</td>
<td>80 ± 11</td>
<td>7 (6 - 9)</td>
<td>0.66 (0.41-0.84)</td>
</tr>
<tr>
<td></td>
<td>Knee 2</td>
<td>14</td>
<td>85 ± 9</td>
<td>5 (4 - 7)</td>
<td>0.70 (0.47-0.87)</td>
</tr>
<tr>
<td></td>
<td>Hip 1</td>
<td>17</td>
<td>64 ± 8</td>
<td>5 (4 - 7)</td>
<td>0.60 (0.33-0.81)</td>
</tr>
<tr>
<td></td>
<td>Hip 2</td>
<td>14</td>
<td>69 ± 9</td>
<td>4 (3 - 5)</td>
<td>0.87 (0.73-0.95)</td>
</tr>
<tr>
<td></td>
<td>Lsp 1</td>
<td>17</td>
<td>21 ± 12</td>
<td>3 (3 - 4)</td>
<td>0.94 (0.88-0.98)</td>
</tr>
<tr>
<td></td>
<td>Lsp 2</td>
<td>14</td>
<td>26 ± 10</td>
<td>3 (3 - 4)</td>
<td>0.92 (0.82-0.97)</td>
</tr>
</tbody>
</table>

Notes: DL = double leg squat; SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; Lsp = lumbar spine; SD = standard deviation; CI = confidence interval
4.2 Intra-athlete day-to-day variation in performance of the TJFT movement tests

Due to absence from school, only 14 athletes (mean age 16.8 ± 0.9 years, mean height 181 ± 5cm, mean weight 75.5 ± 9.9 kg) completed the retesting session. All between-session analyses were therefore, based only on data from these 14 athletes.

4.2.1. Between-session systematic change in performance

Although the mean rating scores of the SLR, HSL and HSR appeared to be slightly higher on Day 2 than they were on Day 1 (Table 4), Wilcoxon signed-rank tests with a Bonferroni corrected alpha level of 0.01 (0.05/5 tests), determined that there was no significant difference between sessions for any of the tests (Z ranged between -2.08 and -0.16, p = 0.04 to 0.88).

4.2.2. Between-session reliability of the TJFT rating scores

The mean TJFT composite score for Day 2 (13.2 ± 5.4 pts) was slightly higher than it was for Day 1 (11.4 ± 5.0 pts), but the reliability between-sessions was ‘excellent’ (ICC 0.84, 95%CI 0.56 to 0.94; TE 2.3 pts, 95%CI 1.6 to 3.6 pts). The typical errors for day-to-day variations in the mean rating scores of the individual movement tests were 0.5 to 1.0 pts for all tests and the between-session ICC’s were ‘good’ to ‘excellent’ for all tests except the HSR, which was ‘poor’ (Table 4).

4.2.3 Between-session reliability of the frontal and sagittal plane angle measurements

With the exception of FPPA during the HSR, which had ‘fair’ between-session reliability and a TE of approximately 8°, the day-to-day reliability of the FPPA and LTM were ‘good’ to ‘excellent’ for all tests with typical errors ranging from 3 to 5° (Table 5). For all tests, the day-to-day reliability of the sagittal plane flexion angles were also ‘good’ to ‘excellent’, except for hip flexion, which was ‘fair’ to ‘excellent’ (Table 6). Typical errors ranged from 3 to 7° for knee, hip and lumbar spine flexion and 1 to 3° for ankle dorsiflexion for all tests (Table 6).
Table 4. Between-session reliability of mean TJFT rating scores

<table>
<thead>
<tr>
<th>TJFT Test</th>
<th>n</th>
<th>Change in mean ± SD (pts)</th>
<th>TE (95%CI) (pts)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>14</td>
<td>0.1 ± 0.9</td>
<td>0.6 (0.5-1.0)</td>
<td>0.88 (0.67-0.96)</td>
</tr>
<tr>
<td>SLL</td>
<td>14</td>
<td>0.0 ± 0.8</td>
<td>0.5 (0.4-0.9)</td>
<td>0.86 (0.63-0.96)</td>
</tr>
<tr>
<td>SLR</td>
<td>14</td>
<td>0.5 ± 1.1</td>
<td>0.8 (0.6-1.3)</td>
<td>0.65 (0.21-0.87)</td>
</tr>
<tr>
<td>HSL</td>
<td>14</td>
<td>0.6 ± 0.9</td>
<td>0.6 (0.5-1.0)</td>
<td>0.72 (0.33-0.90)</td>
</tr>
<tr>
<td>HSR</td>
<td>14</td>
<td>0.6 ± 1.1</td>
<td>0.8 (0.6-1.2)</td>
<td>0.30 (-0.26-0.7)</td>
</tr>
</tbody>
</table>

Notes: DL = double leg squat; SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; SD = standard deviation; CI = confidence interval; pts = rating points

Table 5. Between-session reliability of frontal plane angles during the TJFT tests

<table>
<thead>
<tr>
<th>TJFT Test</th>
<th>Feature</th>
<th>n</th>
<th>Change in mean ± SD (°)</th>
<th>TE (95%CI) (°)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLL</td>
<td>FPPA</td>
<td>14</td>
<td>-1 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.76 (0.40-0.92)</td>
</tr>
<tr>
<td></td>
<td>LTM</td>
<td>14</td>
<td>2 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.77 (0.40-0.92)</td>
</tr>
<tr>
<td>SLR</td>
<td>FPPA</td>
<td>14</td>
<td>2 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.86 (0.62-0.95)</td>
</tr>
<tr>
<td></td>
<td>LTM</td>
<td>14</td>
<td>2 ± 4</td>
<td>3 (2 - 4)</td>
<td>0.87 (0.63-0.95)</td>
</tr>
<tr>
<td>HSL</td>
<td>FPPA</td>
<td>14</td>
<td>2 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.70 (0.29-0.89)</td>
</tr>
<tr>
<td></td>
<td>LTM</td>
<td>14</td>
<td>1 ± 8</td>
<td>5 (4 - 9)</td>
<td>0.64 (0.19-0.87)</td>
</tr>
<tr>
<td>HSR</td>
<td>FPPA</td>
<td>14</td>
<td>4 ± 12</td>
<td>8 (6 - 13)</td>
<td>0.48 (-0.04-0.80)</td>
</tr>
<tr>
<td></td>
<td>LTM</td>
<td>14</td>
<td>3 ± 4</td>
<td>3 (2 - 4)</td>
<td>0.94 (0.82-0.98)</td>
</tr>
</tbody>
</table>

Notes: SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; FPPA = frontal plane projection angle; LTM = lateral trunk motion; SD = standard deviation; CI = confidence interval
<table>
<thead>
<tr>
<th>TJFT Test</th>
<th>Joint</th>
<th>n</th>
<th>Change in mean ± SD (°)</th>
<th>TE (95%CI) (°)</th>
<th>ICC (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>Ankle</td>
<td>14</td>
<td>1 ± 1</td>
<td>1 (1 - 2)</td>
<td>0.98 (0.92-0.99)</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>14</td>
<td>5 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.91 (0.72-0.97)</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>14</td>
<td>4 ± 7</td>
<td>5 (3 - 8)</td>
<td>0.72 (0.30-0.90)</td>
</tr>
<tr>
<td></td>
<td>Lsp</td>
<td>14</td>
<td>-2 ± 7</td>
<td>5 (3 - 8)</td>
<td>0.86 (0.60-0.95)</td>
</tr>
<tr>
<td>SLL</td>
<td>Ankle</td>
<td>14</td>
<td>-1 ± 2</td>
<td>1 (1 - 2)</td>
<td>0.97 (0.91-0.99)</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>14</td>
<td>1 ± 5</td>
<td>4 (3 - 6)</td>
<td>0.89 (0.69-0.96)</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>14</td>
<td>4 ± 7</td>
<td>5 (4 - 8)</td>
<td>0.62 (0.16-0.86)</td>
</tr>
<tr>
<td></td>
<td>Lsp</td>
<td>14</td>
<td>-2 ± 8</td>
<td>5 (4 - 9)</td>
<td>0.89 (0.69-0.96)</td>
</tr>
<tr>
<td>SLR</td>
<td>Ankle</td>
<td>14</td>
<td>-1 ± 3</td>
<td>2 (1 - 3)</td>
<td>0.92 (0.77-0.97)</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>14</td>
<td>3 ± 5</td>
<td>4 (3 - 6)</td>
<td>0.82 (0.52-0.94)</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>14</td>
<td>5 ± 9</td>
<td>6 (5 - 10)</td>
<td>0.44 (-0.09-0.78)</td>
</tr>
<tr>
<td></td>
<td>Lsp</td>
<td>14</td>
<td>3 ± 7</td>
<td>5 (4 - 8)</td>
<td>0.89 (0.70-0.96)</td>
</tr>
<tr>
<td>HSL</td>
<td>Ankle</td>
<td>14</td>
<td>2 ± 3</td>
<td>2 (2 - 4)</td>
<td>0.88 (0.68-0.96)</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>14</td>
<td>8 ± 9</td>
<td>6 (5 - 10)</td>
<td>0.71 (0.30-0.90)</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>14</td>
<td>5 ± 9</td>
<td>7 (5 - 11)</td>
<td>0.42 (-0.12-0.77)</td>
</tr>
<tr>
<td></td>
<td>Lsp</td>
<td>14</td>
<td>4 ± 7</td>
<td>5 (4 - 8)</td>
<td>0.85 (0.59-0.95)</td>
</tr>
<tr>
<td>HSR</td>
<td>Ankle</td>
<td>14</td>
<td>-1 ± 3</td>
<td>2 (2 - 4)</td>
<td>0.74 (0.37-0.91)</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>14</td>
<td>5 ± 6</td>
<td>4 (3 - 7)</td>
<td>0.76 (0.41-0.92)</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>14</td>
<td>5 ± 5</td>
<td>4 (3 - 6)</td>
<td>0.81 (0.51-0.94)</td>
</tr>
<tr>
<td></td>
<td>Lsp</td>
<td>14</td>
<td>6 ± 7</td>
<td>5 (3 - 8)</td>
<td>0.85 (0.59-0.95)</td>
</tr>
</tbody>
</table>

Notes: DL = double leg squat; SLL = single leg squat, left; SLR = single leg squat, right; HSL = hop & stick, left; HSR hop & stick, right; Lsp = lumbar spine; SD = standard deviation; CI = confidence interval;
Chapter 5: Discussion

The purpose of this study was to investigate the intra-athlete, within- and between-session reliability of the TJFT using 2-D video analysis in development-level, adolescent court and field sport athletes. In general, the between-session reliability of all tests was ‘good’ to ‘excellent’, but the within-session reliability of all measures varied considerably between tests and the rep-to-rep variability in rating scores ranged between 0.5 pts for the DL and 1.5 pts for the HSL and HSR. The major limitation of the study was that 3-D motion analysis could not be used to describe the intra-athlete movement variability that occurred while performing the movement tests. The combination of common clinical analysis and 2-D video analysis techniques used, did however, provide an indication of intra-athlete variability in TJFT performance that is clinically relevant and easily replicated in the clinical environment.

5.1. Intra-athlete rep-to-rep variation in performance of the TJFT movement tests

5.1.1. Comparing the observed movement variability of the three movement tests

For all measures the within-session reliability was highest for the DL, lower for the SLL and SLR, and lowest for the HSL and HSR tests. It is possible fatigue may have contributed to this result because this was also the order the tests were performed in, however, the large rest periods between tests, small total exercise load, and lack of within-session systematic change in rating scores make this unlikely. Movement variability is a feature of skilled movement performance (Seifert et al., 2014; Wagner et al., 2012) and although it typically decreases to an optimal level as a skill is acquired, high variability during the initial stages of skill acquisition results from the use of different movement strategies, relative to the complexity of the movement task, and may increase again during mastery or adaptation of complex skills (Harbourne & Stergiou, 2009). In the initial development of the TJFT, the three movement tests were chosen because they all require similar triple-joint flexion movements, but the postural control and dynamic balance challenge increases with each test. It was presumed that the increased complexity of each movement task would permit different aspects of movement control to be assessed within the same fundamental movement, and that progressively more demanding tasks would be required in order to identify movement control deficits associated with lower limb injury (von Porat et al., 2008). The results of the present study support the idea that larger movement variability occurs during movement tests that demand greater postural control and dynamic balance.
In interpreting these results it is important to consider that because the HSL and HSR were analysed 1 s after initial foot contact and not at the time point maximum knee flexion stabilised, the additional performance component of time to stabilisation would also have contributed to the large rep-to-rep variability observed for these tests. Given the relative proximity to occurrence of maximum knee flexion, the high number of athletes that scored ‘0’s’ for at least one of the hop landing tests (79 to 88%), and the observed difference in reliability between the DL and SL squat tests, it is unlikely this difference in analysis was the major reason the HSL and HSR had the highest within session variability.

5.1.2. Within-session reliability of the TJFT rating scores

There were no significant systematic changes in rating scores over the six repetitions of any of the movement tests and this suggests there was no observable learning effect, within-session, for any of the movement tests. The results indicated that the ‘good’ to ‘excellent’ within-session reliability of the squat tests were associated with a rep-to-rep variability in rating scores of approximately 0.5 to 1 pts for the DL and 1 to 1.5 pts for the SL and SLR. Half point ratings are not possible during the TJFT, so in practical terms the rep-to-rep variability of the athlete’s performance in the squat tests could be expected to be ±1 pt on the TJFT rating scale. The ‘poor’ to ‘fair’ within-session reliability of the HSL and HSR were associated with a rep-to-rep variability in rating scores of approximately 1 to 2 pts and the athlete’s performance in these tests could therefore be expected to vary up to 4 pts within a session. Live ratings are based on visual analysis of several repetitions and although an individual rating for each repetition would be most accurate, it is plausible that for each of the squat tests in the TJFT a visual rating based on several repetitions of the tests could approximately represent the athlete’s repeated performance of the tests within that session. The large rep-to-rep variability in performance of the HSL and HSR suggests however, that an assigned live rating of these tests would probably not represent the athlete’s repeated performance of the tests. A series of ratings or, the number of successfully completed repetitions, could potentially be better representations of what appears to be a test of movement with high inherent variability. Because live ratings permit only one view of each repetition, further investigation is required in order to determine the best way to make live ratings of the HSL and HSR that are representative of the athlete’s performance within the session.

5.1.3. Within-session reliability of the frontal and sagittal plane angle measurements

The ‘good’ - ‘excellent’ within-session reliability of the frontal and sagittal plane angle measurements during the squat tests were similar to those reported by Ford et al. (2007) and Whatman et al. (2011)
analysed using 3-D techniques for all angle measurement during similar triple-joint flexion movement tests. The lack of a specified landing depth in the test requirements and the analysed frame being a constant time from touch down, probably explain the slightly lower ‘good’ to ‘excellent’ within-session reliability observed for the sagittal plane flexion angles during the HSL and HSR. Milner et al. (2011) reported ‘good’ to ‘excellent’ within-session reliability of 3-D peak knee angles during a stop-jump task and suggested that when compared to the findings of Ford et al. (2007), the slightly lower reliability could be attributed to the less constrained nature of the stop-jump task. ‘Good’ to ‘excellent’ within-day reliability has also been reported for the FPPA (Munro et al., 2012), femoral frontal angle and femoral deviation (Levinger et al., 2007) during triple-joint flexion tasks analysed using 2-D video, however, the within-day reliability reported for the FPPA was based on two sessions one hour apart and the TE rep-to-rep variability was not reported in either study. In the present study, the within-session reliability of the frontal plane angle measurements during the HSL and HSR were ‘poor’ with several 95% CIs for ICC’s that included zero and typical errors that ranged from 50 to 150% of the observed mean angle measured. The large rep-to-rep variability in performance of the HSL and HSR is further highlighted by these findings and emphasises the need for further investigation of these tests.

5.1.4. Normative comparisons of the FPPA and LTM

The mean FPPA observed during the HSL and HSR was similar to the normative values that have been reported for single leg landings (1 to 12°) and single leg squats (3 to 12°) with knee flexion in the 45 to 60° range (Herrington & Munro, 2010; Mendonca et al. 2011; Munro et al., 2012). The mean FPPA observed during the SLL and SLR was approximately two times the normative values reported previously, however, the knee flexion angle during the SLL and SLR was approximately 90° and increased sagittal plane motion has been associated with increased frontal plane motion at the knee (Stensrud et al, 2011; Russell, Palmieri, Zinder, & Ingersoll, 2006). The mean LTM angle was similar for all SL tests and slightly higher than that reported by Dingenen et al (2013) for the SL squat (4 to 17°), which suggests that in the present study there was less lateral motion towards the test leg and the trunk remained more upright..

5.1.5. Minimal variability in the sagittal plane ‘shape’ of each movement test

There was little rep-to-rep variability in the combined lumbo-pelvic and lower limb sagittal ‘shape’ each athlete formed for each of the movement tests. The lack of sagittal plane variability was unexpected, because although there was a ROM requirement for the squat tests, the tests that did not meet this requirement were also measured and included in the analysis. In addition, there was no
ROM requirement for the HSL and HSR and considerable rep-to-rep variability in the FPPA and LTM. Poor sagittal positioning during single leg landings has been linked to non-contact ACL injury (Sheehan et al., 2012; Shimokochi, Ambegaonkar, Meyer, Lee, & Shultz, 2013) and decreased ankle dorsiflexion has been identified as a risk factor for ankle injury (de Noronha et al., 2006). In standardised triple-joint flexion tasks, ROM or control deficits at one joint must be compensated for by the other joints in the kinetic chain in order to complete the task and this is the basic premise for their clinical use in identifying movement dysfunction. It appears that in the sagittal plane, rep-to-rep compensatory movements are relatively constant during the TJFT and might therefore, provide reliable rating criteria for visual analysis or the potential to standardise sagittal plane movement requirements in order to identify compensation in the other planes from single view, visual analysis. Future research to determine how observed sagittal plane movement compensations manifest in the frontal and coronal planes during triple-joint flexion tasks and the independent roles ROM and control deficits play in the observed movement compensations is warranted.

5.1.6. Implications of the intra-athlete within-session findings

This is the first investigation of the TJFT movement screening protocol and to our knowledge, the first movement screening study to report rep-to-rep variability in rating scores. The practical implications of these findings could be applicable to other movement screening protocols involving unilateral landing tasks and provide a readily accessible method for investigating a component of reliability that has been largely overlooked in the movement screening research. For all of the movement tests there was generally more rep-to-rep variability in the TJFT scores than the sagittal and frontal plane angle measurements. Because of the reliability of the rating and analysis techniques used, this suggests that the TJFT rating criteria are able to identify more of the variability associated with the movement tests than measurement of sagittal and frontal plane angles. During functional triple-joint flexion tasks, 2-D video analysis of the knee has been shown to inadequately describe the within-subject variance observed with 3-D analysis (McLean et al., 2005; and Willson and Davis, 2008) and to have inadequate sensitivity (67 to 87%) to detect potentially high risk compensatory movements (Ekegren et al., 2009). Given that the TJFT criteria involve visual analysis of multiple joints and multiple planes in a clinical manner, this finding was not unexpected and in the absence of access to 3-D motion analysis, provides support for the use of the TJFT in clinical analysis situations.
5.2. Intra-athlete day-to-day variation in performance of the TJFT movement tests

5.2.1. Between-session reliability of all measures

For all tests, the between-session reliability of most angle measurements and the TJFT rating scores was similar or higher than within-session reliability. In general, day-to-day variability in rating scores and angle measurements was ‘good’ - ‘excellent’ for all tests except the HSR. In contrast, reliability of 3-D trunk and lower limb peak angles during triple-joint flexion movement tests has been reported to be worse between-sessions, compared to within-sessions (Ford et al., 2007; Whatman et al., 2011) and similar between- and within-sessions (Milner et al., 2011). In these studies however, the within-session reliability was also ‘good’ - ‘excellent’, so the use of mean values in between-sessions calculations would potentially have had less impact on this comparison than it did in the present study. Munro et al. (2012) also reported ‘good’ - ‘excellent’ between-session reliability of FPPA during the single leg squat, drop-jump, and single leg landing from 2-D video analysis. Dingenen et al. (2013) reported ‘excellent’ intra-rater reliability for LTM using 2-D video analysis however, to our knowledge the intra-athlete between-session reliability of LTM assessed in this manner has not previously been reported. Similar to previous studies of triple-joint function movement tasks, the findings of the present study suggest that the day-to-day variation in performance of the TJFT is relatively stable. In practical terms it could be expected that the intra-athlete day-to-day variation in mean rating score would be ±1 pt for each test and ±2 to 4 pts for the composite score. When this finding is coupled with the considerably larger rep-to-rep variability that was observed for most tests, the need to observe several repetitions of each test in order to make a representative rating of the athlete’s performance is emphasised.

5.2.2. Possible explanations for outliers

The ‘poor’ between-session reliability of the HSR is difficult to interpret in relation to the other tests and the extremely wide confidence intervals for the ICC of rating score (ICC -0.26 to 0.7) and FPPA (ICC -0.04 to 0.80) show the uncertainty of this estimate. The HSR also had the largest rep-to-rep variability on both days, so a possible explanation for the increased movement variability observed for the HSR was that it was the most novel test for this group of athletes. In right-footed athletes the dominant ‘plant’ leg is the left and 86% of the sample classified themselves as right-footed. Although a learning effect between days was unlikely for any of the tests, it is possible that several of the athletes in this group had little previous exposure to right leg landing tasks and may have adopted protective or experimentitive techniques to compensate for decreased strength or movement control in their non-dominant ‘plant’ leg (Spiteri, Cochrane, Hart, Haff, & Nimphius, 2013; Berlin, 2011).
Given the small sample, incongruous performances by a few athletes could have contributed to this unexpected finding. Further investigation of repeated exposure and skill acquisition during performance of the TJFT are warranted and could assist in determining how a series of live repetitions should be rated. The most parsimonious approach to scoring highly variable movements may be to standardise the sagittal plane requirements, count the number of successfully completed repetitions, and make a series of ratings based predominantly on the same viewing position, as suggested in Sections 5.1.5. and 5.1.2. respectively.

In the sagittal plane, the only measurement with considerable day-to-day variability was hip flexion angle and in the HSL and SL squat tests the expected between-session variation was approximately 4 to 12°, which is considerably larger than the 3 to 5° Whatman et al. (2011) reported for similar tests. Because hip flexion was assessed relative to the inclination of the pelvis using 2-D techniques in the present study, it is possible that the high between-session variability observed was in fact a representation of the movement compensation strategies occurring at the hip as opposed to hip flexion per se. Increased hip adduction and/or internal rotation are considered to be common kinematic features of dynamic knee valgus (Stickler, Finley, & Gulgin, 2015; Lankhorst et al., 2012; Powers, 2010). Increased frontal and coronal plane motion of the thigh and pelvis should therefore, have been expected to accompany the large knee valgus angles observed during the SL tests. In this situation, 2-D sagittal plane measures of hip flexion would include considerable distortion originating from the thigh and pelvis movements that deviate from the image plane (Noehren, Barrance, Pohl, & Davis, 2012). In the absence of 3-D motion analysis it is impossible to determine to what extent this occurred and it is unlikely the day-to-day variation in hip flexion angle could be completely explained by this mechanism. This finding does however, provide support for including sagittal plane criteria in the TJFT and warrants further research with more advanced analysis techniques.

5.3. Limitations

In addition to the limitations already discussed, there are other limitations inherent in the present study. Firstly, the sample size was small and therefore may not be representative of the wider population of adolescent, development-level athletes. Nevertheless, the observed performances included the full range of possible rating scores in the TJFT – a necessary characteristic for the design of reliability studies (Lucas et al., 2010). Secondly, although athletes with injuries were excluded from the study, and this would challenge external validity as it may not be representative of a typical developmental sports-training squad, the study was designed primarily to investigate methodological
aspects rather than direct clinical application. Prior to using the TJFT for live clinical ratings (not video-based) further investigation is required as outlined in Section 5.4.

5.4 Implications for future research

Based on the findings of the present study the specific recommendations for continued investigation and development of the TJFT are:

• To investigate the inter- and intra-rater reliability of the TJFT, in another video-based, repeated clinical measures study using a series of recorded tests involving similar athletes to those in the present study. The design could potentially be similar to that described by Whatman et al. (2012a), but should ensure the video-rating conditions were comparable to live-rating and the same for all raters.

• To investigate the construct validity of TJFT by assessing the relationship between performance in the TJFT and a range of other lower limb screening and performance tests. Because of their similar movement characteristics and scrutiny in the existing literature, the lower limb tests of the Functional Movement Screen (Cooke et al., 2006), the Y-Balance test (Plisky et al., 2009), the Landing Error Scoring System (Padua et al, 2009), and an instrumented measure of time to stabilisation in jump landing tasks (Ross et al., 2009) are potential candidates.

• To investigate, using 3-D motion analysis, the internal validity of ratings made from different viewing positions, and the sensitivity of the rating criteria to detect differences in triple-joint positioning during the movement tests.

Ultimately this combination of studies would lead to the possibility of using the TJFT in intervention studies to monitor change, based on clinical interventions, and to determine the impact of deficits in ROM or neuromuscular control on fundamental lower limb movements.
Conclusion

The TJFT has been developed to meet the practical needs of clinical movement screening with development-level athletes and sports teams. In healthy, adolescent male, court and field sport athletes the inter- and intra-rater reliability of the TJFT can now be investigated with knowledge of the expected intra-athlete variability within- and between-sessions for each of the movement tests. The considerable rep-to-rep variability identified within-session, highlights the need for more investigation in movement screening research of the movement variability associated with the performance, scoring and interpretation of movement tests. In the next phase of development for the TJFT a potential solution for making live ratings of movements with high rep-to-rep variability is to: 1) increase the standardisation of the sagittal plane requirements of the tests, 2) make a series of ratings from the same viewing position or positions, and 3) count how many of the specified number of test repetitions the athlete successfully completes. These suggestions for live ratings are, however, speculative based on the findings of the present study and would require specific investigation to determine the feasibility of their use. Although live-rating the TJFT could be problematic and the reliability of doing so has not yet been determined, the findings of the present study suggest that the intra-athlete, between-session reliability of the TJFT using 2-D video analysis, is adequate to be used for the clinical monitoring of lower limb function in development-level, adolescent athletes.
References


de la Motte, S., Arnold, B.L., & Ross, S.E. (2014). Trunk-rotation differences at maximal reach of the star excursion balance test in participants with chronic ankle instability. *J Athl Train, 49*(3), Online first. doi:10.4085/1062-6050-49.3.74


Appendices

Appendix 1. Triple-Joint Flexion Test protocol and rating criteria

Appendix 2. Origins of the Triple Joint Flexion Test (TJFT) and it’s practical development.

Appendix 3. Ethics documentation: approval letter, information sheet, and consent form
Appendix 1. Triple-Joint Flexion Test protocol and rating criteria
### Triple Joint Flexion Test (TJFT)

**Test #1: Double Leg Squat (DL)**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Score</th>
<th>DL</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set Up:</strong> acromion &amp; ASIS vertically aligned within lateral borders of feet; big toe &lt; 5cm lateral of heel; arms in front with fingers on clavicle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frontal View</strong></td>
<td>Patella lateral to big toe (right)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
</tr>
<tr>
<td>Patella lateral to big toe (left)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Requirements:</strong> 1) No heel lift or change in foot position; 2) Bottom of thigh horizontal; 3) 3s isometric hold at bottom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sagittal View</strong></td>
<td>Pelvis level &amp; central in relation to feet</td>
<td>Yes (+1) / No (0)</td>
<td></td>
</tr>
<tr>
<td>Trunk parallel with lower leg</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar lordosis maintained (no kyphosis)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(Max 6)</td>
<td></td>
</tr>
</tbody>
</table>

**Test #2 & #3: Single Leg Squat (SLL & SLR)**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Score</th>
<th>SLL</th>
<th>SLR</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set Up:</strong> foot straight ahead; free leg in front of body and flexed at hip and knee; straight arms horizontal in front of body</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frontal View</strong></td>
<td>Patella lateral to big toe</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis level</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Requirements:</strong> 1) No heel lift or change in foot position; 2) 90° knee flexion - central long axes of thigh and lower leg segments; 3) 3s isometric hold at bottom; 4) no touch of opposite foot on floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sagittal View</strong></td>
<td>Trunk maintained vertical (no lateral sway)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk parallel with lower leg</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar lordosis maintained (no kyphosis)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(Max 6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Test #4 & #5: Hop & Stick (HSL & HSR)**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Score</th>
<th>HSL</th>
<th>HSR</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set Up:</strong> single leg stance on test leg; toes central &amp; behind start line; free arm swing in take-off &amp; in front on landing; land on test leg in approximately 90° knee flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frontal View</strong></td>
<td>Patella lateral to big toe</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis level</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Requirements:</strong> 1) Clean landing (no foot movement or free foot touch to gain balance); 2) Stick &amp; hold landing position for 3s; 3) Heel and toes in contact with ground (no heel lift)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sagittal View</strong></td>
<td>Trunk maintained vertical (no lateral sway)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk parallel with lower leg</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar lordosis maintained (no kyphosis)</td>
<td>Yes (+1) / No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(Max 6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Composite TJFT Score**

Max /30

Sum Totals of DL, SLL, SLR, HSL & HSR
Appendix 2. Origins of the Triple Joint Flexion Test (TJFT) and its practical development.

The Triple Joint Flexion Test (TJFT) was initially developed as part of a larger movement screening project that was commissioned by the Norwegian Football Association’s Top Football Centre to identify and implement injury reduction strategies for teenage football (soccer) players during their progression into senior football. The initial development was based on the clinical experiences of the author in a range of professional sports (rugby, athletics, volleyball, team handball, and football), in consultation with Kelvin Giles from Movement Dynamics in the United Kingdom (www.movementdynamics.com) and the medical staff from Norwegian Football and the Oslo Sports Trauma Research Centre, especially Thor-Einar Andersen. The screen was subsequently presented to all medical and coaching staff in the Norwegian Premier League for feedback and implemented as a pilot in the teenage and senior teams of a premier club in Norway, Stabaek Fotball. Modifications to the initial screen were then implemented based on the feedback and practical experiences of using the screen, although little objective data was recorded.

The author later incorporated a revised version of the screen into the athlete monitoring program for development (12-18-yrs) athletes at Aspire Academy for Sports Excellence in Doha, Qatar. The screen was used to identify injury risk and help guide physical training interventions and was modified again based on the practical experience of screening 200 athletes four times per year and anecdotal evidence from injury monitoring and physical training results. Significant contributions to the modification and adjustment of the tests and rating criteria that have subsequently been included in the TJFT were made at Aspire by: Strength & Conditioning Coaches Ben Haines, Nick Poulos, and Malcolm Geluk; the head of Physiotherapy, Amanda Johnson; and the Head Sports Physician, Matthieu Sailly.

The TJFT has undergone relatively extensive practical testing and analysis, with input from a large range of expert practitioners with considerable clinical experience. Anecdotally, the tests included in the TJFT have demonstrated excellent clinical utility and fulfill the practical requirements of clinical use with large numbers of athletes, as is common in the screening of sports teams. Although the tests and rating criteria have been successfully integrated into the risk management practices for sports injury in professional and development football teams and an elite youth academy of sport, no objective data on the reliability of the movement tests or rating protocol have previously been analysed. This study is therefore the first piece in the objective analysis of the reliability and clinical utility of the TJFT.
Appendix 3. Ethics documentation: approval letter, information sheet, and consent form
Matiu Taingahue  
47 Kitewaho Rd  
Swanson  
Auckland 0614  

20.6.13  

Dear Matiu,  

Your file number for this application: **2013-1019**  

Title: *The reliability and validity of a four-test movement screening protocol for visually assessing lower limb function in athletes.*  

Your application for ethics approval has been reviewed by the Unitec Research Ethics Committee (UREC) and has been approved for the following period:  

Start date: 30.5.13  
Finish date: 30.5.14  

Please note that:  

1. The above dates must be referred to on the information AND consent forms given to all participants.  
2. You must inform UREC, in advance, of any ethically-relevant deviation in the project. This may require additional approval.  
3. Organisational consent/s must be cited and approved by your primary reader prior to any organisations or corporations participating in your research. You may only conduct research with organisations for which you have consent.  

You may now commence your research according to the protocols approved by UREC. We wish you every success with your project.  

Yours sincerely,  

Gillian Whalley  
Deputy Chair, UREC  
CC: Rob Moran  
Cynthia Almeida
Information sheet for athletes

The reliability and validity of the Triple-Joint Flexion Test for assessing lower limb function in development athletes

About this research
You are invited to take part in a research project investigating the reliability and validity of the Triple Joint Flexion Test, which is a lower limb movement screening protocol and rating system for visually assessing movement quality. This research is being undertaken by Matiu Taingahue (Master of Osteopathy student) under the supervision of Rob Moran (Department of Osteopathy, Unitec).

A movement screening protocol is a series of movement tests used to assess movement quality based on a set of rating criteria. The use of movement screening to identify movement dysfunction and guide intervention has become standard practice in a range of settings. In a sport setting the results of movement screening help inform medical staff, coaches, trainers, and sports scientists about the athlete’s general movement skills, risk of injury, rehabilitation status, and allow targeted intervention to correct and enhance movement patterns. The Triple Joint Flexion Test consists of 3 basic lower limb movements – squat, single-leg squat, single-leg landing. Each movement is rated using a scoring system that grades the quality of each movement

What will happen in this research?
The testing will reflect a typical pre-season screening process and will be repeated in the same format one day later (2 sessions 1 day apart).

Session Outline: Introduction - The test procedure will be explained, example video of the tests being performed will be presented, and the tests will be demonstrated. You would then practice the movements and ask any questions you have before you are prepared for data collection. Several small, stick-on reflective markers will placed at specific anatomical landmarks on your back, hips and legs to assist with video analysis.

Data Collection - You will then perform 6 individual repetitions on each leg of each of the movement screening tests, followed by 3 repetitions on each leg of each movement of the Y-Balance test (48 repetitions in total). You will be videoed from the front and side for each of the movement screening tests (but not the Y-Balance test) and you will be asked to wear your own tight fitting athletic under-shorts. Because the whole squad will be screened during the same session and the video will be captured and synchronised live, there will be some waiting time between athletes. Each athlete is expected to take ~15 - 20mins to complete all stations.

We will be using video recordings of your movements
The video of your movement during the data collection session will be analysed using 2-dimensional video analysis by the principal researcher. You will be offered feedback based on this analysis and if you wish to receive it you will need to indicate that on the consent form. The raw video will be edited into a sequence of clips of you performing the movement tests and this will be shown to raters who will score the movements in real-time.

We seek your permission to use recordings for future research, education and training
In addition to using the video recordings in this current research we are also seeking your permission to use the video for future research, education and training. If you do not want your video clips to be used in the future it will not affect your participation in this research project in any way.
We treat your personal information confidentially
All personal information you provide will be treated as confidential and no material that could personally identify you will be used in any reports on this project.

Information about withdrawing from the study
If you wish to withdraw your participation including the video recordings from the study, you may do so for any reason up until 24-hours after the conclusion of the final data collection session.

Safety of movements
All the movement tests are low intensity, safe, and you are in control at all times. The movements that you need to perform are all body weight only exercises (see images below) and have been used extensively in clinical and sports coaching settings across a wide range of ages without any reports of injury.

Who can I contact with any further questions?
If you have any further questions about this research please feel free to contact one of us:

Principal Researcher:
Matiu Taingahue
Tel: 021 082 36360
Email: matiu.taingahue@gmail.com

Research Supervisor:
Robert Moran
Tel: 021 073 9984 or 815 4321 x8197
Email: rmoran@unitec.ac.nz

UREC REGISTRATION NUMBER: 2013-1019
This study has been approved by the UNITEC Research Ethics Committee from 27.08.14 to 27.08.15 If you have any complaints or reservations about the ethical conduct of this research, you may contact the Committee through the UREC Secretary (ph: 09 815–4321 ext 7248). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.
Participant consent form (Athletes)

The reliability and validity of the Triple-Joint Flexion Test for assessing lower limb function in development athletes

Name of Participant: __________________________________________________________

I have seen and read the information sheet for athletes taking part in the project titled “The reliability and validity of the Triple-Joint Flexion Test for assessing lower limb function in development athletes” and have had the opportunity to discuss the project with Matiu Taingahue or Rob Moran.

I understand that I am volunteering to partake in this study of my own volition, and I may withdraw at any time up to the 24-hours after the conclusion of the final data collection session.

I understand that if I am to suffer an accident or injury while participating in any part of this project that I will be entitled to make a claim under the Accident Compensation scheme.

I understand that my participation in this project is confidential and that no material that could personally identify me will be used in any reports on this project.

I understand that I can see the finished research document.

I have had enough time to consider whether I want to take part and acknowledge that any raw data collected during the study will be stored securely so that only the researchers may access them.

Participant Signature: ____________________________ Date: ______________

I wish / do not wish (delete one) to receive feedback based on analysis of my movement testing.

I consent / do not consent (delete one) to ongoing use of my video clips beyond this research as part of future research studies or for the purposes of educating health and exercise practitioners.

The principal researcher for this project is Matiu Taingahue and principal supervisor is Rob Moran:

Matiu Taingahue                      Robert Moran
Tel: 021 082 36360                  Tel: 021 073 9984 or 815 4321 x8197
Email: matiu.taingahue@gmail.com    Email: rmoran@unitec.ac.nz

The participant should retain a copy of this consent form

UREC REGISTRATION NUMBER: 2013-1019
This study has been approved by the UNITEC Research Ethics Committee from 27.08.14 to 27.08.15
If you have any complaints or reservations about the ethical conduct of this research, you may contact the Committee through the UREC Secretary (ph: 09 815-4321 ext 7248). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.