**Abstract**

*Context:* Anterior Cruciate Ligament (ACL) and Patellofemoral Joint (PFJ) injuries are a significant problem among female athletes. A number of screening tasks have been used in the literature to identify those at greatest risk of injury. To date, no study has examined the relationship in two-dimensional (2D) knee valgus between common screening tasks to determine whether individuals exhibit similar movement patterns across tasks.

*Objective:* to establish whether frontal plane projection angle (FPPA) during the single leg squat (SLS), single leg land (SLL) and drop jump (DJ) are related

*Design:* Cross-sectional Study

*Setting:* University Laboratory

*Participants:* 52 national league female football players and 36 national league female basketball players

*Main Outcome Measures:* 2D FPPA during the SLS, SLL and DJ screening tasks

*Results:* Significant correlations were found between tasks. FPPA in the SLS was significantly correlated with SLL ($r = 0.52$) and DJ ($r = 0.30$), whilst FPPA in the SLL was also significantly correlated to DJ ($r = 0.33$). FPPA was significantly greater in the SLS compared to the SLL ($p<0.001$) and DJ ($p<0.001$) and in the SLL compared to the DJ ($p<0.001$).

*Conclusions:* Our results showed that 2D FPPA is correlated across the SLS, SLL and DJ tasks. However, significantly greater FPPA values in the unilateral tasks suggest that the DJ may not identify risk of injury in sports primary injury mechanisms are during unilateral loading tasks. Therefore it is recommended that both unilateral and bilateral tasks are included when screening for ACL and PFJ injury risk.

## Introduction

A high prevalence of anterior cruciate ligament (ACL) and patellofemoral joint (PFJ) injuries in soccer and basketball players has been widely reported, with females typically at least two times more likely to suffer an ACL or PFJ injury than males [1-3]. Poor alignment of the lower limb, specifically increased knee valgus, during the drop jump (DJ) screening task has been prospectively associated with ACL and PFJ injury in female athletes [4, 5].

The DJ task is often the only test used in research and clinical environments to screen for ACL and PFJ injury risk due to the association between injury risk and poor neuromuscular control. Whilst this may be appropriate for sports where landing is the primary injury mechanism, this may fail to identify athletes at risk of injury in sports such as soccer, where the majority of injuries occur during single leg cutting and pivoting tasks [6]. In such cases the DJ task does not necessarily replicate this mechanism of injury and may therefore limit the ability to fully understand injury risk. Harty et al. [7] have shown that correlations exist between knee valgus angles and moments across the step-down, SLL and DJ tasks. In contrast however, Kristianlund and Krosshaug [8] found that significant correlations were evident between knee valgus angles in DJ and cutting tasks but not for knee valgus moments. These results underline the possible limitations of using a single task when screening for knee injury risk in sports such as soccer.

A unilateral task may be more appropriate for identifying ACL injury risk in sports such as soccer and basketball. Recently, Jones et al. [9] reported correlations between knee valgus angles and moments in single leg landing (SLL), cutting and pivoting tasks in female soccer players. These results suggest that those players who exhibit poor lower limb biomechanics in the SLL are likely to do so in change of direction tasks, which may increase their risk of ACL and PFJ injury. Whatman et al. [10] suggested that the kinematics demonstrated during a single leg squat (SLS) was a useful screening tool to assess an individual's lower limb dynamic alignment and potential injury risk due to strong correlation with knee valgus during jogging. This was further supported by Alenzi et al. [11] who found significant correlations in knee valgus angles between the SLS and running and cutting tasks.

Each of the studies mentioned above have utilised 3-dimensional (3D) analysis to determine motion of the lower limb. However, the limited availability of 3-dimensional (3D) analysis in clinical practice due to financial, spatial and temporal costs has led to the development of 2-dimensional (2D) techniques, which employ less expensive, portable and easy to use equipment. 2D analysis, more specifically frontal plane projection angle (FPPA), has been shown to be a valid and reliable method to quantify knee valgus motion during a number of screening tasks, including the SLS, SLL, DJ, side-step and side jump [12-14]. A small preliminary study of 15 recreational athletes found significant correlations in FPPA between the SLS, SLL and running in women but not men [15], although the small sample means that further investigation with a larger sample is warranted.

To date, no study has fully examined the relationship in FPPA between common screening tasks to determine whether individuals exhibit similar FPPA values across tasks. Therefore the aim of this study is to establish whether FPPA during the SLS, SLL and DJ are related. Based on previous research, we hypothesised that FPPA in each task would be related, but that there would be a greater FPPA in the SLL land due to the higher velocity of movement compared to the SLS and the greater loading due to the unilateral nature compared to the DJ.

## Methods

*Participants*

52 national league female football players (age 19.3±4 years, height 1.61±0.6 m, weight 60±8.5 kg) and 36 national league female basketball players (age 22.1 ± 3.8 years, height 1.71 ± 0.6 m, weight 69.4 ± 11.3 kg) undertook testing on one occasion. All participants were involved in the sports on a part-time basis and participated in training and competition ≥three times per week. All participants were free from lower extremity injury, defined as any complaint which stopped the participant from undertaking their normal exercise routine, for at least 3 months prior to data collection. Written informed consent was obtained from all participants, in the case of those between 16 and 18 years of age from a parent or guardian, and the project was approved by the University's research and ethics committee.

*Procedures*

Prior to testing, markers were placed on the lower extremity of each subject to approximate the radiographic landmarks employed by Willson et al. [16] and Willson and Davis [12]. Markers were placed at the midpoint of the femoral condyles to approximate the centre of the knee joint, midpoint of the ankle malleoli for the centre of the ankle joint, and on the proximal thigh along a line from the anterior superior iliac spine to the knee marker. The midpoints were determined using a standard tape measure and all markers were placed by the same experimenter. These markers were used in order for FPPA of the knee to be determined from digital images using Quintic software package (version 26). A single experimenter digitised the markers placed on the subject, allowing FPPA of the knee to be obtained.

A digital video camera (Sony Handycam DCR-HC37) recording at 30fps was placed at a height of 50cm, 3m anterior to the participants landing target. All participants were asked to perform

3 common screening tasks; the single leg squat, single leg drop landing and bilateral drop jump. Each participant was given the opportunity to practice the tasks until they were comfortable, this was typically 2 practice trials. Participants were then asked to perform 3 test trials for each task with their mean performance being used for later analysis; the sequence of tasks was assigned in block order. Both legs were tested. Reliability of the methods has previously been shown [14].

Single leg squat test (SLS) task

Participants were asked to stand on the test limb, facing the video camera. Participants were asked to squat down as far as possible, to at least 45° knee flexion, over a period of 5 seconds. Knee flexion angle was checked during practice trials using a standard goniometer (Gaiam-Pro) then observed by the same examiner throughout the trials. There was also a counter for each participant over this 5 second period in which the first count initiates the movement, the third indicates the lowest point of the squat and the fifth indicates the end. This standardises the test for each participant, therefore reducing the effect of velocity on knee angles. Trials were only accepted if the subject squats to the minimum desired degrees of knee flexion and they maintain their balance throughout.

Drop Jump (DJ) task

Participants stood with feet shoulder width apart on a 28 cm high step, 30 cm from the landing target. Participants were instructed to lean forward and drop from the step as vertically as possible, in an attempt to standardize landing height [17]. Upon landing, participants were required to immediately perform a maximal vertical jump, finally landing back on the landing target. There were no set instructions regarding arm movement, only for the participants to perform the jump naturally and the initial landing from the step was used for analysis purposes [18].

Single leg landing (SLL) task

As with the drop jump task participants dropped from a 28 cm step, again leaning forward and dropping as vertically as possible. Participants were asked to take a unilateral stance on the contralateral limb and to step forward to drop onto the landing target, ensuring the contralateral leg made no contact with any other surface.[18]

FPPA

FPPA of the knee was measured as the angle subtended between the line from the markers on the proximal thigh to the knee joint and the line from the knee joint to the ankle [16] and was measured at the frame which corresponded with the point of maximum knee flexion, as shown in figure 1. The point of maximum knee flexion was determined as the lowest point of the squat and landing tasks as observed on the video. Positive FPPA values reflected knee valgus, excursion of the knee towards the midline of the body so that the knee marker was medial to the line between the ankle and thigh markers, whilst negative FPPA values reflected knee varus.

*Statistical Analyses*

All statistical analyses were performed in SPSS for Windows version 17 (SPSS Inc., Chicago, IL). Normality for each variable was inspected using the Shapiro-Wilk test. Within-session reliability was calculated using Intraclass Correlation Coefficient ($ICC_{3,1}$) and interpreted according to the criteria set by Coppieters et al. [19]. Pearson correlation coefficient and coefficient of determination were used to explore relationships between FPPA in the 3 screening tasks. A repeated-measures ANOVA with Bonferonni post-hoc analysis was used to determine whether any significant differences in FPPA were evident between tasks. Effect sizes were also calculated to determine the magnitude of any differences between screening tasks and interpreted based on the recommendations of Rhea [20] where <0.35, 0.35-0.80, 0.80-1.50 and >1.5 are trivial, small, moderate and large, respectively. Statistical significance was set at $p<0.05$.

## Results

All variables were found to be normally distributed ($p>0.05$). Within-session reliability was good to excellent (ICC 0.89-0.92). The results of the repeated-measures ANOVA (figure 2) showed that FPPA was significantly greater in the SLS (9.72 ± 6.04º) compared to the SLL (7.63 ± 6.40º, $d$ = 0.34, $p<0.001$) and DJ (0.67 ± 9.65º, $d$ = 1.12, $p<0.001$) and in the SLL compared to the DJ ($d$ = 0.85, $p<0.001$).

Significant correlations were also evident between each of the tasks (figures 3a-c). FPPA in the SLS was significantly correlated with SLL ($r = 0.52$, $r^2 = 27\%$) and DJ ($r = 0.30$, $r^2 = 9\%$), whilst FPPA in the SLL was also significantly correlated to DJ ($r = 0.33$, $r^2 = 11\%$).

## Discussion

The results of the current study supported the hypothesis that FPPA would be related across the SLS, SLL and DJ tasks. Previous research has shown that relationships exist for 3D knee valgus motion in the step-down, SLL and DJ tasks [7]; DJ and cutting [8]; SLL and cutting [9]; and jogging with the SLS, squat, lunge, hop-lunge and step-down [10]. However, it was unclear from the previous literature whether these associations would be evident using 2D motion analysis.

Our results showed a strong relationship between FPPA in the SLS and SLL (r = 0.52) and moderate relationship between the SLS and DJ (r = 0.30). The relationship between SLS and SLL supports the findings of the preliminary study on by Atkin et al. [15], albeit the strength of the correlation is weaker in the current study. Atkin et al. only studied eight women and therefore the stronger correlations may not represent those of the larger population. In addition, they studied recreational athletes, whose biomechanics may differ to the female athletes in the current study. Considering that strong correlations in 3D knee valgus angles have previously been shown between the SLS and jogging and cutting [10, 11], this suggests that dynamic knee valgus motion during the SLS task is likely to be exhibited across more dynamic tasks. Furthermore, Atkin et al. [15] have shown a relationship in women between 2D FPPA in the SLS and running which demonstrates the potential clinical utility of 2D FPPA to screen female athletes using a simple SLS test.

Previous research by Jones et al. [9] found strong correlations for knee valgus angles and moments between the single leg landing (SLL), cutting and pivoting tasks in female soccer players. In the current study the SLL task also showed a moderate correlation to the DJ (r = 0.33) which was greater than the correlation between the SLS and DJ tasks. Considering that knee valgus motion during the DJ task has been shown to predict ACL and PFJ injury and that ACL injury often occurs during cutting and pivoting manoeuvres, the SLL task may be a more useful screening tool than the SLS for individuals participating in sport.

Although Kristianlund and Krosshaug [8] found the relationship between DJ and cutting were evident for knee valgus angles, they noted that no relationships existed for knee valgus moments. The lack of relationship in valgus moments between the tasks highlights the potential drawback of using a single screening task to identify injury risk, particularly in sports where the majority of ACL injuries occur during single leg cutting and pivoting tasks. Whilst the DJ task has been shown to predict ACL injury, the ability to fully understand injury risk may be limited by the use of the DJ task alone as it does not replicate the often unilateral mechanism of injury. The moderate relationships found between the tasks along with the significantly greater FPPA values in the SLS and SLL tasks in the current study, highlight the potential difference between unilateral and bilateral tasks. Furthermore, the strong correlations for knee valgus angles and moments between the single leg landing (SLL), cutting and pivoting tasks found by Jones et al. suggest that the inclusion of a unilateral screening task alongside the DJ should be considered in future prospective studies to determine their efficacy for ACL injury risk screening.

We also hypothesised that FPPA would be greatest in the SLL land due to the higher velocity of movement compared to the SLS and the greater loading due to the unilateral nature compared to the DJ. This in part was correct; the SLL resulted in greater FPPA values than the DJ. However, we also found that FPPA was slightly greater in the SLS compared to the SLL, a result which was unexpected; although the effect sizes demonstrated that the magnitude of differences was trivial. This result is supported by a previous study we conducted with recreational men and women where, although no statistical tests were undertaken, SLS FPPA was around 4° greater than SLL [14].

The greater FPPA during the SLS may be explained by a lack of familiarity with the task being executed. Soccer and basketball players commonly perform bilateral and unilateral landing manoeuvres within their sporting and training performance, whereas they rarely perform a unilateral squat. Therefore, their relatively better performance in the SLL and DJ tasks compared to the SLS may be due to the effect of skill acquisition. A recent study by Herrington et al. [21] found that changes in FPPA in specific tasks may be attributed to the type of training undertaken. They found that participants who underwent 6 weeks of jump-landing training showed significant improvement in SLL and DJ FPPA, whilst those who undertook strength training improved their SLS and SLL scores. Participants who completed the jump-landing training were continuously practicing unilateral and bilateral plyometric techniques whilst the strength training programme including bilateral and unilateral squatting tasks. The authors argued that the changes observed were likely a result of the type of training and tasks undertaken during the training programme.

The findings are limited to women who participate in soccer and basketball and cannot be attributed to the wider population, although similar findings have been noted in recreationally active women. Whilst our results indicate that injury risk screening should utilise both bilateral and unilateral tasks, caution should be exercised as no study has yet shown that 2D screening tests prospectively identify athletes at risk of ACL or PFJ, therefore further research is warranted. It is not clear whether the frontal plane estimation of maximum knee flexion angle used in this study is accurate, therefore future studies should consider the inclusion of a camera in the sagittal plane to ensure the correct frame is analysed.

## Conclusion

In line with previous research using 3D motion analysis, our results showed that 2D FPPA is correlated across the SLS, SLL and DJ tasks. However, significantly greater FPPA values in the unilateral tasks suggest the ability of the DJ to identify those who are at risk of injury in sports where injury mechanism is mainly during unilateral loading tasks may be limited. Therefore it is recommended that both unilateral and bilateral tasks are included when screening for ACL and PFJ injury risk to gain a more complete understanding of an individual's movement strategies and potential injury risk.

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