Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females

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Patellofemoral pain (PFP) is a prevalent lower limb musculo-skeletal injury in adolescent females. Female athletes with PFP display increased frontal plane knee joint motion in comparison to control subjects. The current investigation aimed to determine prospectively whether two-dimensional knee valgus displacement during landing could predict the risk of developing PFP. Seventy-six injury-free adolescent female athletes (age = 12.9 ± 0.35 years) participated. At baseline participants performed three drop vertical jump trials from a 31-cm box. A standard video camera was used to record frontal plane knee joint kinematics. Over the 24-month follow-up, eight participants developed PFP, as diagnosed by a Chartered Physiotherapist. Knee valgus displacement was significantly increased in those who developed PFP compared to those who did not (mean difference = 7.79°; P = 0.002; partial eta squared = 0.07). Knee valgus displacement ≥10.6° predicted PFP with a sensitivity of 0.75 and specificity of 0.85. The associated positive likelihood ratio was 5. These results have clinical utility suggesting that two-dimensional analysis could be implemented to screen for increased risk of PFP in adolescent female athletes.

Patellofemoral pain (PFP) is a prevalent lower limb musculo-skeletal injury in adolescent females (Myer et al., 2010; Rathleff et al., 2013a, b). Up to one-third of all adolescents experience knee pain with a large proportion of this attributable to PFP (Molgaard et al., 2011; Rathleff et al., 2013a, b). An even higher prevalence is reported in adolescent female athletes (Barber Foss et al., 2012). In general, females experience a higher incidence and prevalence of PFP in comparison to males (Taunton et al., 2002; Boling et al., 2010).

PFP is characterized by diffused retro-patellar and peri-patellar knee pain which is aggravated during many activities of daily living such as stair ascent/descent, prolonged sitting or running (Fagan & Delahunt, 2008; Witvrouw et al., 2014). Symptoms are highly persistent in adolescent females, with a high proportion experiencing recurrent pain in both short- and long-term follow-up (Nimon et al., 1998; Stathopulu & Baildam, 2003; Rathleff et al., 2013a), which can result in both localized and distal hyperalgesia (Rathleff et al., 2013c). The debilitating effect of PFP is magnified by its detrimental influence on physical activity (Stathopulu & Baildam, 2003) and its association with patellofemoral osteoarthritis (Utting et al., 2005; Thuillier et al., 2013; Hinman et al., 2014). Early identification of risk factors and ultimately prevention of PFP is therefore critical to maintain knee joint health and function in adolescent athletes.

Previous investigations have demonstrated that females with PFP display altered knee joint kinematics in comparison to non-injured control subjects. Particularly, symptomatic PFP patients exhibit increased frontal plane knee joint motion and loads during dynamic activities such as squatting, running, jumping, and stepping (Levinger et al., 2007; Willson & Davis, 2008; Nakagawa et al., 2012, 2013, 2015). However, due to the observational and retrospective nature of these investigations, it is unclear whether these abnormal frontal plane knee joint kinematics cause PFP or occur secondary to knee pain. It is theorized that increased valgus load during dynamic activities increases laterally directed forces on the patellofemoral joint, which could be an intrinsic risk factor precipitating the onset and development of PFP (Powers, 2003). One prospective study has identified a relationship between increased frontal plane moments and PFP (Myer et al., 2010); however, in order to quantify knee abduction moments, the use
of sophisticated three-dimensional (3D) analysis is required, which is both costly and inaccessible to most sports settings outside of the research environment. Measurement of frontal plane knee joint kinematics by two-dimensional (2D) video analysis has previously been validated (McLean et al., 2005) and may present a more time and cost-effective screening methodology.

The current investigation developed as a corollary to a longitudinal investigation of the development of adolescent knee joint jump landing kinematics and aimed to determine whether altered knee joint landing kinematics could be used to predict the risk of developing PFP in this population. We hypothesized that increased knee valgus displacement, as measured by 2D analysis during jump landing, would be increased in those who developed PFP relative to those who did not.

Although 2D analysis has previously been validated against 3D motion analysis (McLean et al., 2005), we utilized a modified method for calculating knee valgus displacement. Therefore, validation of this protocol was conducted in conjunction with this study in order to ensure this modified method maintained correlation with 3D measures of knee valgus displacement.

Materials and methods

Participants

Seventy-six adolescent female athletes were recruited from three secondary schools in the University catchment area as part of a longitudinal study on the development of adolescent knee joint jump landing kinematics. Participants were included in the study if they were currently participating in high school sports and free from lower limb injury. Participants were engaged in a variety of sports, including court or field-based sports (e.g., field hockey, Gaelic football, basketball, etc.), track and field athletics, or athletic dance (e.g., gymnastics, cheerleading). Exclusion criteria were a current injury or previous history of major lower limb surgery and/or knee injury. Written informed parental consent for each participant was obtained prior to testing, with participant assent obtained on the day of testing. All testing was undertaken in the relevant schools’ gymnasium. Participants were tested at baseline and at 6-, 12-, 18-, and 24-month intervals. Baseline characteristic (age, height, body mass) are displayed in Table 1. The study was approved by the University Human Research Ethics Committee.

Baseline drop vertical jump landing kinematics

Upon recruitment to the study, each participants’ 2D landing kinematics were assessed. This baseline assessment is part of a longitudinal study investigating the development of knee joint jump landing kinematics in adolescent athletes. For the current investigation, the baseline (pre-injury) data were used. Performance of the drop vertical jump (DVJ) was initially explained and demonstrated to participants by one of the investigators. Participants initially stood with feet shoulder width apart and hands on their hips on top of a 31-cm box. They were then required to drop directly off the box and upon landing immediately perform a maximum effort vertical jump. Participants performed a minimum of three to five practice repetitions until they were comfortable with the technique required to correctly execute the DVJ. Each participant then performed three DVJ test trials. Trials were not included if the participant removed their hands from their hips or lost their balance during landing. Two-dimensional frontal plane knee joint kinematics was captured by a standard video camera (Canon Legria HF R306, Canon Inc, Tokyo, Japan) with an acquisition rate of 50 Hz. The camera was positioned at a height of 1.03 m. Retro-reflective markers (Vicon Motion Systems Ltd, Oxford, United Kingdom) were placed on the greater trochanter, lateral knee joint line, and lateral malleolus of both legs of participants during data acquisition. Markers were placed directly onto the skin of participants and as such, required them to wear athletic shorts which were taped in a manner that exposed skin around the greater trochanter of the hip so the marker could be visually identified and digitized during the data processing. All markers were placed by the same researcher.

Data reduction

Knee joint valgus angles were measured and averaged across the three test trials for both the dominant and non-dominant limbs of participants. Knee joint valgus angle was calculated from the video frame just prior to initial contact (IC) by digitizing the reflective markers on the hip, knee, and ankle in order to calculate the angle formed between the three markers (see Fig. 1 for marker placement). IC was defined as the frame in which the participants’ toes initially came in contact with the force plate and was visually identified by watching the video of the jump frame by frame. This process was repeated to measure knee valgus angle at the video frame representing maximum frontal plane knee joint motion. Knee valgus displacement was then calculated as the difference in angle between the two time points (displacement = IC angle – peak angle).

Follow-up

Athletes were prospectively followed at 6 months intervals for 2 years. At each subsequent test session, participants were questioned regarding any injuries obtained since the last testing session. If knee pain was reported, participants were clinically evaluated by a Chartered Physiotherapist for the presence of PFP. Diagnosis was based on the following and is in agreement with previously published criteria in the literature (Stefanyshyn et al., 2006; Boling et al., 2009; Rathleff et al., 2013d): long-standing anterior knee or retro-patellar pain of insidious onset, provoked by at least two of the following activities: prolonged sitting or kneeling, squatting, running, hopping, or stair walking; negative findings on examination of knee ligament, menisci, bursa, and synovial plica. In addition, the PFP group could not have had a previ-
Participants were instrumented with the Codamotion (Leicester, United Kingdom) bilateral lower limb gait setup prior to validation trials. This included recording specific anthropometric details for the calculation of hip, knee, and ankle joint centers, and the placement of lower limb markers and wands as outlined in Monaghan et al. (2007). All anthropometrics and marker/wand placement were undertaken by the same researcher. Subsequent to marker and wand placement, a neutral stance trial was used to align the participant with the laboratory coordinate system and to function as a reference position for subsequent kinematic analysis. During the validation trials, 3D kinematic data acquisition was made at 200 Hz using 3 Codamotion cx1 units (Codamotion, Leicester, United Kingdom), while kinetic data acquisition was made using two AMTI (Watertown, Massachusetts, USA) walkway-embedded force plates sampling at 1000 Hz. The CODA mpx1 units were time synchronized with the force plates.

Kinematic data were analyzed using the Codamotion software. Dynamic valgus has previously been described as a medial collapse of the knee during dynamic movement (Krosshaug et al., 2007; Paterno et al., 2010). Therefore, estimated hip, knee, and ankle joint centers were used to calculate frontal plane knee joint angular displacement during landing; a method which has been demonstrated to be sensitive to injury (Paterno et al., 2010). Knee joint angular displacement was calculated for the frontal plane only. The point at which the vertical ground reaction force exceeded a 10N threshold was defined as IC. The frontal plane knee angle was recorded at 20 ms pre-IC and at the point of maximum frontal plane knee motion in order to calculate frontal plane angular displacement. Valgus angular displacement was defined as positive, while varus angular displacement was defined as negative.

2D kinematics

As previously described, 2D frontal plane kinematics were captured simultaneously with a standard digital video camera (Canon Legria HF R306) with an acquisition rate of 50 Hz. Cameras were positioned on a tripod at a height of 1.03 m. Retro-reflective markers (20 mm; Vicon Motion Systems Ltd) were placed on the greater trochanter, lateral joint line, and lateral malleolus to enable calculation of the 2D knee valgus displacement. The video recordings were analyzed using a commercial software package (Dartfish Motion Analysis Software; Dartfish, Fribourg, Switzerland) as previously described.

Statistical analysis

Prospective investigation

Statistical means and standard deviations of all variables of interest were calculated from the three trials of the DVJ. A between-groups multivariate analysis of variance (MANOVA) was used to investigate the effect of group (control vs PFP) on knee valgus displacement and participant characteristics (age, height, and body mass). Four participants acquired unilateral PFP, with the symptomatic knee being included in the PFP group for subsequent analyses and four participants acquired bilateral PFP, with both knees being included in the PFP group. Therefore, a total of 12 knees developed new PFP during the follow-up period and were included in the PFP group for analysis. The control group consisted of the uninjured knees of the total tested population (n = 140).

Logistic regression analysis was used to determine whether knee valgus displacement could predict PFP injury risk. The predictive accuracy was quantified with the use of the C-statistic, which measures the area under the receiver operating characteristic curve (ROC). Significance was set a priori at $P < 0.05$.

A chi-square test for independence was undertaken to examine the relationship of activity level and PFP. The categorical variables used were development of PFP (yes or no) and number of sports played (one, two, or three).

Concurrent validation

The average knee valgus angular displacement was calculated from three trials for both limbs of all participants. Therefore,
the average values for 14 limbs were used to examine the concurrent validity of the 2D measures of knee valgus angular displacement. Pearson product correlation coefficients were used to determine the relationship between the 2D values to those obtained from the 3D motion analysis system. A Bland–Altman plot was also used to examine the concurrent reliability of the 2D values to the 3D derived values. Significance was set a priori at \( P < 0.05 \).

**Results**

**Prospective investigation**

The cumulative incidence risk of developing PFP in this population was 10.5%. There were no significant differences between the PFP group and control group for participant characteristics of age, height, or body mass \( (P > 0.05; \text{Table 1}) \). Knee valgus displacement was significantly different between groups at baseline (mean difference = 7.79°; 95% CI: 3.26–12.32°; \( P \leq 0.001 \); partial eta squared = 0.071). Specifically, knee valgus displacement was increased in the PFP group (10.88 ± 2.2°; Fig. 2) in comparison to the control group (3.09 ± 0.64°). Receiver operating curve (ROC) analysis demonstrated that knee valgus displacement was a significant predictor of PFP (C-statistic = 0.77; \( P = 0.002 \)). Knee valgus displacement \( \geq 10.6° \) predicted PFP with a sensitivity of 75% and specificity of 85%. The associated positive likelihood ratio (sensitivity/1 – specificity) was 5. The chi-square test indicated no significant association between the development of PFP and number of sports played \( (\chi^2 = 2.96; P = 0.23; \text{phi} = 0.19) \).

**Concurrent validation**

There was a strong significant correlation between 2D and 3D measured knee valgus angular displacement \( (r = 0.946; r^2 = 0.894; P < 0.001) \). The Bland–Altman plot confirmed there were no systematic differences between the two systems (Fig. 3). A scatterplot of the 2D vs 3D results can be seen in Fig. 4.

**Discussion**

The incidence of PFP reported in the current investigation (10.5%) is slightly higher than that which has been previously reported in prospective investigations of adult populations (Stefanyshyn et al., 2006; Boling et al., 2009). This is probably reflective of the high incidence of PFP in adolescent females as these studies examined adult populations which included males in their analyses. Myer et al. (2010) prospectively investigated a population of adolescent females of the same age as the current investigation and reported a comparable cumulative incidence of
9.66%. It has long been postulated that female adolescents may be at higher risk of developing PFP than their male and/or adult counterparts and as such, may be the best sample to target from an injury prevention perspective.

There were no observed differences between the PFP and control group for baseline measures of age, height, body mass, or number of sports participated in. However, in the current investigation, we observed that baseline measures of knee valgus displacement \( \geq 10.6^\circ \), as measured by 2D analysis, were predictive of PFP with high sensitivity and specificity. The high sensitivity found for this threshold indicates that it correctly identified 75% of the knees that went on to develop PFP (i.e., 8 of 12), while the specificity means that this threshold value was correctly negative for 85% of people who did not develop PFP. The positive likelihood ratio was 5, indicating a 30% increased probability of developing PFP if above the 10.6°, as measured by 2D analysis, were predictive of PFP with high sensitivity and specificity. The high sensitivity found for this threshold indicates that it correctly identified 75% of the knees that went on to develop PFP (i.e., 8 of 12), while the specificity means that this threshold value was correctly negative for 85% of people who did not develop PFP. The positive likelihood ratio was 5, indicating a 30% increased probability of developing PFP if above the 10.6° of knee valgus displacement during the DVJ (McGee, 2002). Myer et al. (2010) reported that high school females who developed PFP displayed significantly higher frontal plane knee abduction moments than those who did not; however, the predictive capacity of this was not statistically evaluated. The addition of logistic regression analysis, with associated sensitivity, specificity, and positive likelihood ratio in the current investigation strengthens the evidence for decreased frontal plane control of the knee joint as a risk factor for developing PFP.

Knee valgus displacement measured in the current investigation may in fact be a manifestation of frontal and transverse plane motions at the hip. Dynamic knee valgus has been described to be attributable to a combination of femoral adduction and internal rotation as well as tibial abduction and external rotation (Powers, 2003; Levinger et al., 2007). This is in agreement with previous investigations which identified a relationship between hip adduction and internal rotation and the development of PFP, both prospectively (Boling et al., 2009; Noehren et al., 2013) and retrospectively (Souza & Powers, 2009; Noehren et al., 2012a, b; Nakagawa et al., 2015). Additionally, a randomized control trial by Baldon et al. (2014) reported that a functional training program which targeted hip strengthening and control reduced hip adduction and internal rotation. This hip focused intervention was more beneficial in improving pain and function than standard training which consisted of stretching, as well as traditional weight-bearing and non-weightbearing exercises emphasizing quadriceps strengthening. Considering the effect of hip adduction and internal rotation on patellofemoral joint pressures, it is easy to conceptualize how repetitive valgus loading during sporting activities could cause PFP. Lee et al. (2003) reported that more than 30° of femoral internal rotation results in a significant increase in patellofemoral contact pressures while Huberti and Hayes (1984) discovered that a 10° increase in Q-angle increase peak contact forces on the lateral aspect of the patellofemoral joint by 45%.

In order to develop appropriate injury prevention strategies, there is a need to identify predisposing risk factors for PFP and develop clinically applicable tools that will aid in the detection of such risk factors. The results of the current study are in agreement with research from Myer et al. (2010) which established a relationship between knee abduction moment during landing and the development of PFP in adolescent females. In their cohort they found that a peak external knee abduction moment \( \geq 15.4\) Nm was associated with a 6.8% risk of developing PFP. Nevertheless, 3D motion analysis does not provide a feasible method to facilitate screening adolescents for knee injury risk. 2D analysis of dynamic knee valgus has provided a surrogate measure of knee joint control in the frontal plane (Levinger et al., 2007; Willson & Davis, 2008). Research has shown that it is valid, reliable, and sensitive to altered kinematics both in patients with symptomatic PFP and post-intervention. However, prior to the current investigation, no study had evaluated whether 2D analysis would be able to prospectively identify those who may be at risk of developing PFP. Although 2D analysis has previously been validated against 3D motion analysis (McLean et al., 2005), we utilized a modified method for calculating knee valgus displacement. The modification entails digitizing retro-reflective markers placed on specific anatomic landmarks rather than joint centers, due to the variability associated with estimating joint centers on video images. However, high levels of adiposity (e.g., on the hips) may influence the angle measured from markers placed on the skin. Therefore, angular displacement (i.e., change in angle) during the deceleration phase of landing was used to control for this. The direction and magnitude in the change of angle will be the same, irrespective of whether it is measured from joint centers or markers placed on the skin. The modified technique outlined in the current investigation demonstrates excellent correlation with measures from 3D motion analysis and has previously been shown to have excellent reliability (Holden et al., 2015). By measuring valgus angular displacement, we quantified dynamic valgus (which is described as medial collapse of the knee), rather than the static “Q-angle” which is a measure of anatomic alignment. A previous study found no relationship between standing Q-angle and knee valgus angle during dynamic activity (Pantano et al., 2005). Targeting the deficits associated with dynamic valgus may therefore offer the opportunity for intervention if
people “at risk” are subjected to exercise-based neuromuscular training which minimizes aberrant lower limb mechanics.

Future investigation should evaluate whether interventions which aim to reduce knee valgus displacement could prevent PFP in adolescent females. Prevention programs that focus on improving neuromuscular control of the knee have been effective in the reduction of ACL injury incidence in female athletes (Gagnier et al., 2013) and in reducing “high-risk” movements such as dynamic valgus during functional tasks (Myer et al., 2013a). Adolescent females appear to be more receptive to such interventions than adult females (Myer et al., 2013b). As the incidence of PFP in adolescence is much higher than the incidence of ACL injury, theoretically, it should require smaller sample sizes to determine the efficacy of such injury prevention programs on the incidence of PFP.

The current investigation is not without limitations. Although there is good correlation between 3D and 2D analysis, 3D analysis represents the gold standard for kinematic analyses. As dynamic knee valgus can be influenced by both proximal (hip adduction/internal rotation) and distal (tibial abduction) factors to the knee it is important to consider the entire kinetic chain in efforts to prevent knee joint injuries. Moreover, the predictive capacity of knee valgus displacement found in this study is specific to adolescent females. It has been suggested that there may be subgroups of PFP (Witvrouw et al., 2014) and that the underlying etiology of PFP may be sex specific (Nakagawa et al., 2012; Willy et al., 2012). As females athletes are typically characterized by increased valgus during dynamic activities which may predispose them to PFP and/or ACL injury, screening and prevention efforts may need to be specialized according to sex.

**Perspective**

This study is the first to prospectively identify the link between clinical measures of knee valgus and risk of developing PFP. Although previous research has identified increased knee valgus as a characteristic of patients presenting with PFP, it was hard to determine whether this precipitated the condition or was as a result of it. The identification of increased knee valgus displacement as a predictor for PFP has important implications for the implementation of neuromuscular control training in adolescent female athletes in order to minimize aberrant lower extremity kinematics, and thereby reduce the risk of developing PFP. Additional research is needed to design, implement, and assess the efficacy of such individualized programs.

**Key words:** Adolescent, patellofemoral pain, risk factor, biomechanics, kinematics, prospective.

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