Concurrent Validity between Two-Dimensional and Three-Dimensional Motion Systems for Evaluation of Frontal Plane Knee Kinematics during a Drop Vertical Jump Task

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Abstract

Identifying increase risks for ACL injuries and PFPS have become essential in order to decrease its incidence in the recreational and competitive athlete. Risk factors predisposing to lower extremity injuries have been identified using motion analysis system. 3D motion analysis is considered the gold standard for kinematic analysis of the lower extremities, but its highly instrumented nature makes it difficult to be used as a preventive screening tool. Alternatively, 2D video systems could serve this purpose. Therefore, the aims of this study are to establish the concurrent validity and intrarater/interrater reliability of four different 2D video-based techniques. It was hypothesized that all four 2D measures were reliable (ICC > 0.80) and highly correlated (ICC > 0.80) with the 3D system for the outcomes of interest. All four 2D measures showed good to excellent intrarater and interrater reliability with ICC values ranging from .82 to .97. Knee to ankle separation ratio (KASR) and knee separation distance (KSD) showed excellent correlation with ICC value of 0.91 and 0.88 respectively, while both method of frontal plane projection angle (FPPA) showed non to poor correlation with ICC values ranging from 0 to 0.40. 2D KASR and KSD are comparable with 3D measures indicating that a 2D cost-effective reliable and valid screening for dynamic knee valgus can be established.

Keywords: Correlation, Interrater, Intrarater, Vicon, Dartfish

214 Words
Introduction

Among the injuries that occur in different joints of the lower extremity, knee injuries have the highest incidence. The rise of sports, physical activity and exercise are possible causes for the increase in the rate of knee injuries, especially injuries to the anterior cruciate ligament (ACL) and patellofemoral pain syndrome (PFPS) (Murphy, Connolly & Beynon, 2003). McLean and Beaulieu (2010) reported that the ACL is the most frequently injured ligament of the knee with approximately 300,000 new cases reported each year in the USA. Furthermore, PFPS is one of the most common musculoskeletal disorders and reportedly affects between 15% - 33% of the active adult population and between 21% - 45% of the population of adolescents (Lindberg, Lysholm & Gillquist, 1986). In a recent study, Boling et al. (2010) reported that the incidence rate for PFPS was 22/1000 person-years. Therefore, the prevention of sports and physical activity related ACL and PFPS injuries is essential. The mechanisms and risk factors associated with an ACL injury or PFPS have been widely investigated. Among the most discussed are joint biomechanics, neuromuscular control and alignment of the lower extremity (Nagano et al., 2010). Altered kinematics of the hip and knee on the frontal and transverse planes during weight bearing activities are described as dynamic valgus (Earl, 2003; Willson & Davis, 2008). More specific, dynamic knee valgus has been described as a movement pattern characterized by excessive knee abduction combined with femoral adduction, femoral internal rotation and relative external tibial rotation (Hewett et al., 2005; Alentorn-Geli et al., 2009). An excessive dynamic knee valgus during bilateral or unilateral landing activities and during stance phase of gait has been reported to be associated to ACL injuries by Hewett et al. (2005) and patellofemoral joint injuries by Willson and Davis (2008).

To identify the potential mechanisms and risk factors for knee injuries many investigators rely on motion analysis techniques (Ford, Myer & Hewett, 2007). Three dimensional (3D) motion analyses has been the method of choice for the majority of the studies investigating dynamic knee valgus and its relationship to injury. Hewett et al. (2005) reported that knee abduction angles
quantified with 3D motion analysis techniques predicted ACL injury risk in female athletes with high sensitivity and specificity. For this reason, this technique is becoming common practice in many research laboratories and it is considered the gold standard for kinematic analysis of the lower extremities during dynamic tasks (Sigward, Havens & Powers, 2011). One of the most used testing tasks for dynamic knee valgus is a drop vertical jump (DVJ). Ford et al. (2007) stated that the majority of the kinematic and kinetic variables in young athletes during a DVJ have excellent to good reliability when measured with 3D motion analysis systems. Nonetheless, 3D motion analysis system has several disadvantages. (1) It requires a substantial investment of money to acquire all the equipment. (2) The equipment itself is not portable. (3) Preparation of a large area is needed for placement of the equipment and (4) preparation of the subject, data collection and data analysis is time consuming and required technical skilled and knowledge (Myklebust et al., 2003). All these factors could make it difficult to implement this system as an injury prevention screening tool in the everyday clinical practice or sports settings.

A two dimensional (2D) motion analysis video system could be a solution for these disadvantages. It has been suggested in the literature that in order to quantify dynamic knee valgus using 2D motion analysis video system, frontal plane knee motions must be measured (Willson & Davis, 2008; Sigward et al., 2008; Sigward et al., 2011). Recently, new studies have proposed a 2D low-cost motion analysis method to screen for dynamic knee valgus and the results have been promising. In a comparison study, Mizner, Chmielewski, Toepke and Tofte (2012) concluded that the frontal plane projection angle (FPPA) and knee to ankle separation ratio (KASR) for assessing dynamic knee valgus have the potential to be used as an acceptable proxy for expensive multicamera motion analysis systems. Similarly, Willson and Davis (2008) used the frontal plane projection angle (FPPA) to quantify knee valgus motion during a single leg squat and found that FPPA values representing medial displacement of the knee during single-leg squats were associated with increased hip adduction and knee external rotation. Therefore, they concluded that the FPPA
during single-leg squats may be a useful clinical measure for identifying dynamic knee valgus, but should not be used to quantify 3-D joint rotations (Willson & Davis, 2008). McLean et al. (2005) expressed that “an obvious and well documented concern is whether a constant relation exists between knee valgus as measured using the 3D approach and measures of 2D frontal plane knee angles” (p. 356). In that same study, McLean reported that 2D frontal plane knee valgus data were consistent with frontal plane calculations based on 3D multi-camera tracking for both side step and side jump tasks in college basketball players (McLean et al, 2005).

In a recent case study, a new way to measure knee valgus collapse using the 2D computer movement analysis system called Dartfish was proposed. This new technique of quantifying frontal plane projection angle differs from the previous one in that the fulcrum of the angle was set at the ankle joint instead of the knee. The authors concluded that Dartfish motion analysis software using this new technique was capable of identifying knee valgus collapse in college-aged females (Glass, Priest & Hayward, 2011). Other 2D measures used to identify dynamic knee valgus during functional tasks are the knee to ankle separation ratio (KASR) and the knee separation distance (KSD). Mizner et al. (2012) reported in their study that the KASR might be a more promising 2D video-analysis technique to develop in order to screen athletes for knee injury risks. On the other hand, KSD measures have been identified as being a predictor of knee abduction angles (Sigward et al, 2011).

If 2D measures of frontal plane hip, knee and ankle motion like the frontal plane projection angle, knee to ankle separation ratio and knee separation distance correlates with their 3D counterparts, a cost-effective injury prevention screening could be established in the everyday clinical practice and sports settings. Therefore, the purpose of this study was: 1) to correlate two different 2D motion analysis techniques for quantifying frontal plane projection angle (FPPA) with 3D measures of knee abduction angle (KAA) during a two-legged drop vertical jump from a 40-cm box. 2) To correlate 2D measures of knee to ankle separation ratio and knee separation distance
with their 3D counterparts during a two-legged drop vertical jump from a 40-cm box, and 3) to establish the interrater and intrarater reliability for each of the 2D measures taken. The working hypothesis were: 1) the correlation between joint angles would be high to excellent (ICC ≥ 0.80) for both 2D measures FPPA when compared to the 3D measures of knee abduction angle. 2) The correlation between joint distances would be high to excellent (ICC ≥ 0.80) for both knee to ankle separation ratio and knee separation distance measures when compared to their 3D counterparts and 3) good to excellent (ICC ≥ 0.80) inter-rater and intra-rater reliability between and across all three investigators would be obtained.

Methods

Subjects

Sixteen healthy subjects (9 males, 7 females; mean ± SD age, 25.5 ± 2 years; height, 1.68 ± 0.1 m; mass, 68.59 ± 11.76 kg; BMI, 24.33 ± 2.98 kg/m²; dominance, 81 % Rt and 19 % Lt) volunteered to participate in this study and reported to the University of Puerto Rico Medical Science Campus biomechanics research laboratory for a single testing session. Before subjects were selected, investigators were responsible of filling out the assessment document in order to identify if the participants met the inclusion/exclusion criteria. Inclusion criteria included: 1) age range from 21-30 years old, 2) self-reported capacity of performing jumps with two legs, and 3) willingness to be videotaped and use the require laboratory clothes. Exclusion criteria included: 1) neuromusculoskeletal conditions affecting walking or jumping, 2) back or lower extremity pain or surgery, 3) injuries to the back and lower limbs in the past 6 months, and 4) pregnancy. All sixteen subjects met the inclusion/exclusion criteria and completed an informed consent form that described the testing protocol, which was approved by the University of Puerto Rico Medical Science Campus Institutional Review Board for protection of human subjects. Subjects were University of Puerto Rico graduated students who reported no symptoms of injury at the time of testing, were able to
perform the desire activity/test, had no history of ACL or PFPS injury and had no recent (within the past 6 month) history of low back or lower extremity surgery.

**Testing Procedure**

Male subjects were required to wear only shorts (mid-thigh level), low ankle soaks and low ankle tennis shoes. Female subjects were required to wear a sport bra, shorts (mid-thigh level), low ankle soaks and low ankle tennis shoes. Clothing requirements were necessary to allow a better visualization of the retro-reflective markers and tape markers by each motion analysis systems, respectively. After signing the informed consent form, anthropometric measurements were obtained from each subject. The anthropometric measures included height, weight, and circumference of wrist, elbows, shoulder, pelvis, knees and ankles. Weight and height were measured with a scale and stadiometer, while circumferences were measured with an anthropometric device and taken while the subject was supine (facing up) on a treatment table. Anthropometric measurements were required in order to digitize subjects in the 3D Vicon System. Afterward each subject was instructed in the drop vertical jump (DVJ) task to be performed. A member of the research team demonstrated the DVJ to each subject. Each subject was given the opportunity to practice the DVJ task three times with rest intervals of no less than one minute. After all practice trials were performed, subjects were instrumented with the retro-reflective markers based on the plug-in-gait model (Appendix A). Each subject performed seven trials of the drop jump. Similar to the practice trials, subjects had no less than one minute between trials. One minute of rest was sufficient to recover from a bout of activity of less than 10-20 seconds. The specific procedure performed was as previously described by Ortiz (2007, 2008) for the DVJ. Briefly, the procedure is described:

**DVJ:** Subjects stand on top of a 40-cm box with arms crossed across their chest and feet shoulder width apart. On the command “go”, the subject dropped from the box and landed on the defined landing area (.61m x .61m). After beginning the drop, subjects were allowed to use their arms as desired to maintain balance. Upon landing double-legged, a maximal vertical jump was achieved as
trying to touch the ceiling. This procedure was accomplished seven times with rest intervals as previously described.

**Instrumentation**

The instruments used in this study were a Vicon (Vicon Motion System, Denver, CO) three-dimensional system, and a 30-Hz commercial camcorder. The Vicon system was used to measure joint angles of the knees (knee abduction angles) and distance between anatomic landmarks during the DVJ task. To accomplish this, 38 retro-reflective markers were placed on body landmarks according to the plug-in-gait model (Appendix A) embedded in the software. Before any data collection sessions, the equipment was calibrated as recommended by the manufacturer. After space calibration, a static trial with the participant standing in a T-position (Appendix A) was performed to identify and align each subject joint coordinates to the laboratory space. This trial was performed with the purpose of estimating the subject neutral position. Data was recorded at 120 Hz with 6 infrared cameras. The camcorder was placed 1.82-2.43 meters in front (perpendicular) of the landing area of the DVJ task (Appendix B). A 0.61 meter pressure platform or mat was placed in front of the drop box with the purpose of serving as a reference object for the 2D video analysis system (Appendix B).

**Data Reduction**

**Three Dimensional Data**

All data was integrated by using Vicon Nexus 1.7 (Vicon Motion Systems, Denver, CO). Peak joint angles in the frontal plane and distance between anatomic landmarks were derived from the trajectory of retro-reflective markers using a Butterworth filtering process in order to obtain the outcome measures of knee abduction angles of both lower extremities, knee to ankle separation ratio and knee separation distance. Knee abduction angles and knee to ankle separation ratios were obtained when peak knee flexion on the sagittal plane was observed. In order to extract the data for the knee separation distance outcome, measurements of knee separation distance were obtained on
two different time-frames; first during initial contact of both subject’s forefeet with the ground during landing and secondly when peak knee flexion on the sagittal plane was observed. In Vicon Nexus 3D motion analysis system the three previously mention measures were acquired using the functions “projected angles” and “distance between” and selecting the desire retro-reflective markers. Once this function was applied the system automatically calculated the projected angle or distance between the selected markers based on the subject anthropometric measurements, subject calibration and system calibration (global coordinate system).

3D Vicon measurements were acquired and analysed by one of the three principal investigators. All three investigators are physical therapy graduate students who are performing this research study as part of the partial requirements for the degree of Master of Science in Physical Therapy. The investigator in charge of acquiring Vicon 3D data had previous experience using this motion analysis system for extraction of knee abduction angles and knee separation distances.

**Two Dimensional Data**

Data recorded at 30 Hz with the commercial camcorder was imported to Dartfish 2D Pro Suite Software (Dartfish, Switzerland) for conversion to still images. Dartfish 2D software was used to obtain all four outcomes measures: method 1 & 2 of Frontal Plane Projection Angles (FPPAs), Knee to Ankle Separation Ratio (KASR) and Knee Separation Distance (KSD). All 2D Dartfish measurements were made by all three members of the research team on two different occasions separated by one week. It should be mention that all results were kept confidential. None of the researchers had access to the results of the other two researchers. Previously to initiating the actual research all members of the team underwent a four week training session using Dartfish 2D software. FPPAs were calculated by Dartfish software using two different techniques:

**A. Frontal Plane Projection Angle – Method 1:**

Method 1 for calculating FPPAs was described by Willson and Davis in their 2008 study evaluating the utility of the FPPA. It was established as the angulation exhibited by the subject in
figure 1A. The body landmarks used as referenced for this angulation were the anterior superior iliac spine (ASIS), mid-patella and the midpoint between both malleoli at the distal tibia. Another important landmark identified was a midpoint in the thigh, place in a straight line connecting the ASIS with the mid-patella. This landmark was used in those trial were the ASIS could not be identified due to excessive trunk flexion at landing. This measure was collected when the subject reached peak knee flexion just before performing the maximum vertical jump. For the 2D video system, peak knee flexion was defined as the one frame before the subject started to increase knee extension in order to perform his/her maximum vertical jump.

**B. Frontal Plane Projection Angle – Method 2:**

Method 2 for calculating FPPAs was described by Glass, Hayward and Priest in their 2011 study. It was established as the angulation exhibited by the subject in figure 1B. The body landmarks used as reference for this angulation were mid-patella and the center of the ankle joint between both malleoli. This measure was taken when the subject reached peak knee flexion just before performing the maximum vertical jump. The difference in method 2 was that the fulcrum point of the angle was set at the ankle joint. The first side of the angle was placed as a perpendicular line from the horizontal line running through the vertex of the angle and the second side of the angle was placed on the mid-patella, as describe by Glass et al. (2011).

**Figure 1A and 1B – Method 1 and 2 of FPPA**

![Figure 1A and 1B](image)

**C. Knee to Ankle Separation Ratio**
The Knee to Ankle Separation Ratio (KASR) was measured in the 2D Dartfish software following the description provided by Mizner in their 2012 study comparing 2D measurement techniques for predicting knee abduction angle and moment. In the current study, the KASR was determined by placing a horizontal line between the retro-reflective markers positioned on each lateral femoral epicondyle, and another horizontal line between the retro-reflective markers positioned on each lateral ankle malleoli. Therefore, in order to calculate the KASR it was necessary to obtain two different measures, these were: 1) the distance between the lateral femoral epicondyles when peak knee flexion was observed, and 2) the distance between the lateral ankle malleoli when peak knee flexion was also observed (figure 2). Then, the KASR was defined as the ratio of distance between lateral femoral epicondyles (Knee) and lateral malleoli (Ankle) obtained during peak knee flexion:

\[ KASR = \frac{\text{Knee}}{\text{Ankle}} \]

**Figure 2 – Knee to Ankle Separation Ratio**

D. Knee Separation Distance

The Knee Separation Distance (KSD) was quantified using the method previously provided by Sigward et al. (2011). In the current study, we defined the knee separation distance as the distance (in meters) between the right and left lateral femoral epicondyles markers. This measure was taken in two different periods; first, the knee separation distance was measured during landing when initial contact of subject’s forefeet with the floor was observed (Figure 3a). Secondly, the knee
separation distance was measured when the subject reached peak knee flexion just before performing the maximum vertical jump (Figure 3b). Finally, the knee separation distance were expressed as the subtraction of the distance between lateral femoral epicondyles when peak knee flexion was observed (d2) and the distance between lateral femoral epicondyles when initial contact of subject’s forefeet with floor was observed on landing (d1).

\[ KSD = d2 - d1 \]

**Figure 3A and 3B – Knee Separation Distance**

### Statistical Analysis

Data were analyzed using SPSS for Windows, Version 16.0 (2007): Chicago, SPSS Inc. For the first aim of this study, where Vicon 3D measures of knee abduction angles were compared with each of the two 2D frontal plane projection angle (FPPA) methods, the first three consecutive trials of the DVJ were chosen for each subject and the data from each system was used for analysis. For the second aim of this study, where 3D measures of knee to ankle separation ratio (KASR) and knee separation distance (KSD) were compared with 2D measures of KASR and KSD respectively, the first four consecutive trials of the DVJ were chosen for each subject and the data from each system was used for analysis. The difference in the number of trials selected is due to the highly instrumented nature of this study were missing data was bound to occur.

Two-way mixed and two-way random analysis of variance (ANOVA) models were conducted to estimate variance due to subjects’ effect and rater, time or system effects and determine intraclass correlation coefficients (ICC) depending on which reliability measure was evaluated. Interrater and
intrarater reliability were calculated for each of the four 2D Dartfish outcomes measures. ICC for intrarater reliability was assessed using ANOVA two-way random effects models (ICC(2,1)): where both subjects’ effects and raters’ effects were considered to be random as to be able to generalize results to a larger population of potential raters. In contrast, ICC for intrarater reliability was assessed using ANOVA two-way mixed effects models ICC(3,1): where subjects’ effects were random and time of measurement effects were fixed as these represented the only two times of interest. ICC to estimate the reliability between Vicon 3D motion system and Dartfish 2D motion system was assessed using ANOVA two-way mixed effects models ICC(3,1): where subjects’ effects were random and systems’ effects were fixed as these represented the only two systems of interest. These ICC measures were considered to establish the reliability and consistency of the 2D measures of FPPA, KASR and KSD. Significance level was considered at 5% (p < 0.05) for all ANOVA models.

**Results**

Mean values for each of the 2D and 3D outcome measures are presented in table 1 below. ICC values for intrarater reliability, interrater reliability and correlation between 2D and 3D variables of each of the outcome measures are presented in table 2 below. All results are going to be organized and described individually.

**Frontal Plane Projection Angle (FPPA) – Method 1**

The mean values for method 1 of FPPA were 14.89 degrees for the dominant leg and 14.08 degrees for the non-dominant leg. The mean values for the 3D measure of knee abduction angle were 8.15 degrees for the dominant leg and 7.82 degrees for the non-dominant leg. The mean values are reported solely for the purpose of a descriptive comparison between systems. Intraclass correlation coefficients (ICC) were established using the first three successful consecutive trials for each subject (n = 39) and the results were the following. Method 1 of FPPA showed good to excellent intrarater and interrater reliability for both dominant and non-dominant leg with ICC
values ranging from > 0.95 for the intrarater reliability and > 0.82 for the interrater reliability (table 2). This FPPA method demonstrates non to poor correlation with 3D measures of knee abduction angle as shown by the ICC values. ICC values for the dominant leg was -0.11 with a significance of 0.83 and 0.21 with a significance of 0.04 for the non-dominant leg (table 2). The ICC average of the three selected trials were 0.93 for the dominant leg and 0.95 for the non-dominant leg.

Frontal Plane Projection Angle (FPPA) – Method 2

The mean values for method 2 of the FPPA were 10.52 degrees for the dominant leg and 10.14 degrees for the non-dominant leg (table 1). Mean 3D values of knee abduction angle were as previously mentioned. As with the FPPA method 1, ICC for FPPA method 2 were established using the first three successful consecutive trials for each subject (n = 39). FPPA method 2 showed excellent intrarater and interrater reliability for both dominant and non-dominant legs with ICC values ranging from > 0.94 for the intrarater reliability and > 0.93 for the interrater reliability (table 2). FPPA method 2 also demonstrates non to poor correlation with 3D measures of knee abduction angle as shown by the ICC values. ICC values for the dominant leg was -0.39 with a significance of 0.99 and 0.40 with a significance of 0.003 for the non-dominant leg (table 2). The ICC average of the three selected trials were 0.98 for both legs.

Knee to Ankle Separation Ratio (KASR)

2D and 3D mean values of the KASR are presented in table 1 for a descriptive comparison. The KASR outcome measure showed an excellent intrarater and interrater reliability, as well as an excellent correlation with 3D measures of the knee to ankle separation ratio. ICC were established using the first four successful consecutive trials for each subject (n = 64). ICC values were > 0.92 and > 0.88 for the intrarater and interrater reliability respectively, and an ICC value of 0.91 with a significance of 0.001 was established for the correlation between systems.

Knee Separation Distance (KSD)
2D and 3D mean values of the KSD are also presented in table 1 for a descriptive comparison. The KSD outcome measure showed a good to excellent intrarater reliability, interrater reliability and correlation with 3D measures of the knee separation distance. Also, ICC values were established using the first four successful consecutive trials for each subject \((n = 64)\). ICC values were > 0.81 and > 0.93 for the intrarater and interrater reliability respectively, and 0.88 with a significance of 0.001 for the correlation between systems.

<table>
<thead>
<tr>
<th>Measures</th>
<th>2D</th>
<th>3D</th>
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<tbody>
<tr>
<td>Frontal Plane Projection Angle / Knee Abduction Angle: (Method 1)</td>
<td></td>
<td></td>
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<tr>
<td>A. Dominant Leg ((n = 39))</td>
<td>A. 14.89 ± 7.65</td>
<td>A. 8.15 ± 5.24</td>
</tr>
<tr>
<td>B. Non-Dominant Leg ((n = 39))</td>
<td>B. 14.08 ± 8.37</td>
<td>B. 7.82 ± 7.20</td>
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<tr>
<td>Frontal Plane Projection Angle / Knee Abduction Angle: (Method 2)</td>
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<tr>
<td>A. Dominant Leg ((n = 39))</td>
<td>A. 10.52 ± 6.40</td>
<td>A. 8.15 ± 5.24</td>
</tr>
<tr>
<td>B. Non-Dominant Leg ((n = 39))</td>
<td>B. 10.14 ± 5.38</td>
<td>B. 7.82 ± 7.20</td>
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<tr>
<td>Knee to Ankle Separation Ratio ((n = 64))</td>
<td>1.23 ± 0.19</td>
<td>1.17 ± 0.21</td>
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<tr>
<td>Knee Separation Distance ((n = 64))</td>
<td>-0.007 ± 0.044</td>
<td>-0.011 ± 0.035</td>
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<p>| Table 2: Correlation between 2D and 3D Variables |</p>
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<tr>
<th>Measures</th>
<th>Intrarater Reliability ICC Sig</th>
<th>Interrater Reliability ICC Sig</th>
<th>Correlation between Systems ICC Sig</th>
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<tr>
<td>A. Dominant Leg ((n = 39))</td>
<td>A. &gt; 0.95 – 0.001</td>
<td>A. &gt; 0.93 – 0.001</td>
<td>A. -0.11 – 0.83</td>
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<td>B. Non-Dominant Leg ((n = 39))</td>
<td>B. &gt; 0.96 – 0.001</td>
<td>B. &gt; 0.86 – 0.001</td>
<td>B. 0.21 – 0.04</td>
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<tr>
<td>Frontal Plane Projection Angle: (Method 2)</td>
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<tr>
<td>A. Dominant Leg ((n = 39))</td>
<td>A. &gt; 0.95 – 0.001</td>
<td>A. &gt; 0.93 – 0.001</td>
<td>A. -0.39 – 0.99</td>
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<tr>
<td>B. Non-Dominant Leg ((n = 39))</td>
<td>B. &gt; 0.94 – 0.001</td>
<td>B. &gt; 0.94 – 0.001</td>
<td>B. 0.40 – 0.003</td>
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<tr>
<td>Knee to Ankle Separation Ratio ((n = 64))</td>
<td>&gt; 0.92 – 0.001</td>
<td>&gt; 0.88 – 0.001</td>
<td>0.91 – 0.001</td>
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<tr>
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<td>&gt; 0.81 – 0.001</td>
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<td>0.88 – 0.001</td>
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Discussion

The main objective in this study was to evaluate four different two dimensional (2D) techniques for the analysis of frontal plane knee kinematics. In order to perform this, all four 2D measures used in this study were compared with their corresponding three dimensional (3D) counterparts. All four 2D techniques have been previously tested in their ability to quantify and predict dynamic knee valgus during dynamic task for potential use in clinical screening. Nevertheless, not all of them have been compared with 3D measures in order to confirm their validity. Frontal plane projection angles, knee to ankle separation ratio and knee separation distance have been reported to be promising 2D video-based techniques for such analyses (McLean et al., 2005; Glass et al., 2011; Sigward et al., 2011; Mizner et al., 2012). Therefore, the purpose of this study was to establish the concurrent validity, interrater reliability and intrarater reliability of such 2D techniques.

Myer et al. (2010) demonstrated that high knee abduction moment during landing activities increase the risk for ACL injuries in female athletes. Authors identified that increased knee valgus measures, among others, predict high knee abduction moment status in female athletes with high sensitivity and specificity (Myer et al., 2010). Three dimensional measures of knee abduction angles and two dimensional measures of frontal plane projection angles have been used to identify increase knee valgus in multiple populations. Therefore, in this study we wanted to establish the correlation between these two measurements. The majority of the studies that use frontal plane projection angles as a clinical obtainable measure of knee valgus only test the dominant leg (McLean et al., 2005; Sigward et al., 2008; Mizner et al., 2012). In contrast, our study also focused in testing the dominant and non-dominant leg to observe any variation between them, as well as difference when correlation between systems was performed.

Our results indicate that both 2D techniques of frontal plane projection angles (method 1 and 2) demonstrate good to excellent interrater reliability and intrarater reliability for both dominant and non-dominant leg with ICC values ranging from 0.82 to 0.96 (Table 2). These results of reliability
are comparable with those of Mizner’s study, where they reported ICC values for intrarater and interrater reliability of the method 1 of frontal plane projection angle to be 0.95 and 0.89 respectively during a drop vertical jump task (Mizner et al., 2010). ICC values of interrater and intrarater reliability for method 2 of frontal plane projection angle have not been established in the literature. To the best of our knowledge, this is the first study to investigate the reliability and validity of such technique.

On the other hand, when both 2D techniques of frontal plane projection angles were compared with 3D measures of knee abduction angles no correlation was found for the dominant leg ($ICC_{M1} = -.11, p = .83$ and $ICC_{M2} = -.39, p = .99$) and poor correlation was found for the non-dominant leg ($ICC_{M1} = .21, p = .04$ and $ICC_{M2} = .40, p = .003$). Our results do not support the findings in Mizner’s study where they report an excellent correlation between 2D frontal plane projection angles and 3D knee abduction angles with an ICC value of 0.92 (Mizner et al., 2010). We have to point out, the results of Mizner’s study are only for the dominant leg and based on only one trial per subject of drop vertical jump. Our results of non to poor correlation between 2D and 3D measures are supported by the findings of Willson and Davis (2005). These authors reported poor correlation between 2D frontal plane projection angles and 3D projected angles during single leg squats and single leg jumps tasks (Willson & Davis, 2005).

A particular explanation for the non to poor correlation between 2D frontal plane projection angles and 3D knee abduction angles found in this study and for the difference observed between the dominant and non-dominant leg is that the measures of frontal plane projection angles have been significantly associated with transverse plane kinematics at the knee and hip (Willson & Davis, 2005). Authors reported that 3D tibiofemoral valgus (knee abduction angle) was weakly associated with frontal plane projection angles during single leg squats, and that during single leg landings, the frontal plane projection angle was more highly correlated with peak tibiofemoral internal rotation than peak tibiofemoral abduction (Willson & Davis, 2005). It has also been noted that during
unilateral landings subjects have a tendency to exhibit greater total hip adduction and rotation excursion (Pappas et al., 2007). Another important fact is that Ford, Myer and Hewett (2003) reported a trend toward a higher valgus angle on the dominant leg at initial contact in female basketball players when compared with males during a drop vertical jump. Therefore, the non to poor correlation between 2D frontal plane projection angles and 3D knee abduction angles, as well as the difference observed between dominant and non-dominant legs could be due to the influence of transverse plane motions on the FPPA measure and that higher rotation excursion have been found on the dominant leg or leg landing first.

As mentioned before, this is the first study using the alternative method of frontal plane projection angle described by Glass and colleagues in which the fulcrum of the angle was placed on the ankle joint instead of the knee. Our results showed great similarity between both frontal plane projection angle methods. Although mean values of FPPA method 2 were much closer to the 3D mean values of knee abduction angle. A possible explanation is that the influence of transverse plane motion is less in this measure since it is only taking into consideration movement on the knee and ankle joints, thus discarding the influence of rotation excursion of the hip. Following this same line of thought, when mean values of both 2D frontal plane projection angles and 3D knee abduction angles were compared, the 2D values were always higher (approximately by 7° for method 1 and 3° for method 2) when compared to the 3D values. We consider that 2D measures of frontal plane projection angles tend to overestimate the actual knee abduction angle since it cannot differentiate movement on the transverse plane from the frontal plane. This observation supports the current knowledge that knee valgus, when measured through the use of frontal plane projection angle, can be explained by a combination of transverse and frontal plane kinematics of the hip and knee (Mizner et al, 2012).

Regarding our other two outcome measures, it has been reported that the knee to ankle separation ratio explains 39.4% of the variance for the knee abduction moment, more than
explained by the frontal plane projection angle (35%) (Mizner et al., 2012). Furthermore, the knee separation distance explains 53% of the variance for the knee abduction angle after having taken into consideration the stance width (Sigward et al. 2011). Due to the relationship between the knee to ankle separation ratio, knee separation distance and the knee abduction moment and angle, we decided to evaluate the concurrent validity, interrater reliability and intrarater reliability of such measures. The knee to ankle separation ratio is a measure proposed by Mizner and colleagues, which is a modification of the knee separation distance proposed by Noyes and colleagues (Mizner et al., 2012). In Mizner’s study, the concurrent validity and reliability of the knee to ankle ratio was established using only one drop vertical jump trial per subject (n = 36), whereas we use four per subject (n = 64). Thus, adding information to the increasing knowledge of the potential of 2D video-based techniques for quantifying dynamic knee valgus.

Our results for the knee to ankle separation ratio measure and knee separation distance measure showed good to excellent interrater and intrarater reliability as well as an excellent correlation with 3D measures (Table 2). These results are comparable with those reported by Mizner (2012) for the knee to ankle separation ratio where ICC values for interrater and intrarater reliability were 0.92 and 0.97, respectively and correlation between 2D and 3D measures was 0.94 (Mizner et al., 2012). On the other hand, the knee separation distance has been previously used to identify dynamic knee valgus differences due to gender (Barber et al., 2005), explore the effectiveness of neuromuscular training in dynamic knee valgus (Noyes et al., 2005) and to establish the association between knee separation distance and knee abduction angle (Sigward et al., 2011). Nevertheless, its concurrent validity and reliability has not been established. Our results for the knee separation distance measure shows excellent interrater reliability (ICC > 90), good to excellent intrarater reliability (ICC > 81) and excellent concurrent validity (ICC = 88) when compared with its 3D counterpart. Sigward et al. (2011) reported that 97% of the variance in the knee separation distance measure is explained by hip adduction and stance width. Therefore, higher correlation coefficients for the 2D
distance-based measures were obtained since the influence of transverse plane excursion on the KASR and KSD is minimum.

This study does have limitations that need to be taken in consideration when interpreting the outcomes. The primary purpose of this study was to correlate measurements taken with a 2D motion analysis video system with measurements taken with a 3D motion analysis system; we do not intend to determine ACL or PFPS injury risk with these results. Like in Mizner’s study, our results do not confirm that these measurements are able to identify young healthy adults with high risk of ACL injury nor provide threshold values (Mizner et al., 2012). Below we intend to explain difficulties and limitations found during the process of recollecting the data.

The principal difficulty or limitation encountered was due to the natural biomechanics presented by each subject when performing the drop vertical jump task. Some of the subjects tended to excessively flex the trunk during the landing portion of the task in such a way that the markers for the anterior superior iliac spine (ASIS) would be covered by their own body for a period of time. In some cases the period of time was long enough to make the 3D reconstruction of the trial impossible, as well as the identification of the ASIS in the 2D system very difficult, leaving us with no other option but to discard the trial. Due to this reason, the data of three of the sixteen subjects was eliminated for the first aim of the study. Another possible limitation was due to the commercial camcorder used in this study. In the literature it is reported that a 30 Hz camcorder, like the one used in the current study, is ideal for recording walking and stepping activities. However, in order to preserve good quality and resolution of the image when faster activities, like dropping and jumping, are recorded, a 50 Hz camcorder is needed (Payton, 2005). It is possible that poor resolution at specific image frames lead to errors in identifying the skin markers used for our outcome measures, thus having a direct impact on the reliability measurements. However, the results of the current study showed that a 30 Hz commercial camcorder has the capacity of obtaining reliable and valid measures of dynamic knee valgus. This could eliminate the need to purchase a more expensive 2D
camera for the evaluation of frontal plane knee kinematics during drop vertical jumps and other similar tasks. Finally, the use of a 0.61 x 0.61 meter mat or platform to identify the landing area could have affected the normal landing mechanics used by each subject to perform the drop vertical jump task, since they had to land in the desired space. This is considered a random error since it was maintained the same throughout the whole study but may be a factor when mean values of each of the outcome measures of the current study are compared with mean values of other studies.

**Conclusion**

In conclusion, all four two-dimensional video-based techniques evaluated during the current study have the potential to be used as a cost-effective alternative for expensive three dimensional motion analysis system in the assessment of frontal plane knee kinematics during a drop vertical jump task. Of the four 2D techniques, the knee to ankle separation ratio and the knee separation distance showed more promising results. The results of the current study and of other available studies indicate that the knee to ankle separation ratio and knee separation distance are reliable, reproducible and valid measures of frontal plane knee kinematics when compared to 3D measures. On the other hand, the information provided by both methods of frontal plane projection angle needs to be analyzed carefully. Our results support the current knowledge that frontal plane projection angle measures are reliable and reproducible but its validity when compared to 3D knee abduction angle is questionable. In order to validate these measures, we recommend that large prospective study be performed in order to establish normative data and threshold values for both 2D frontal plane projection angle measures. Finally, as Mizner proposed, we also recommend that all four of these measures be included in prospective epidemiological research in order to identify which 2D video-based technique reveal variables associated with ACL and PFPS injury risk.
Reference


Appendix A

Figure 1: Plug-in-Gait Model in T-position for subject calibration.

Appendix B

Drop jump

Data Collection Method

- Infrared camera
- Vicon System

40 cm Drop Box

Mat Scan

Camera with Dartfish

Laboratory arrangement.