ABSTRACT

Purpose/Background: Multi-center collaborations provide a powerful alternative to overcome the inherent limitations to single-center investigations. Specifically, multi-center projects can support large-scale prospective, longitudinal studies that investigate relatively uncommon outcomes, such as anterior cruciate ligament injury. This project was conceived to assess within- and between-center reliability of an affordable, clinical nomogram utilizing two-dimensional video methods to screen for risk of knee injury. The authors hypothesized that the two-dimensional screening methods would provide good-to-excellent reliability within and between institutions for assessment of frontal and sagittal plane biomechanics.

Methods: Nineteen female, high school athletes participated. Two-dimensional video kinematics of the lower extremity during a drop vertical jump task were collected on all 19 study participants at each of the three facilities. Within-center and between-center reliability were assessed with intra- and inter-class correlation coefficients.

Results: Within-center reliability of the clinical nomogram variables was consistently excellent, but between-center reliability was fair-to-good. Within-center intra-class correlation coefficient for all nomogram variables combined was 0.98, while combined between-center inter-class correlation coefficient was 0.63.

Conclusions: Injury risk screening protocols were reliable within and repeatable between centers. These results demonstrate the feasibility of multi-site biomechanical studies and establish a framework for further dissemination of injury risk screening algorithms. Specifically, multi-center studies may allow for further validation and optimization of two-dimensional video screening tools.

Level of Evidence: 2b

Keywords: ACL; Injury Prevention; Knee injury; Large scale research projects Multi-site research; patellofemoral pain
INTRODUCTION

Young female athletes are at two- to ten-fold greater risk than male athletes of sustaining devastating knee injuries such as acute anterior cruciate ligament (ACL) ruptures and chronic patellofemoral pain (PFP).1-4 Screening methods that utilize three-dimensional (3D), laboratory-based measures accurately predict the quantifiable risk of sustaining these debilitating knee injuries.5,6 However, this approach is time consuming, costly, and requires extensive training for proper implementation. Accordingly, there are growing efforts to develop equally accurate and more feasible surrogate screening methods that require fewer and less expensive resources. These clinically-based assessments, such as the use of two-dimensional (2D) screening, may be more practical (i.e. simpler methods and less technology needed) to implement and have the potential for widespread application, but the reliability of these screening measures performed across multiple institutions has not been tested. While the effectiveness of screening protocols used to identify high-risk athletes have been reported independently by single research groups,6,7,8,9 identification of methodological consistency and subsequent validation between laboratories is a critical step toward widespread injury risk screening using such methods. Ultimately, these clinical screening tools will both enhance the ability of sports medicine practitioners to identify athletes that will benefit from targeted intervention and determine the efficacy of such training.

Multi-center collaborations for prospective, longitudinal investigations provide appealing alternatives compared to single-center study designs. Primarily, a multi-center approach has the capacity to generate large sample sizes and is thus likely to yield more powerful and generalizable results.10 Studies that investigate difficult or relatively uncommon phenomena as their primary outcome of interest, such as ACL injury, may particularly benefit from this approach.11-13

While peer-reviewed reports of multi-center kinematic and kinetic reliability are absent in the literature, the reliability of the drop vertical jump (DVJ) at a single institution has been documented.13 3D analysis of the DVJ has demonstrated excellent within-session reliability for kinetic and kinematic measures at the hip, knee, and ankle (interclass correlation coefficient (ICC) 0.78-0.99).14 Kinetic and kinematic reliability for the DVJ decreases between sessions (ICCs 0.60-0.92 and 0.59-0.87, respectively).15 A second study also supported excellent within-session 3D reliability for the DVJ with respect to knee abduction angle, knee abduction moment and frontal plane projection angle (ICCs > 0.84).14 Reliability of the frontal plane projection angle from 2D video was also excellent for between- and within-session intra- and inter-rater assessments (ICCs 0.83-0.95).14,15 Therefore, both 2D and 3D video have the potential to reliably assess frontal plane knee motion and loads within a single institution. The excellent reliability of the DVJ task has permitted its use in clinical prediction nomograms that require dependable measures in order to assess relative injury risk.16

A study conducted within a single research institution reported that prospective measures of high knee abduction moment (KAM) during landing predict ACL injury risk in young female athletes.7 Retrospective observations of ACL injuries in female athletes reported knee alignments at the time of injury that have been associated with high KAM.17-19 Previous reports from data collected at a single institution indicated that increased knee abduction angle, increased relative quadriceps recruitment, decreased knee flexion range of motion (ROM), increased tibia segmental length, and increased mass normalized to body height that accompany growth contribute to approximately 80% of the measured variance in KAM during landing (Figure 1).20 Therefore, a clinic-based assessment algorithm using these variables was systematically developed and validated in order to address the limitations of 3D motion capture. The ability to screen for injury risk with a simpler tool provides the opportunity to increase the dissemination and utilization of targeted injury prevention training programs.8,21-24 Preliminary results indicate that this clinic-based assessment tool, used as part of an algorithmic methodology, can precisely quantify 3D kinematics and accurately predict the probability for the critical outcome of high KAM that determines risk of ACL injury in female athlete population.8,22-27 The development of inexpensive, reliable assessment tools that can be administered in a clinic or field testing environment can support screening for injury risk on a more widespread basis.
The current study examined the reliability of an affordable, accessible, clinic-based algorithm that uses 2D camcorder-based methods to screen young athletes who may be at high risk of knee injury. The validity, intra-rater reliability, and intra-session reliability of this protocol at a single institution have been reported previously. The goal of the current investigation was to measure the within-center and between-center reliability of measures utilized in this protocol at three institutions. Specifically, the authors aimed to measure the within-center and between-center reliability of included testing measures using 2D screening techniques at three different institutions. It was hypothesized that the 2D risk screening methods would provide good-to-excellent reliability within and between institutions for frontal and sagittal plane biomechanics and variables that contribute to high knee abduction loads as predicted by the aforementioned nomogram.

METHODS

Subjects
Nineteen female, varsity and junior varsity level high school volleyball players participated in this study (Mean age ± 1SD - 15.27 ± 1.0 years; height- 1.69 ± 0.42 m; mass- 61.08 ± 7.9 kg). A thorough medical history questionnaire was completed by each subject. Any subject with an acute lower extremity injury within the past six months was excluded. There were no known ACL deficient or reconstructed conditions present among the tested subjects, however participants with anterior knee pain were not excluded from the testing. All subjects were on the current team roster and cleared for full athletic participation. Frontal plane video from each of the subjects was recorded at each of three testing centers. Due to technical errors at one center (Institution III), sagittal plane video at all three testing centers could only be obtained for eight participants (Mean age- 15.83 ± 0.95 years; height- 1.70 ± 0.43 m; mass 63.09 ± 5.7 kg). All subjects were tested as a group at each testing center on separate dates within a three-week period during the preseason. A research assistant scheduled and coordinated the dates for each of the testing locations. The subjects were initially brought to Cincinnati Children's Hospital Medical Center Human Performance Laboratory (Institution I). The second location was University of Kentucky Biodynamics Laboratory (Institution II) and finally subjects were tested at The Ohio State University Sport Medicine Biodynamics Laboratory (Institution III). The team's coach attended all three testing sessions with the athletes.

Screening Stations
Prior to the testing sessions, personnel from all three laboratories met with the study coordinators at Institution I to review the testing stations and procedures. A uniform testing protocol was developed

![Figure 1. Clinician friendly nomogram that was developed from the regression analysis. This nomogram can be used to predict high KAM outcome based on tibia length, knee valgus motion, knee flexion ROM, body mass and quadriceps to hamstrings ratio.](image-url)
for use in each of the testing laboratories. The same research assistant coordinated participation of the athletes at all three locations and helped direct their progression between each testing station.

After written informed consent was obtained from parents or legal guardians and assent from the participants, a multi-station protocol, previously approved by the institutional review board at each institution, with six stations was used to implement the injury screening that assessed factors associated with increased risk of ACL injury and PFP. The stations consisted of 1) pubertal maturity and medical history, 2) anthropometrics, 3) flexibility and laxity, 4) alignment, 5) strength, 6) PFP assessment, and 7) 2D and 3D motion analysis. Stations 1, 3, 5 and 6 were not included in this investigation’s reliability analysis.

**Anthropometrics**

Height (cm) for each subject was measured by a research assistant at each site using a standard stadiometer. Tibia length (cm) was measured with a standard measuring tape by a certified athletic trainer at each site and was determined to be the distance between the lateral joint line of the knee and the lateral malleolus. Body mass was measured by a research assistant at each site on a calibrated physician’s scale.

**2D Landing Biomechanics**

**Pre-collection Preparation.** A total of 42 skin-mounted, retroreflective markers were applied to each subject as part of a larger study using 3D motion testing. Specifically for the 2D motion analysis used in the current investigation, markers were fixed bilaterally on greater trochanter, the medial and lateral epicondyles (medial and lateral knee joint line) and the medial and lateral malleoli were used.

**Video Capture.** Motion analysis setup consisted of a 2D video capture using two digital cameras, as previously described. Both of the cameras were synched using firewire cables directly connected to the data acquisition computer through Cortex (Motion Analysis Corp, Santa Rosa, CA) for Institutions I and II, and through Vicon Nexus (Vicon Motion Systems Ltd, Los Angeles, CA) for Institution III. The 2D video cameras used at Institutions I and III were Panasonic PV-GS300 (Panasonic Corporation, Kadoma, Japan). The 2D video cameras used at Institution II were Sony Handycam DCR-HC52 (Sony Electronics, Tokyo, Japan). 2D frontal plane knee kinematic data were collected using standard video cameras during each of the three DVJ trials. Two cameras were positioned three meters from the approximated location of landing at a height of 54.6 centimeters (21.5 inches) to capture sagittal (left side only) and frontal plane lower extremity motion during the DVJ (Figure 2). The frontal plane camera was aligned with the subject’s midline, as determined by standardized foot position on the box prior to beginning the task. The sagittal plane camera was located perpendicular to the frontal plane camera and was centrally located relative to the force platforms where subjects performed the DVJ. Landing sequence images were captured using VirtualDub (virtualdub.org). Coordinate data for the hips, knees, and ankles were captured from the video frame just prior to initial contact and again at maximum medial knee displacement in the frontal view and maximum knee flexion in the sagittal view.

**Video Processing.** Kinematic data were recorded by a technician from each of the participating institutions. All videos were compiled and analyzed by one tester using ImageJ (http://imagej.nih.gov/ij/). The height of the box used for the DVJ was measured in the video and this distance was converted using

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**Figure 2. Pictorial presentation of the testing centers.**
the actual known box height. This video correction factor was then used to calibrate coordinate data. In the frontal plane, the hip joint center was estimated relative to a marker placed on the greater trochanter (intersection of the vertical line of the center of the ASIS and knee joint center and the horizontal line between the greater trochanters), the knee joint center was estimated as the mid-point between two markers placed on the medial and lateral knee joint lines and the ankle joint center was estimated as the mid-point between two markers placed on the medial and lateral malleoli (Figure 3). Sagittal plane joint center locations were determined for each subject’s left leg, due to the placement of the sagittal plane camera on the athlete’s left side. The left hip joint center was identified in the sagittal plane view as the marker on the left greater trochanter, the left knee joint center was estimated to be at the location of a marker on the subject’s left lateral knee joint line, and the left ankle joint center was estimated to be at the location of the marker on the left lateral malleolus (Figure 4).

In the frontal plane view, medial knee displacement (cm) was calculated as the difference between the frontal plane knee joint center at initial contact and at maximum medial knee displacement (Figure 3). Maximum frontal plane knee angle was calculated from hip, knee and ankle joint centers at maximum medial knee displacement (MMD). Valgus alignment was defined as a positive angle in the frontal plane. In the sagittal-plane view, knee flexion range of motion was calculated as the difference between the knee joint angle at initial contact and at maximum knee flexion. To calculate the nomogram for the right leg, the sagittal-plane measure of knee flexion range of motion was substituted from the left limb video measurement. This substitution was necessary as 2D sagittal plane video was only captured from the left-side profile of each subject. Therefore, calculation of

![Figure 3](image-url)

**Figure 3.** A. The coordinate position of knee joint center is digitized in the frontal view measured at the frame prior to initial contact is used as the knee valgus position \(X_1\). B. The coordinate position of knee joint center is digitized in the frontal view measured at the frame with maximum medial position and is utilized as the knee valgus position \(X_2\). C. The calibrated displacement measure between the two digitized knee coordinates \((X_2 - X_1)\) is representative of knee valgus motion during the drop vertical jump.
the right knee sagittal plane angle would have been inaccurate as the left limb obstructed the view of the contralateral leg.

**Surrogate Measure of Relative Quadriceps and Hamstrings Strength:** In addition, the prediction nomogram can include a relative measure of quadriceps to hamstrings strength that is prescribed for measurement on an isokinetic dynamometer. For the current project, as is the case with other clinical settings, the same isokinetic testing devices may not be readily available. In this case, a surrogate measure of the quadriceps to hamstrings ratio can be employed that was defined using a linear regression analysis to predict quadriceps to hamstrings ratio based on the athlete's body mass. The surrogate quadriceps to hamstrings ratio measure can be obtained by multiplying the athlete's mass by 0.01 and adding the resultant value to 1.10.8 If even greater simplicity is desired, the mean value of 1.53 can be substituted into the prediction algorithm for the quadriceps to hamstring ratio.24 An example of a completed nomogram for a subject is presented in Figure 5.

**Statistical Analysis**

The nomogram tool used to predict the risk of high knee loads is based on a multivariate logistic regression model developed from previously described data.7,8 The discrete variables and injury risk calculations computed for use in the high knee load risk algorithm were evaluated in the current study for reliability using interclass correlation coefficients (ICC). Within-center (ICC (2,k)) and between-center (ICC (2,1)) reliability was examined for each variable, (height, mass, bilateral tibia length, bilateral knee flexion ROM, bilateral knee valgus excursion). Reliability was calculated separately for the right and left limbs. Within-center reliability was determined using all three DVJ trials for each subject, whereas between-center reliability was based on mean values calculated from the three DVJ trials for each subject. ICC calculations were conducted using MATLAB.
and verified with SPSS (Version 20.0, IBM Corporation, Armonk, NY). The range of ICC values were described using the classifications of Fleiss, where ICC < 0.4 was considered poor, 0.4 < ICC < 0.75 was considered fair-to-good, and ICC > 0.75 was considered excellent.\textsuperscript{28} The approximations of the Fleiss scale are supported by additional literature that has shown frontal and sagittal plane ICC values for 3D knee angles collected between-session on the same subjects with in the same location were 0.616 and 0.855, respectively.\textsuperscript{13} These values produce an average ICC of 0.735 and suggest that any ICC value above this threshold is excellent as it represents normal biological variability between sessions within the same location. Typical error was also calculated for each variable and used to calculate the nomogram score and risk probability measured between each center.

RESULTS

Anatomical Variables

Between-center reliability of all anatomical measures was classified as either excellent or fair-to-good (Table 1). Height and mass demonstrated excellent between-center reliability with combined ICC values of 0.92 and 0.99, respectively. Tibia length demonstrated fair-to-good between-center reliability for both the left and right limb with ICCs of 0.66 and 0.73, respectively.

Frontal Plane Variables

The average of all front plane within-center ICC values were higher than the average of all frontal plane between-center ICC values (within ICC = 0.83, between ICC = 0.72; Table 1). The combined ICC values indicate that overall within-center reliability was excellent for the frontal plane, while between-center frontal plane reliability was fair-to-good. Combined frontal plane reliability was excellent within each center, but only one of the between-center comparisons demonstrated excellent agreement for these variables. Left knee frontal plane excursion consistently demonstrated the lowest reliability of all frontal plane variables for both within and between-center analyses.

Sagittal Plane Variables

Within and between-center ICC values for knee flexion range of motion were similar for all measured sagittal plane variables combined (within ICC = 0.83, between ICC = 0.78; Table 1). Sagittal plane reliability was excellent for both the within and between-center evaluations. Maximum flexion angle exhibited excellent within and between-center reliability, while flexion angle at initial contact demonstrated excellent within-center and fair-to-good between-center reliability (Table 1). Sagittal plane measures demonstrated consistent reliability between measures within single center and for the same measures between centers.
Within-center reliability of the variables that comprise the nomogram was consistently classified as excellent, but between-center reliability was classified as fair-to-good. The within-center ICCs for all nomogram variables combined was 0.98 (ICC range 0.95-0.99), while combined between-center ICC was 0.63 (ICC range 0.51-0.78). Typical errors for variables that contributed to the nomogram calculation are represented as the average within-subject differences for within- and between-center analysis (Table 2). The average typical error for frontal plane knee excursion was 2.3 cm for within-center comparisons and 2.5 cm for between-center comparisons. The average typical error for knee flexion range of motion was 5.9° for within-center comparisons and 6.7° for between-center comparisons. Typical errors were less than 1% of the mean for height and less than 1.5% of the mean for mass in all between-center comparisons. Tibia length typical error was approximately 2.5% of the mean for both the right and left limb.

**DISCUSSION**

In current practice, screening athletes for risk of knee injuries is most often conducted using expensive and technically-daunting 3D motion capture systems. Injury risk assessments using less costly, clinic-based tools have been proposed as an alternative to improve the ability of clinicians to quickly and accurately determine the needs of individual athletes. In addition, these tools must be appropriate for large-scale assessments, as several types of knee injuries are rare and large samples are needed.

### Nomogram Variables

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### DISCUSSION

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### Table 1. Between-center and within-center reliability taken individually for each variable

<table>
<thead>
<tr>
<th>Anatomic Measures</th>
<th>BETWEEN-CENTER ICC (2-1)</th>
<th>WITHIN-CENTER ICC (2-k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>Mass</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Left Tibia Length</td>
<td>0.66</td>
<td>0.52</td>
</tr>
<tr>
<td>Right Tibia Length</td>
<td>0.73</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Frontal plane</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left angle at IC (°)</td>
<td>0.79</td>
<td>0.75</td>
</tr>
<tr>
<td>Right angle at IC (°)</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>Left angle at MMD (°)</td>
<td>0.64</td>
<td>0.58</td>
</tr>
<tr>
<td>Right angle at MMD (°)</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>Left excursion (mm)</td>
<td>0.63</td>
<td>0.52</td>
</tr>
<tr>
<td>Right excursion (mm)</td>
<td>0.68</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Sagittal plane</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion angle at IC (°)</td>
<td>0.71</td>
<td>0.66</td>
</tr>
<tr>
<td>Maximum flexion angle (°)</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Flexion ROM (°)</td>
<td>0.75</td>
<td>0.71</td>
</tr>
</tbody>
</table>

| IC = initial contact with ground; MMD = maximum medial displacement; ROM = range of motion |

### Table 2. Within-center and between-center typical errors for each nomogram variable

<table>
<thead>
<tr>
<th>Anatomic Measures</th>
<th>BETWEEN-CENTER TYPICAL ERROR</th>
<th>WITHIN-CENTER TYPICAL ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.66</td>
<td>0.81</td>
</tr>
<tr>
<td>Left Tibia Length (cm)</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Right Tibia Length (cm)</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Flexion ROM (°)</td>
<td>6.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Left Valgus Excursion (cm)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Right Valgus Excursion (cm)</td>
<td>2.5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

ROM = range of motion
in order to study these phenomena prospectively. A recently established nomogram (Figure 1) for prediction of knee injury risk has been determined valid and reliable.8,22-27 In order to determine the validity of this approach on a widespread basis, the reliability of this protocol across multiple institutions must be established (Figure 6).

Figure 6. Frontal plane and sagittal plane measurements of a representative participant tested at each site with an example completed risk nomogram using each sites biomechanical measures.

The between-centers reliability needed to be established prior to the pursuit of our multi-center coupled investigations that require the use of biomechanical and neuromuscular testing during dynamic tasks. Therefore, the purpose of this study was to document within- and between-center reliability of a set of clinical screening measures that effectively predict injury risk in youth athletes. The current data indicated that between-center collaboration, using a standardized data collection and analysis protocol can yield consistent results across centers. Documentation of variability in injury prediction variables between centers will aid the development of rigorous protocols in order to maximize the reliability of variables collected. The between-center reliability of the three centers at frontal plane of the knee joint demonstrated fair-to-good and excellent ICCs with values between 0.63 and 0.81 (Table 2). Similarly, the between-center reliability in sagittal plane measurements ranged from 0.71 to 0.87 (Table 2), which was rated fair-to-good and excellent ICC values. These values were slightly below the previously reported ICCs for between-session 3D kinematics in the frontal plane and slightly above in the sagittal plane.13 It is important to have the highest reliability possible for each variable since the nomogram consists of a combination of multiple anthropometric and biomechanical variables.8,22,23 Consequently, the nomogram will incorporate and compound the variability from each variable in its calculation.

As expected, the current data confirms that between-center measures have greater variability than within-center measures. Identification of potential sources of between-center variability in a multi-center investigation is imperative for the production of repeatable biomechanical data sets. It was reported that between-session movement deviations and inconsistency in marker placement have been attributed to variability in kinematic motion data.29 A previous report indicated fair-to-good within-session repeatability and poor between-session repeatability of kinematic data, and suggested that marker placement discrepancy was a primary factor in variability among testing
centers. To reduce error and variability associated with marker placement, marker placement must be undertaken by uniformly trained individuals at each research center who can document their own marker placement reliability in order to further establish known sources of error between centers. Other possible sources of variability in multi-center collaborations can include differences in system accuracy and disparities in the interpretation of results. An important method for control of this inherent variability is the incorporation of a standardized protocol. A study by Gorton et al. reported a reduction in variability of several kinematic variables over 12 centers following the implementation of a standardized testing protocol. The between-center reliabilities were consistent in the current study, which may be attributed to systematic training of all participating investigators using the standardized methods.

The lowest ICC values were observed in left leg frontal plane angle at MMD and left leg tibia length. Tibia length was measured at each institution by experienced, certified athletic trainers using measuring tape. Therefore, the relatively lower ICCs observed in the measure may indicate a need for more specific and detailed training for standardization of anatomical measurements of the tibia. For frontal plane measures, greater variability has been reported at maximal values rather than initial contact. Increased variability reduces reliability, which may explain why the frontal plane angle exhibited lower ICC at MMD than at IC. Increased motion variability may be a result of reduced neuromuscular control. In a population demographic similar to that used in the current study, 93.3% of subjects indicated their right limb to be preferred. It has been demonstrated that female subjects tend to exhibit greater neuromuscular control and fewer non-contact ACL injuries in their preferred (right) limbs versus the non-preferred (left) limb. This may explain why ICCs of dynamic frontal plane variables were typically lower in the left limb than the right limb.

The time between testing sessions at each institution may have further influenced increased variability and may have reduced the reliability of our clinical measures in multiple ways. First, these athletes had begun their pre-season activities for the upcoming volleyball season. Testing at the initial center (Institution I) was completed within a week of their first week of training. By the time the athletes performed for final testing session at the third institution (Institution III), they had undergone nearly three weeks of pre-season training. Furthermore, while all athletes were fully participating in their daily practices, five athletes reported mild anterior knee pain in one or both knees at some point throughout the testing period, which is common in this adolescent athletic population. It is well known that anterior knee pain, like PFP, is related to abnormal movement mechanics, but it is unknown whether the severity of symptoms can contribute to variability in that movement. Though the time between the three testing sessions was relatively short, it may be that changes in fitness and injury status may have affected our between-center reliability results. Completion of the current testing protocol at each center within days of each other and avoidance of pre- or in-season training would have been ideal for reducing inter-subject variability. Minimization of the time between biomechanical assessments may have enhanced the between-center reliability of these clinically-based measures.

Single-center studies that aim to examine relatively rare injuries or conditions often have restricted generalizability due to statistical limitations and homogenous participant characteristics. Multi-center collaborative efforts can effectively overcome these limitations by substantially increasing the potential for increased subject enrollment and testing. As an example, a recent investigation that aimed to evaluate several outcomes related to total knee arthroplasty necessitated compilation of data from a total of 90 individual centers in order to have adequate statistical power. Only with this large-scale investigation involving 1027 knees from hundreds of patients with total knee arthroplasty, were the authors able to statistically analyze tibiofemoral axial rotation patterns using video fluoroscopy. A recent numbers-needed-to-treat (NNT) analysis for ACL injury demonstrated that between 108 (95% CI: 86 to 150) and 120 (95% CI: 74 to 316) female athletes would need to be trained to prevent one noncontact or one overall ACL injury during one competitive season. Although a prophylactic effect of NMT has been reported, these relatively large NNT indicate a need to screen for high-risk athletes. As mentioned previously, a prospective cohort study found that a greater KAM during a DVJ was a highly
specific and sensitive predictor of future ACL injury.\textsuperscript{7} When predictive modeling of factors was evaluated to determine the propensity for increased external knee abduction moment, several clinically feasible measures had the potential to evaluate ACL injury risk athletes by identification of greater KAM landing mechanics. The reliability of screening methods reported in the current study results support the integrated application of athlete risk assessment algorithms on a widespread basis. Previous authors have indicated that targeted training to athletes with high injury risk biomechanics with the appropriate intervention may more efficiently and effectively reduce injury risk factors.\textsuperscript{26,27,41} The applicability of the reported multi-center reliability may be a critical step in the prevention of injury in sports. The long-term goals of future projects will build upon the findings of the current reliability study to determine the mechanisms that underlie the high incidence of knee injury in young female athletes. This knowledge can be readily applied to the development of targeted, affordable and well-disseminated interventions that prevent athletic injuries in female population. In order to apply patient-specific interventions, future work is warranted to continue the development of clinically feasible and reliable tools to predict who is at risk for the development of specific knee injuries such as ACL injury or PFP, in order to apply patient-specific interventions.

Multi-center collaborations for prospective, longitudinal investigations provide an appealing alternative to single-center studies. Primarily, a multi-center approach has the capacity to generate large sample sizes and is thus likely to yield more powerful and generalizable results.\textsuperscript{12} Studies that investigate difficult or rare phenomena as their primary outcome of interest, such as ACL injury, may particularly benefit from this approach.\textsuperscript{13,15}

**CONCLUSION**

The results of this multi-center reliability study demonstrate that the risk screening protocols examined were reliable within centers and repeatable between centers when compared with previously reported measures of 3D motion capture reliability. The current results support efforts to validate and disseminate an injury risk screening algorithm for young athletes. Specifically, the proposed multi-center studies may allow for validation and optimization of readily accessible and inexpensive 2D camcorder based screening tools to identify younger female athletes at high risk for knee injury. In addition, the screening tools may be a successful practice to support injury prevention training in younger girls thereby allowing them to avoid more severe knee injuries as they mature.\textsuperscript{35,42}

**REFERENCES**


