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Various Methods for Assessing Static Lower Extremity Alignment: Implications for Prospective Risk-Factor Screenings

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Context: Accurate, efficient, and reliable measurement methods are essential to prospectively identify risk factors for knee injuries in large cohorts.

Objective: To determine tester reliability using digital photographs for the measurement of static lower extremity alignment (LEA) and whether values quantified with an electromagnetic motion-tracking system are in agreement with those quantified with clinical methods and digital photographs.

Design: Descriptive laboratory study.

Setting: Laboratory.

Patients or Other Participants: Thirty-three individuals participated and included 17 (10 women, 7 men; age = 21.7 ± 2.7 years, height = 163.4 ± 6.4 cm, mass = 59.7 ± 7.8 kg, body mass index = 23.7 ± 2.6 kg/m^2) in study 1, in which we examined the reliability between clinical measures and digital photographs in 1 trained and 1 novice investigator, and 16 (11 women, 5 men; age = 22.3 ± 1.6 years, height = 170.3 ± 6.9 cm, mass = 72.9 ± 16.4 kg, body mass index = 25.2 ± 5.4 kg/m^2) in study 2, in which we examined the agreement among clinical measures, digital photographs, and an electromagnetic tracking system.

Intervention(s): We evaluated measures of pelvic angle, quadriceps angle, tibiofemoral angle, genu recurvatum, femur length, and tibia length. Clinical measures were assessed using clinically accepted methods. Frontal- and sagittal-plane digital images were captured and imported into a computer software program. Anatomic landmarks were digitized using an electromagnetic tracking system to calculate static LEA.

Main Outcome Measure(s): Intraclass correlation coefficients and standard errors of measurement were calculated to examine tester reliability. We calculated 95% limits of agreement and used Bland-Altman plots to examine agreement among clinical measures, digital photographs, and an electromagnetic tracking system.

Results: Using digital photographs, fair to excellent intratester (intraclass correlation coefficient range = 0.70–0.99) and intertester (intraclass correlation coefficient range = 0.75–0.97) reliability were observed for static knee alignment and limb-length measures. An acceptable level of agreement was observed between clinical measures and digital pictures for limb-length measures. When comparing clinical measures and digital photographs with the electromagnetic tracking system, an acceptable level of agreement was observed in measures of static knee angles and limb-length measures.

Conclusions: The use of digital photographs and an electromagnetic tracking system appears to be an efficient and reliable method to assess static knee alignment and limb-length measurements.

Key Words: posture, risk factor assessment, digital photographs

Key Points

- Digital photographs are a reliable tool to assess static knee alignment and limb-length measurements.
- An electromagnetic tracking system is an efficient and acceptable method to assess static frontal-plane knee alignment and limb-length measures.
- Incorporating measures of static lower extremity alignment in prospective study designs will help researchers identify individuals at greatest risk of injury and continue to help develop more appropriate intervention programs to reduce the risk of knee injuries.

Investigators generally accept that the causes of knee injuries, in particular anterior cruciate ligament (ACL) injury and patellofemoral pain syndrome (PFPS), are multifactorial. Identifying and understanding factors that may increase the risk of ACL injury and PFPS will continue to help identify individuals at risk and assist with the development of effective programs to reduce the risk of these injuries. Based on consensus statements stemming from research retreats focused on ACL injury[1] and PFPS,[2] large-scale prospective studies are needed to better understand factors that increase the risk of injury. One of the major challenges with prospective risk-factor studies is that successful completion of the studies requires accurate and efficient assessment of multiple factors in large cohorts.

Static lower extremity alignment (LEA) is among many factors suggested to increase the risk of ACL injury[3–6] and

PFPS[7–10] and warrants inclusion in prospective study designs. To achieve accurate data collection, researchers[11,12] have suggested that risk factors should be measured by a single experienced investigator. This recommendation is appropriate because investigators[13–19] have reported inconsistent agreement among multiple testers in the clinical measurement of static LEA. Reasons to explain the inconsistent intertester reliability in clinical measurements of LEA include varied clinical experience of investigators, inconsistency in the identification of anatomic landmarks, and error associated with the use of the measurement instruments (ie, goniometer, inclinometer, caliper). Given the inconsistencies in the measurement of static LEA among multiple testers, and given that measurements by a single examiner are impractical in large-scale prospective studies, a consensus statement[1] highlighted the need to develop "more efficient, affordable, reliable, and readily available measurement methods" of anatomic and structural factors as an important step toward identifying potential risk factors for injury.

During large-scale prospective risk-factor screenings, having time-efficient methods is imperative for evaluating theorized risk factors for lower extremity injury. The use of digital photographs could eliminate some of the error associated with clinical measurement methods and potentially could be a time-efficient and reliable method in the measurement of LEA that is cost effective and readily accessible to investigators. Only a few researchers[20,21] have examined the use of digital photographs in the measurement of static LEA. A limitation of these studies was that static LEA values were derived after printing the digital photographs, drawing intersecting lines, and physically taking the alignment measures[20] or were derived through the use of a software constructional program.[21] Printing photographs could be an added cost, and the physical measurement of the printed images potentially increases the time necessary for data reduction. Furthermore, we do not know if using a software constructional program is time efficient for health care professionals. Another limitation of previous studies was that only frontal-plane alignment measures were examined and no comparisons were made with clinical measures, which are used in prospective risk-factor studies.[10]

Therefore, the primary purpose of our study was to examine the reliability (measurement consistency) of digital photographs and agreement (magnitude of difference) between digital photographs and clinical methods in the measurement of frontal- and sagittal-plane static LEA (pelvic angle, quadriceps angle, tibiofemoral angle, genu recurvatum, femur length, and tibia length) and whether the experience of the investigator influences the measurements made with digital photographs. In addition, multiple factors contribute to the increased risk of knee injuries, which has led to the use of various motion-analysis systems to examine biomechanical factors as part of large-scale prospective studies. Using a motion-analysis system provides another potential method for assessment of static LEA as part of multifactorial prospective studies. Although using a motion-analysis system is costly, authors of many prospective risk-factor studies have collected motion-analysis data to determine if faulty movement patterns increase the risk of future injury. Therefore, to determine efficient methods for assessment of LEA, our second purpose was to examine the agreement among clinical measures, digital pictures, and an electromagnetic motion-analysis system in the measurement of static LEA.

METHODS

Participants

To examine the reliability of the different methods used to measure static LEA, we conducted 2 separate projects. To examine the reliability of using digital photographs, 17 college-aged participants (10 women, 7 men; age = 21.7 ± 2.7 years, height = 163.4 ± 6.4 cm, mass = 59.7 ± 7.8 kg, body mass index = 23.7 ± 2.6 kg/m^2) volunteered for a project in which we evaluated the agreement between clinical methods and digital photographs and also evaluated whether the agreement was consistent when comparing a trained investigator (A.-D.N.) and a novice investigator (C.A.S.) in the measurement of static LEA with measurements taken on both the right and left lower extremities. The trained investigator had more than 12 years of experience, and the novice investigator was in her first year of an athletic training education program and knew proper palpation techniques for locating the selected bony landmarks through course work and clinical experiences. Sixteen individuals (11 women and 5 men; age = 22.3 ± 1.6 years, height = 170.3 ± 6.9 cm, mass = 72.9 ± 16.4 kg, body mass index = 25.2 ± 5.4 kg/m^2) volunteered to participate in a separate project in which we examined whether static LEA measured with an electromagnetic motion-analysis system was consistent with static LEA measured using clinical methods and digital photographs (measurements were taken on the right lower extremity). All alignment measures were assessed by the trained investigator for the second investigation. All participants provided written informed consent, and the studies were approved by the Institutional Review Board for Protection of Subjects at the College of Charleston and the University of North Florida.

Static LEA Characteristics

Six alignment characteristics were measured on the pelvis and lower extremity using the different measurement techniques (clinical measures, digital photographs, electromagnetic motion-analysis system). For all methods, the static LEA variables were evaluated with participants standing in a *neutral-stance posture*, which was defined as feet positioned shoulder-width apart, toes facing forward, and upper extremities crossed over the chest. *Pelvic angle* was defined as the angle formed by a line from the anterior-superior iliac spine (ASIS) to the posterior-superior iliac spine (PSIS) relative to the horizontal plane.[14] *Quadriceps angle* was defined as the angle formed by a line from the ASIS to the center of the patella and a line from the center of the patella to the tibial tuberosity.[22] *Tibiofemoral angle* represented the angle formed by the anatomic axis of the femur and tibia in the frontal plane.[23] Specifically, this angle was formed by a line from a *proximal landmark*, which was defined as the midpoint between the ASIS and the most prominent aspect of the greater trochanters, to the *knee-joint center*, which was defined as the midpoint between the medial and lateral joint line in the frontal plane, and a line from the knee-joint

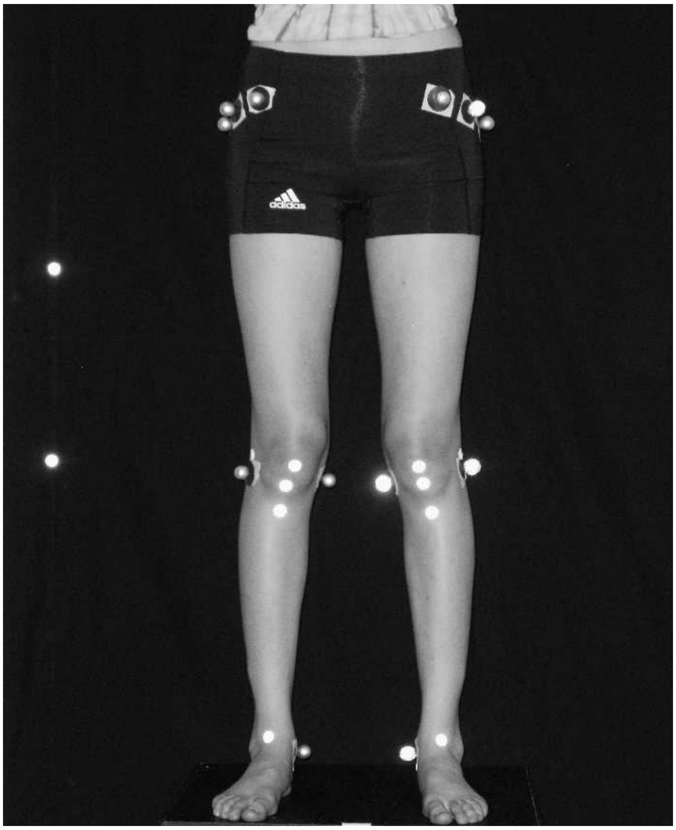

Figure 1. Frontal view of digital photographs.

center to a *distal landmark*, which was defined as the midpoint between the medial and lateral malleoli.[15] *Genu recurvatum* was defined as the sagittal-plane alignment of the femur (ie, line from the lateral femoral epicondyle to the greater trochanter) and the tibia (ie, line from the lateral femoral epicondyle to the lateral malleolus) as participants actively extended their knees.[24] *Femur length* was defined as the distance from the superior aspect of the greater trochanter to the lateral joint line of the knee, whereas *tibia length* was defined as the distance from the medial joint line of the knee to the inferior tip of the medial malleolus.[15]

Measurement Techniques

Clinical Measurements. All clinical measurement procedures for both projects were performed by a single examiner (A.-D.N.) who had established good to excellent test-retest reliability on all measures (intraclass correlation coefficient [ICC] [2,3] $\geq$ 0.87),[15,25] using techniques that have been described in detail.[15,24–26] Clinical measures of pelvic angle were performed using an inclinometer (Performance Attainment Associates, St Paul, MN), whereas quadriceps angle, tibiofemoral angle, and genu recurvatum were measured using a standard goniometer modified with an extension rod attached to the stationary arm to improve accurate alignment with the proximal landmarks. Clinical measures of femur and tibia length were performed with a sliding anthropometric caliper (Lafayette Instrument Company, Lafayette, IN). Each measure was repeated 3 times. The assessment of static LEA with clinical measures took approximately 10 to 12 minutes total.

Digital Photographs. Participants stood on a 45-cm-high box with their toes aligned with the front of the box (Figure 1). Circular, self-adhesive reflective stickers (15-mm diameter) were secured to anatomic landmarks representing the point midway between the ASIS and the greater trochanter, the center of the patella, the tibial tuberosity, the knee-joint center in the frontal plane, the lateral femoral condyle, the ankle-joint center (a point midway between the medial and lateral malleoli), and the lateral malleolus. Custom-made reflective markers (22.2-mm diameter) also were secured to anatomic landmarks representing the PSIS, ASIS, superior tip of the greater trochanter, lateral joint line of the knee, medial joint line of the knee, and inferior tip of the medial malleolus. Two additional reflective stickers were secured to the wall 30 cm apart to provide a known reference distance to calculate length measures during data reduction. A digital camera (Cybershot; Sony Electronics, San Diego, CA), which was mounted on a tripod equipped with bubble levels to ensure level positioning in the frontal and sagittal planes, was positioned perpendicular to the center of the box at a distance 3 m away from the front of the box. The midpoint of the front of the box was measured and marked with athletic tape, and a perpendicular 3-m line was used to ensure that the tripod was aligned to the center of the box. To ensure that the camera was parallel to the plane of the box, we adjusted it (rotated it in the transverse plane) to where an equal amount of space was available on either side of the box when viewed on the liquid crystal display screen. Participants were instructed to stand with their toes at the edge of the box with their feet shoulder-width apart and were positioned with oral directions so the marked midpoint of the box was estimated visually to be equidistant between the feet for frontal-plane images. For sagittal-plane positioning, participants were instructed to stand with their feet shoulder-width apart and were positioned with oral directions so the lateral side of the front foot (dependent on right-side or left-side image) was aligned with the front edge of the box and the lateral malleolus was aligned with the marked midpoint of the box. The height of the camera was adjusted so zooming in on the pelvis and lower extremity was maximal while all of the reflective markers were still captured. A frontal-plane (neutral-stance) and 2 sagittal-plane (neutral-stance and active-extension–stance) digital photographs were taken for each participant (Figure 2). *Active-extension stance* was defined as having the participants contract their quadriceps to maximally extend at the tibiofemoral joints. These methods took approximately 3 to 4 minutes to complete for each participant. All adhesive markers were removed, and the identification of landmarks was repeated to attain a second set of digital images needed to assess intratester reliability. Before the data collection, the novice investigator was provided a manual describing the clinical measurement methods, including pictures, and completed a single training session lasting approximately 1 hour. During the training session, the trained investigator demonstrated the proper method for identifying the anatomic landmarks used in the measures, and the novice investigator was given time to practice and was provided with corrective feedback. Minimal training for this research project was purposeful to observe the influence of tester experience and training.

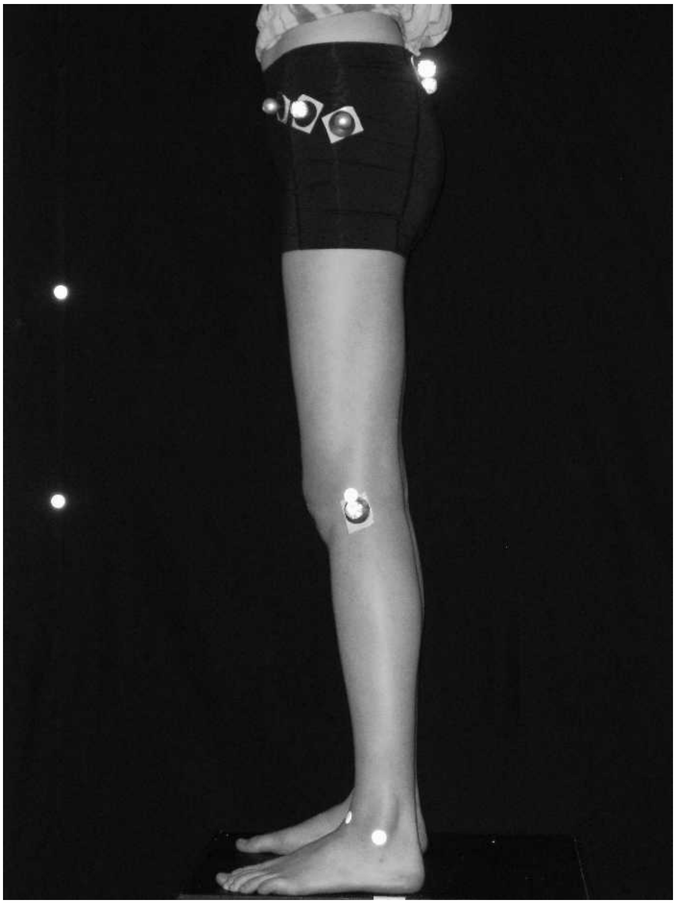

Figure 2. Sagittal view of digital photographs.

Electromagnetic Motion-Analysis System. A 3-dimensional electromagnetic motion-analysis system (Flock of Birds; Ascension Technology Corporation, Burlington, VT) interfaced with MotionMonitor software (Innovative Sports Training, Inc, Chicago, IL) also was used to assess static LEA. Electromagnetic sensors were placed on the center of the low back (base of the sacrum), the midshaft of the medial tibia, and the lateral aspect of the midshaft of the femur. The sensors were secured to the skin using double-sided tape and athletic tape. Using the centroid method, the medial and lateral malleoli were digitized to estimate the ankle-joint center, and the medial and lateral femoral epicondyles were digitized to estimate the knee-joint center. Additional bony landmarks on each participant were digitized and consisted of the PSIS, the ASIS, the greater trochanter, a point midway between the ASIS and the greater trochanter, the center of the patella, the tibial tuberosity, the center of the tibiofemoral joint, the lateral femoral epicondyle, the lateral knee-joint line, the medial knee-joint line, the inferior tip of the medial malleolus, and the lateral malleolus. After digitization, we collected one 5-second neutral-stance trial and one 5-second active-extension–stance trial.

Data Reduction and Analysis

All static LEA variables except genu recurvatum were evaluated during the neutral-stance position. Genu recurvatum was evaluated during the maximal active-extension stance for all 3 methods (clinical measurement, digital photographs, electromagnetic motion analysis). The average of the 3 trials using clinical measurement methods for each static LEA variable was used for data analysis.

For static LEA measures collected with digital photographs, frontal- and sagittal-plane digital images were imported into ImageJ software (National Institutes of Health, Bethesda, MD), where quadriceps angle, tibiofemoral angle, femur length, and tibia length were calculated using the frontal-plane images. Genu recurvatum (active-extension image) and pelvic tilt (neutral-stance image) were assessed using the sagittal-plane images. With the angle tool, the center of the sticker or marker respective to the landmarks described earlier for each LEA variable was selected manually to create 2 intersecting lines. The center of the sticker or marker was estimated visually by zooming in to 33% and aligning the crosshairs within the borders of the sticker or marker. The software then computed the angle formed by the lines to represent the pelvic angle, quadriceps angle, tibiofemoral angle, and genu recurvatum. Femur and tibia length were calculated by using the straight-line tool. To set the scale of the line, a line connecting the center of the stickers placed on the wall was digitized and recorded as a 30-cm known distance. Next, the respective anatomic landmarks were selected, and the software calculated the distance based on the known distance reference value. Each static LEA variable was calculated 3 times for each participant using the digital images, and the average of the 3 trials was used for data analysis. To determine intrarater reliability, the average of the 3 trials for each testing session for the novice and trained investigators was used for data analysis.

For the static LEA measures collected with the electromagnetic motion-analysis system, position data for the digitized landmarks were exported. A customized MATLAB (The MathWorks, Natick, MA) program was designed to calculate the average value of each LEA measure over the 5-second trial, which was used for data analysis.

To examine intratester (test-retest) and intertester (trained-novice) reliability of the digital photograph method for the trained and novice investigators, separate repeated-measures analyses of variance with 1 within-subject variable at 2 levels (intratester: trial 1, trial 2; intertester: trained, novice) were used to calculate ICC (2,k)[27] and standard errors of measurement (SEMs). The following criteria were used to interpret ICC values: *poor* indicated less than 0.50; *moderate*, from 0.50 to 0.75; and *good*, greater than 0.75.[28] To examine the measurement agreement among the various measurement methods (clinical measures, digital photographs, electromagnetic tracking system), 95% limits of agreement (LOAs) were calculated and Bland-Altman plots[29,30] were interpreted graphically for each comparison. These methods of statistical analyses have been proposed as more appropriate than correlation analysis to assess agreement between 2 measurement methods, particularly when a “true” value is unknown, because the latter can be highly dependent on the distribution of values in the sample. The 95% LOAs were calculated as the mean difference between measurement methods $\pm$ 1.96 times the SD and represented the range of differences between measurements. No guidelines indicate an acceptable level of agreement; instead, interpretation is based on clinical judgment. Bland-Altman plots were used

Table 1. **Descriptive Data for Each Lower Extremity Alignment When Comparing Agreement Between Clinical Measures and Digital Photographs (Mean ± SD [95% Confidence Interval])**

Alignment Variable	Trial	Digital Photographs: Trained Tester, Right	Digital Photographs: Trained Tester, Left	Digital Photographs: Novice Tester, Right	Digital Photographs: Novice Tester, Left	Clinical Measures, Right	Clinical Measures, Left
Pelvic angle, °	1	13.1 ± 5.2 (10.4, 15.8)	12.2 ± 6.0 (9.1, 15.2)	8.5 ± 5.3 (5.8, 11.2)	8.1 ± 5.1 (5.5, 10.7)	10.7 ± 4.3 (8.5, 12.9)	11.1 ± 4.0 (9.1, 13.1)
	2	14.1 ± 4.6 (11.7, 16.5)	12.0 ± 4.9 (9.5, 14.5)	7.8 ± 5.3 (5.0, 10.5)	7.3 ± 5.3 (4.6, 10.0)		
Quadriceps angle, °	1	15.0 ± 6.2 (11.8, 18.2)	11.9 ± 6.0 (8.8, 15.0)	13.3 ± 7.0 (9.7, 16.9)	14.6 ± 6.5 (11.3, 18.0)	13.4 ± 4.8 (10.9, 15.9)	9.5 ± 4.6 (7.1, 11.8)
	2	14.3 ± 5.3 (11.6, 17.1)	12.0 ± 5.4 (9.3, 14.8)	14.3 ± 6.4 (11.0, 17.6)	14.2 ± 6.6 (10.8, 17.6)		
Tibiofemoral angle, °	1	11.5 ± 2.7 (10.1, 12.9)	11.3 ± 2.6 (10.0, 12.6)	10.1 ± 2.8 (8.6, 11.5)	10.0 ± 2.5 (8.8, 11.3)	10.7 ± 2.2 (9.6, 11.8)	9.0 ± 2.5 (7.7, 10.2)
	2	11.5 ± 2.6 (10.2, 12.9)	11.3 ± 2.6 (9.9, 12.6)	10.0 ± 3.2 (8.3, 11.6)	10.1 ± 2.9 (8.6, 11.5)		
Genu recurvatum, °	1	3.1 ± 2.7 (1.7, 4.5)	3.1 ± 2.7 (1.7, 4.5)	3.8 ± 2.9 (2.6, 5.3)	3.4 ± 3.0 (1.9, 5.0)	1.3 ± 3.0 (−0.3, 2.8)	1.6 ± 3.2 (0.0, 3.2)
	2	3.4 ± 2.5 (2.0, 4.6)	3.2 ± 1.7 (2.3, 4.1)	4.3 ± 2.8 (2.8, 5.7)	3.4 ± 1.9 (2.4, 4.4)		
Femur length, cm	1	41.6 ± 3.6 (39.8, 43.5)	41.9 ± 3.6 (40.0, 43.7)	44.3 ± 4.1 (42.2, 46.4)	44.5 ± 3.9 (42.5, 46.5)	43.2 ± 2.9 (41.7, 44.6)	43.2 ± 2.9 (41.7, 44.1)
	2	40.9 ± 3.8 (39.0, 42.9)	41.7 ± 3.3 (40.0, 43.4)	43.8 ± 3.3 (42.1, 45.4)	43.9 ± 3.5 (42.2, 45.7)		
Tibia length, cm	1	37.8 ± 2.7 (36.4, 39.2)	37.7 ± 2.8 (36.3, 39.1)	38.6 ± 2.8 (37.2, 40.1)	38.7 ± 2.9 (37.2, 40.1)	36.8 ± 2.4 (35.5, 38.0)	36.8 ± 2.6 (35.4, 38.1)
	2	47.8 ± 2.5 (36.5, 39.1)	37.7 ± 2.7 (36.3, 39.1)	38.4 ± 2.7 (37.0, 39.7)	38.4 ± 2.8 (36.9, 39.8)		

for graphic representation of agreement where the differences among methods were plotted against the respective individual means.[29,30] Bland-Altman plots were used to identify the magnitude of agreement and any systematic bias among measurement methods by examining the scatter around the zero line.

RESULTS

Means and SDs for each variable by tester and trial for the project in which we examined the reliability of digital photographs are presented in Table 1. Means and SDs for each variable by measurement method for the project in which we examined agreement between the different measurement methods are presented in Table 2. The ICCs and SEMs for intratester and intertester reliability of the digital photograph methods for each tester are presented in Tables 3 and 4, respectively. The 95% LOAs between clinical measures and digital photographs and their agreement with the electromagnetic motion-analysis system are presented in Tables 5 and 6, respectively.

Tester Reliability Using Digital Photographs

Both investigators consistently measured all LEA variables using digital photographs on both the right and left limbs with good to excellent repeatability (ICC $\geq$ 0.80) and a relatively high level of measurement precision (SEM range = 0.29–1.19 cm and 0.35°–2.46°), with the exception of the trained investigator in the measurement of genu recurvatum on the right limb (Table 3). Digital photograph measurement between investigators generally was consistent across trials, with good to excellent reliability (ICC $\geq$ 0.80) and a relatively high level of precision (SEM range = 0.49–1.97 cm and 0.59°–2.83°) in the measures of quadriceps angle, tibiofemoral angle, genu recurvatum, femur length, and tibia length (Table 4). Poor to moderate reliability and high measurement error between investigators was observed for measures of pelvic angle (ICC range = 0.43–0.59, SEM range = 3.41°–4.25°).

Agreement Among LEA Measurement Methods

When comparing agreement of clinical measures of LEA with the digital photograph method, an absolute systematic bias was evident; LEA values measured with digital photographs were consistently greater than those obtained using clinical measures for quadriceps angle, tibiofemoral angle, and tibia length for both investigators. This was evident from the negative mean difference values (Table 5) and was illustrated graphically where values were scattered below the zero line (Figure 3). Based on clinical interpretation, the difference between clinical measures and values derived from digital photographs was least in the measures of limb length, with mean differences for both investigators ranging from 0.92 to 1.78 cm for tibia length and 0.74 to 2.26 cm for femur length. The 95% LOAs associated with the limb-length measures were wider for femur length than tibia length. Mean differences were relatively small for both testers in the measurement of tibiofemoral angle (range = 0.99°–2.30°); however, the 95% LOAs associated with these differences were somewhat wide, with values reaching more than 3.5°. A poor level of agreement between clinical measures and digital photo-

Table 2. Descriptive Data for Each Lower Extremity Alignment When Comparing Agreement Among Clinical Measures, Digital Photographs, and Electromagnetic Tracking System (Mean ± SD [95% Confidence Interval])

Alignment Variable	Clinical Measures	Digital Photographs	Electromagnetic Tracking System
Pelvic angle, °	9.6 ± 4.0 (7.4, 11.9)	9.3 ± 3.0 (7.6, 11.1)	12.4 ± 3.6 (10.3, 14.4)
Quadriceps angle, °	13.8 ± 4.3 (11.4, 16.2)	15.4 ± 5.8 (12.2, 18.6)	12.6 ± 4.5 (10.1, 15.1)
Tibiofemoral angle, °	10.7 ± 3.2 (8.9, 12.8)	12.7 ± 4.1 (10.3, 15.0)	10.2 ± 4.2 (7.8, 12.6)
Genu recurvatum, °	2.3 ± 2.4 (1.0, 3.6)	4.4 ± 4.5 (1.9, 6.9)	3.0 ± 5.6 (−0.1, 6.1)
Femur length, cm	43.1 ± 1.8 (42.1, 44.1)	44.5 ± 1.6 (43.6, 45.4)	43.5 ± 1.2 (42.8, 44.1)
Tibia length, cm	37.6 ± 1.6 (36.7, 38.5)	39.3 ± 1.7 (38.3, 40.3)	37.8 ± 1.8 (36.7, 38.8)

graphs regardless of investigator experience was observed in measures of pelvic angle, quadriceps angle, and genu recurvatum. The mean differences were large and the 95% LOAs were wide; the discrepancy was greater in the novice investigator.

The agreement in frontal-plane knee and limb-length measures between the electromagnetic motion-analysis system and clinical measures and digital photographs was good, with relatively small mean differences. A higher level of agreement (lower mean difference and relatively narrow 95% LOA) was observed in these measures between the electromagnetic tracking system and clinical measures than the level of agreement between the electromagnetic tracking system and digital photographs (Table 6). Agreement was good in the measurement of genu recurvatum between the electromagnetic tracking system and digital pictures; however, a wide 95% LOA suggested that poor agreement existed between the electromagnetic tracking system and clinical measures. A systematic bias with higher values recorded using the electromagnetic tracking system and wide 95% LOAs was observed, suggesting a poor level of agreement with clinical measures and digital photographs for the measurement of pelvic angle.

DISCUSSION

Our findings suggest that using digital photographs to assess multiple static LEA variables can be repeated consistently for measures of quadriceps angle, tibiofemoral angle, femur length, and tibia length with minimal training. Whereas an acceptable agreement between digital photographs and clinical measures was observed in limb-length measures, using these methods interchangeably to assess static knee and pelvic angles may not be appropriate. Our results suggest that an electromagnetic tracking system is an acceptable option to assess static knee angles and limb length; a high level of agreement was observed when compared with clinical measures and digital photographs. Overall, our findings provide efficient and acceptable options when assessing specific measures of static LEA as part of large-scale, prospective risk-factor studies.

Reliability of Digital Photographs

The reported reliability of static LEA using clinical measurement methods varies throughout the literature. Shultz et al[15] published the most comprehensive examination of intratester and intertester reliability of LEA using clinical measures across multiple testers and alignment variables. Relative to the LEA variables assessed in our study, they observed an acceptable level of intratester agreement in most of the measures (ICC range = 0.64–0.99), but the agreement among multiple testers was much lower and may be considered insufficient for use during large-scale studies that require multiple sites and testers (ICC range = 0.48–0.97). The intratester reliability we observed when using digital photographs is consistent with that reported by Shultz et al,[15] with ICC values ranging from 0.70 to 0.99 in the trained and novice investigators. Furthermore, we observed an acceptable level of agreement between testers in most of the static LEA measures with the use of digital photographs. One reason for the higher observed intertester reliability we observed when using digital photographs than when using the clinical methods that Shultz et al[15] reported may be elimination of inconsistencies with the use of the testing instruments (eg, alignment of the goniometer) between testers because all values were derived using a computer software program. In addition, the error associated with varied levels of clinical experience of investigators and inconsistency in the identification of anatomic landmarks across multiple testers also does not appear to be a factor when using digital photographs to assess quadriceps angle, tibiofemoral angle, femur length, and tibia length. The investigators in our study had a wide range of clinical experience and

Table 3. Intratester (Test-Retest) Reliability of Digital Photographs

	Tester 1				Tester 2			
	Right		Left		Right		Left	
Alignment Variable	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement
Pelvic angle, °	0.90	1.65	0.92	1.73	0.92	1.53	0.94	1.32
Quadriceps angle, °	0.84	2.46	0.95	1.30	0.97	1.23	0.94	1.65
Tibiofemoral angle, °	0.93	0.72	0.98	0.41	0.97	0.60	0.99	0.35
Genu recurvatum, °	0.70	1.35	0.79	1.24	0.87	1.07	0.80	1.34
Femur length, cm	0.90	1.19	0.97	0.65	0.92	1.16	0.95	0.83
Tibia length, cm	0.99	0.29	0.99	0.28	0.99	0.26	0.99	0.31

Table 4. Intertester Reliability Between Trained and Novice Investigators Using Digital Photographs

	Trial 1				Trial 2			
	Right		Left		Right		Left	
Alignment Variable	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement	Intraclass Correlation Coefficient (2,k)	Standard Error of Measurement
Pelvic angle, °	0.43	3.99	0.49	4.24	0.59	3.41	0.54	3.59
Quadriceps angle, °	0.84	2.83	0.89	2.16	0.87	2.34	0.84	2.63
Tibiofemoral angle, °	0.94	0.72	0.95	0.59	0.86	1.21	0.86	1.08
Genu recurvatum, °	0.75	1.49	0.87	1.09	0.83	1.17	0.86	0.93
Femur length, cm	0.77	1.97	0.74	1.97	0.75	1.87	0.79	1.60
Tibia length, cm	0.94	0.67	0.94	0.69	0.95	0.61	0.97	0.49

consistently could identify anatomic landmarks, as shown by the good intertester reliability we observed in most of the static LEA measurements.

Given that we observed an acceptable level of intertester reliability with a 1-hour training session, the use of the digital photograph technique described also would reduce the time spent training investigators before data collection. This is drastically less time than the time reported by Shultz et al.[15] They examined the reliability of clinical measurement methods across multiple testers who had professional credentials, such as athletic trainer, occupational therapist, and physical therapist, and were trained for 2 hours per day 3 times per week over a 4-week period, and found an acceptable level of agreement was achieved only among those who had more than 6 years of clinical experience.[15] The ability to efficiently train investigators to collect accurate data is especially advantageous for future risk-factor studies in which researchers require data collection at multiple sites and over multiple years and, thus, new research assistants must be trained because investigators will be replaced.

Agreement Among Various Measurement Methods

Whereas an acceptable level of reliability within and between testers can be achieved using digital photographs, the agreement between values attained using digital photographs and values attained using clinical methods, which are used in prospective risk-factor studies, needs to be established to ensure accuracy in the data collected. Furthermore, biomechanical factors that increase the risk of ACL injury and PFPS are among the multiple factors that should be included in prospective studies. Recently, an electromagnetic tracking system was used successfully to collect biomechanical data in large cohorts.[10,31] Whereas our purpose for using an electromagnetic tracking system was to assess static LEA, the method for digitizing the lower extremity was identical to that commonly used to assess biomechanical outcomes in the literature. Assessing static LEA as part of prospective studies in which researchers also assess lower extremity biomechanics would require the digitization of additional anatomic landmarks. Based on our observation, digitization of these additional landmarks can be accomplished easily in less than 1 minute, which would make this a very efficient method to assess static LEA in large cohort studies in which researchers already are collecting biomechanical data. However, before any new or alternative methods are used to assess static LEA clinically or in prospective research studies, the level of agreement among the various methods should be assessed to make clinically meaningful interpretations and comparisons of the LEA values. To our knowledge, we are the first to examine the agreement among clinical measurement methods, digital photographs, and an electromagnetic tracking system. Whereas an electromagnetic tracking system may not be a practical or cost-effective tool to assess static LEA in the clinical setting, our findings suggest that using an electromagnetic tracking system to assess quadriceps angle, tibiofemoral angle, femur length, and tibia length and using digital photographs to assess tibiofemoral angle, femur length, and

Table 5. Mean Difference ± 95% Limits of Agreement for Clinical Measures Versus Digital Photographs

		Right		Left	
Alignment Variable	Tester[a]	Trial 1	Trial 2	Trial 1	Trial 2
Pelvic angle, °	1	−2.50 ± 4.69	−3.73 ± 5.51	−3.04 ± 2.47	−2.89 ± 2.30
	2	2.24 ± 8.73	2.93 ± 8.57	2.99 ± 9.24	3.82 ± 9.80
Quadriceps angle, °	1	−3.14 ± 3.12	−3.08 ± 4.41	−2.79 ± 2.00	−3.00 ± 2.16
	2	−3.11 ± 4.61	−2.83 ± 4.51	−4.88 ± 5.25	−4.78 ± 4.69
Tibiofemoral angle, °	1	−1.58 ± 2.71	−1.46 ± 2.04	−2.30 ± 3.58	−2.27 ± 3.01
	2	−1.12 ± 3.49	−0.99 ± 3.62	−1.75 ± 1.92	−1.96 ± 2.59
Genu recurvatum, °	1	−1.78 ± 3.12	−2.93 ± 3.00	−1.71 ± 2.10	−2.27 ± 2.74
	2	−2.52 ± 3.45	−2.94 ± 3.19	−2.05 ± 2.41	−2.14 ± 2.95
Femur length, cm	1	2.16 ± 3.04	2.26 ± 3.62	1.77 ± 2.49	1.50 ± 2.06
	2	−1.00 ± 4.19	−0.74 ± 3.44	−1.44 ± 3.30	−1.18 ± 4.00
Tibia length, cm	1	−1.04 ± 0.98	−1.05 ± 1.30	−1.03 ± 1.32	−0.92 ± 1.40
	2	−1.73 ± 1.67	−1.52 ± 1.55	−1.78 ± 1.71	−1.58 ± 1.63

[a] Tester 1 was the trained investigator; Tester 2, the novice investigator.

Table 6. Mean Difference ± 95% Limits of Agreement for Clinical Measures and Digital Photographs Versus Electromagnetic Tracking System

Alignment Variable	Clinical Measures Versus Electromagnetic Tracking System	Digital Photographs Versus Electromagnetic Tracking System
Pelvic angle, °	−2.25 ± 9.36	−2.93 ± 5.59
Quadriceps angle, °	−1.28 ± 0.98	1.95 ± 2.00
Tibiofemoral angle, °	−0.83 ± 1.25	1.90 ± 1.43
Genu recurvatum, °	−1.30 ± 5.07	1.80 ± 1.34
Femur length, cm	−0.34 ± 2.30	1.15 ± 1.08
Tibia length, cm	−0.13 ± 0.95	1.52 ± 0.75

tibia length are efficient and acceptable methods to include as part of multifactorial prospective studies and in clinical practice.

Limb Length and Frontal-Plane Knee Angles. Femur and tibia lengths are anatomic variables that have been suggested to contribute to static postures that influence dynamic lower extremity biomechanics and increase the risk of knee injuries.[16,32,33] We observed an acceptable level of agreement across measurement methods when assessing measures of limb length. Whereas the best agreement was observed between clinical measures and the electromagnetic tracking system for measures of femur and tibia length, differences overall were very small; the greatest mean difference between methods was approximately 2 cm. A very small systematic bias appears to exist between clinical measures and digital photographs in measures of tibia length, where values were approximately 1 to 2 cm greater with digital photographs than clinical measures. Given the consistency of the systematic bias across trials and testers, a simple adjustment would be appropriate when using these methods interchangeably for measures of tibia length. We also observed a systematic bias between clinical measures and digital photographs in the measurement of femur length, but the difference was opposite across testers. Femur length values were lower with digital photographs than clinical measures in the trained investigator but appeared to be higher in the novice investigator. This could be attributed to the differences in identifying the proximal bony landmark used for the measure, because accurate identification of the superior tip of the greater trochanter can be influenced by the amount of soft tissue in the area. This systematic bias also would explain the somewhat lower intertester reliability (ICC = 0.74–0.79) in measures of femur length with digital photographs.

When examining the agreement between clinical measures and digital photographs for measures of frontal-plane knee alignment, a systematic bias appears to exist such that quadriceps angle and tibiofemoral angle values were consistently higher with the use of digital photographs (Figure 3). Considering that this systematic bias appears to be consistent across limbs and independent of tester experience, the interchangeable use of these measurement methods may be appropriate by adjusting for the systematic difference. However, considering the wide range of the 95% LOAs (range = ±2°–5°) associated with the mean differences, values obtained through digital photographs may not accurately represent values obtained through clinical measurement methods. This does not mean that digital photographs are not an efficient tool to assess frontal-plane knee alignment in the clinical or research settings, but values obtained from digital photographs are not representative of clinical measures. Based on our findings that good reliability can be achieved by testers of varying clinical experience, using digital photographs for the initial assessment of frontal-plane knee alignment is a reliable and cost-effective option to follow alignment changes during rehabilitation and for multiyear prospective studies and requires very minimal training.

The high level of agreement when comparing the electromagnetic motion-analysis system with clinical measures and digital photographs provides empirical data to support its use in prospective injury-risk studies. As mentioned, we estimated that the digitization of the additional landmarks to extract static LEA measures can be accomplished in less than 1 minute. This is in contrast to the time spent in our study (we estimate approximately 15 minutes including data collection and reduction) and other studies in which researchers have used digital photographs to assess static LEA. The procedures described in our study provide a method that is even more time efficient.

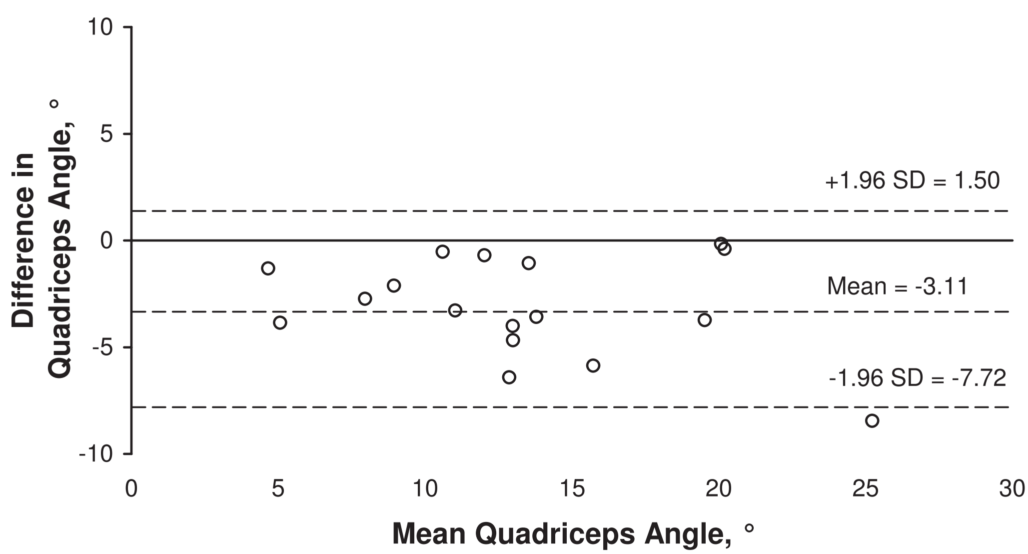

Figure 3. Representative Bland-Altman plot for quadriceps angle with clinical measures and digital photographs.

Moncrieff and Livingston,[20] who used adhesive markers, reported a wide range of intratester and intertester reliability from poor to excellent in the measurement of quadriceps angle, tibiofemoral angle (knee varus and valgus), and femur length using digital photographs. Aside from the large range of observed reliability, no comparisons were made with clinical measures, and the data-reduction methods may not be efficient when examining large cohorts. The authors derived static LEA values after printing the digital photographs, drawing intersecting lines, and physically taking the alignment measures. Whereas a digital camera allows for repeated capture of images and is a cost-effective instrument for multiyear prospective studies, printing digital images would increase the cost associated with this method, and physical measurement of the printed images would seem to increase the time demand associated with data reduction. Schmitt et al[21] compared the reliability of frontal-plane knee-alignment measurements obtained from digital photographs and a software constructional program. Knee alignments were calculated using landmarks that were determined with various methods and based on soft tissue borders. Excellent reliability was reported between testers and when compared with radiographic measurements of frontal-plane knee alignment. However, we do not know if this method of data reduction is time efficient and whether the computer software is readily available to health care professionals.

Pelvic Angle. The intertester reliability using digital photographs and agreement among the measurement methods was relatively low with measures of pelvic angle. A reason for the poor agreement may be inconsistencies in the identification of the landmarks. The size and shape of the ASIS and PSIS, which are anatomic landmarks used in the measurement of pelvic angle, vary among individuals. Accurately identifying the ASIS and PSIS can be difficult secondary to abnormal bony variation of the ilium or presence of excessive soft tissue in individuals with high body fat mass. The difficulty of consistently palpating these landmarks increases with increased body mass that, in combination, increases the error involved with the measure. In addition to the difficulty of consistently palpating the anatomic landmarks, the measurement of pelvic angle can be influenced by differences in muscle activation during the standing posture. Given that contraction of the muscles that control the pelvis (ie, rectus abdominis, erector spinae, gluteal muscles, hip flexors) will affect the position of the pelvis,[34] a consistent standing posture during the measurement is necessary for the measurement to achieve a high level of agreement for measures of pelvic angle.

Genu Recurvatum. We measured genu recurvatum in standing because the intertester reliability using clinical methods was reported to be higher with a standing measurement with quadriceps contraction (ICC $= 0.95$)[19] than a supine method with a passive posteriorly directed force (ICC $= 0.57$).[15] In addition, the standing active measures may be more reflective of a functional posture, and Shultz et al[25] reported that no systematic difference exists compared with an active measure in a supine position. Good to excellent intratester and intertester reliability was observed with digital photographs. However, the agreement was poor when comparing the values attained with clinical measurement methods with those obtained from digital photographs and an electromagnetic tracking system. We observed a consistent systematic bias, such that values relying on clinical measurement were less than those relying on other methods; 95% LOAs occupied a wide range. Interestingly, we observed excellent agreement between the electromagnetic tracking system and digital photographs. Given that a high level of agreement was observed between the digital photographs and the electromagnetic tracking system but a low level of agreement was observed when each was compared with the clinical measure, a systematic difference can be attributed to the clinical measurement method. This difference may be due to the error associated with the use of a goniometer while taking the measure using clinical methods. Even with the extension rod attached to the goniometer to reduce error, the proper alignment of the goniometer with anatomic landmarks may be difficult and result in a systematic difference during active knee extension compared with the other methods that do not require a goniometer. To confirm which method is a valid measure of genu recurvatum, comparisons with a criterion standard, such as standing radiographs, are needed.

CONCLUSIONS

The use of digital photographs is a reliable method to assess static knee alignment and limb-length measures in the clinical setting or as part of prospective risk-factor studies. However, we caution clinicians in generalizing our reliability results to their practice when only 1 trial or measurement is taken to assess static LEA alignment, because we assessed reliability based on the average of 3 measures. An electromagnetic tracking system is an efficient and acceptable option to assess static frontal-plane knee alignment and limb-length measures as part of large-scale prospective cohort studies. In future studies, researchers should investigate which method is the most valid for measuring static LEA when compared with a criterion standard, such as radiographs. Our findings provide one resolution to the challenges associated with determining the role of static LEA in increasing the risk of lower extremity injury. Incorporating measures of static LEA in prospective study designs will help us identify individuals at greatest risk of injury and continue to help develop more appropriate intervention programs to reduce the risk of knee injuries.

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