3-1-2017

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HHS Public Access

Author manuscript

Knee. Author manuscript; available in PMC 2018 March 01.

Published in final edited form as:

Knee. 2017 March ; 24(2): 224–230. doi:10.1016/j.knee.2016.11.014.

Smartphone Assessment of Knee Flexion Compared to Radiographic Standards

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Abstract

Purpose—Measuring knee range of motion (ROM) is an important assessment for the outcomes of total knee arthroplasty. Recent technological advances have led to the development and use of accelerometer-based smartphone applications to measure knee ROM. The purpose of this study was to develop, standardize, and validate methods of utilizing smartphone accelerometer technology compared to radiographic standards, visual estimation, and goniometric evaluation.

Methods—Participants used visual estimation, a long-arm goniometer, and a smartphone accelerometer to determine range of motion of a cadaveric lower extremity; these results were compared to radiographs taken at the same angles.

Results—The optimal smartphone position was determined to be on top of the leg at the distal femur and proximal tibia location. Between methods, it was found that the smartphone and goniometer were comparably reliable in measuring knee flexion (ICC = 0.94; 95% CI: 0.91–0.96). Visual estimation was found to be the least reliable method of measurement.

Conclusions—The results suggested that the smartphone accelerometer was non-inferior when compared to the other measurement techniques, demonstrated similar deviations from radiographic standards, and did not appear to be influenced by the person performing the measurements or the girth of the extremity.

Keywords

smartphone; accelerometer; motion; measurement

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1. Introduction

The measurement of postoperative knee range of motion (ROM) after total knee arthroplasty (TKA) is a key piece of information that allows surgeons to evaluate patient satisfaction, success of a knee prosthesis, and patient function after surgery. Functional flexion of 90–105° is necessary to perform activities of daily living.[1] Patients that demonstrate flexion below these values may require an intervention such as specialized braces, manipulation under anesthesia, and even revision surgery. Therefore, it is important that knee range of motion is accurately evaluated.[1]

Radiographic measurement has been accepted as the most accurate method of evaluating knee flexion.[1,2] However, due to radiation exposure and the need for repeated examinations, this method is not clinically feasible. As a result, knee ROM has traditionally been evaluated using visual estimation or long-arm goniometry.[1–4] Recent smartphone technology, however, has led to the development of accelerometer-based applications that have the potential to be used for measuring ROM.[3] As a clinical tool for measuring ROM, the accuracy, intraobserver, and interobserver reliability has not been established compared to radiographic assessments. Furthermore, no standard exists for the use or positioning of the smartphone when obtaining measurements.

The purpose of this study was to develop, standardize, and validate a method of utilizing smartphone accelerometer technology. Based on the identification of an optimal location at which a smartphone could be placed, the smartphone accelerometer, accuracy of visual estimation, and long-arm goniometer were compared against radiographic assessment for measuring knee ROM. Additionally, the impact of leg circumference on the smartphone's ability to accurately measure range of motion and the experience level of the observer were assessed.

2. Material and Methods

This study was approved by the Institutional Biosafety Committee prior to initiation. Two cadaveric specimens of different sizes disarticulated at the hip were obtained from the institutional Human Gift Registry. A small cadaver leg (upper leg circumference: 40.6cm and lower leg circumference: 27.9cm) and large cadaver left leg (52.7cm upper and 37.5cm lower) were utilized. Two custom devices were constructed so that each leg could be positioned in reproducible angles allowing for unobstructed views of the lower extremity (Fig. 1a&b). These devices also allowed for rotation of the hip around a fixed axis recreating various angles of knee flexion.

The study was designed with two independent phases. The first phase was designed to determine an optimal position for the smartphone, in order to provide an efficient use of resources for the second and independent phase of the study that would address the utility of a smartphone for measuring knee ROM. The second phase was designed to assess differences between the smartphone and the other assessment tools (i.e. accuracy of visual estimation, long-arm goniometer, and radiographic assessment). This study was powered for identifying the main effects of the measurement devices while taking into account the finite resources of this single site study.

2.1 Phase I: Smartphone position on leg

Six orthopaedic surgeons observed the two separate cadaver legs at three different flexion angles. At each position, the surgeon gave a visual estimation of knee flexion, took a series of smartphone measurements, and measured flexion with a long-arm goniometer. For smartphone measurements, the femur and tibia of each leg were divided into thirds (proximal, medial, and distal). An iPhone 5 (Apple Inc., Cupertino, CA) containing an intrinsic, accelerometer-based angle measurement application, was obtained and calibrated for use in the study. The orthopaedic surgeon, blinded to the output of the smartphone, placed the smartphone on top of one of the designated thirds of the femur with the output of the smartphone visible only to a data collector. The data collector then zeroed the smartphone application and instructed the orthopaedic surgeon to place the phone on top of a designated third of the tibia. This process resulted in placing the smartphone in a total of nine different combinations. The process was repeated by placing the smartphone on the side of the leg in all nine positions as well. The entire procedure was repeated in triplicate for three different knee flexion positions. A total of 324 positions were obtained (162 top of leg/162 side of leg).

2.2 Optimization procedure for Phase I

An optimal smartphone position for flexion measurement was defined as the location for using a smartphone that minimizes the deviation from the gold standard, radiographic measurement of knee flexion. For each of the six orthopaedic surgeons, deviations of each smartphone measurement from the radiographic knee flexion measurement were obtained. The triplicate readings were averaged and then ranked. The location that consistently minimized the deviations amongst the surgeons was chosen as an optimal location to use the smartphone for Phase II of the study and to provide insight for smartphone measurement knee ROM utility against other standards of measurement. This analysis was conducted for both the small and large leg.

2.3 Radiographic measurement of knee flexion angle

Prior to any measurements being obtained, radiographs were taken of each leg at the three positions. An orthopaedic surgeon not involved in the study measured the flexion angle of each position for both legs based on the posterior cortex of the femur and tibia.[1] The radiographic measurements for the small leg were 36°, 59°, and 76°. The angles measured for the large leg were 48°, 73°, and 88°.

2.4 Phase II: Comparison of measurement techniques

Measurements were obtained using five methods of measuring knee ROM (two locations for the smartphone, goniometer, visual, and radiographic), for three leg positions (angles), and two leg sizes based on a 5-by-3-by-2 fully orthogonal analysis of variance (ANOVA) design.[5,6] This design was replicated fifteen times, each time by a different orthopaedic surgeon (5 junior residents, 3 senior residents, and 7 attendings).[5] The experience level of each surgeon was obtained in order to account for variation based on experience, assuming exchangeability of surgeons within experience levels.

For each replicate of this design, the surgeon performed flexion measurements of both the small and large legs at three different flexion angles per leg based on the custom positioning devices. First, the physician would stand facing the lateral side of the leg and give a visual estimation of knee flexion. Second, the physician would measure knee flexion using the smartphone accelerometer application using the optimal placement determined from Phase I of the study. The phone was placed on the top of the distal third femur, zeroed, and then placed on the top of the proximal third tibia. As in Phase I of the study, the physician was blinded to the output of the smartphone and a data collector recorded the smartphone's measurement. This process was repeated with the smartphone on the side of the leg. Finally, the physician measured the knee's flexion using a long-arm goniometer. The number markings on the physician's side of the goniometer were covered so that only the data collector on the opposite side of the leg could read the measurement.

2.5 Statistical Analysis for Phase II

An ANOVA model was used to assess the statistical significance of the study design features (measurement tool, leg position, and leg size) as well as to provide insight concerning surgeon experience. Comparisons of interest were determine post-analysis, thus Tukey's HSD (Honest Significant Differences) for multiple comparisons was used while maintaining the desired family-wise 5% alpha-level of significance across all comparisons.[6]

As a secondary analysis, we used the intraclass correlation (ICC) for rater reliability to assess the consistency of the goniometer, smartphone, and visual assessment measurement methods for knee flexion for each leg type and angle combination. [7] Rater is defined as the measurement device and the ICC(3,1) measure is used to provide an estimate of consistency across different measurement devices.[7] Although this formulation is non-traditional, it provides a measure of device consistency marginalized across users. All statistical analysis was performed using the R Software Environment (R Foundation, Vienna, Austria) for statistical computing and graphics.

3. Results

3.1 Phase I: Smartphone position on leg

In Phase I of the study, we sought to determine an optimal location for placing a smartphone for the ANOVA design of Phase II. When measuring flexion in the small leg, it was determined that using a smartphone on the top of the leg located on the distal femur and proximal tibia most frequently minimized the deviation from the radiographic measure across different smartphone users. When measuring flexion in the large leg, it was found that placing the smartphone on the side of the distal femur and proximal tibia most frequently minimized the deviation from the radiographic measure across different smartphone users (showing a high percentage agreement among users at 83.3%). For both legs, the distal femur and proximal tibia were the preferred positions for placement of the smartphone when measuring flexion. To be conservative in our method, we utilized the side and top of the leg of the distal femur and proximal tibia for assessment of the smartphone in Phase II of this study.

3.2 Phase II: Assessing measurement techniques

In Phase II of the study, the angle measurements from a fully orthogonal ANOVA design were analyzed. Table 1 shows that there is a statistically significant three way interaction between the position of the leg (Position), the leg type (Leg), and the surgeon's level of experience (p=0.007). Additionally, there are statistically significant two way interactions for position and leg type (p=0.027), leg and experience (p=0.006), and method and leg ($p < 0.001$). The main effects of method ($p < 0.001$), position ($p < 0.001$), and leg type ($p < 0.001$) are statistically significant as well. The different measurement devices were compared using Tukey's HSD. Table 2 indicates that the goniometer, smartphone on the side of the leg, smartphone on the top of the leg, and the visual method of measurement are positively inflated when compared against the radiographic gold standard and have a statistically significant difference (adjusted $p < 0.001$ for each comparison). There is a statistically significant difference between the visual and the smartphone on the top of the leg (p = 0.001), with the visual method yielding larger angles, on average, than the smartphone.

Using the same methodology as with the comparisons of the measurement devices, it is observed that there are no statistically significant differences among the different levels of experience: PGY (post graduate year) 1-3 versus Attend (p = 0.804), PGY 4-5 versus Attend (p = 0.241), and PGY 1-3 versus PGY 4-5 (p = 0.522). Thus, there is insufficient evidence that measurement assessment will be less reliable for less experienced than experienced observers for both small and large legs. There is a significant difference between leg types ($p < 0.001$).

Conditional on the type of leg (small or large), similar results are observed. Table 3 reveals that the goniometer, smartphone on the side of the leg, smartphone on the top of the leg, and the visual method of measurement are positively inflated when compared against the radiographic gold standard and having a statistically significant difference (adjusted $p < 0.001$ for each comparison), which is consistent with the previous observations. Additionally, there is a statistically significant difference between the visual and the smartphone on the side of the small leg (p = 0.003), with the visual method yielding larger angles, on average, than the smartphone. The same is observed for the smartphone on the top of the leg (p=0.001). These are unique findings from the conditional analysis that are not reflected in Table 2.

Conditional on the large leg, analogous results occur (Table 4). Again, the goniometer, smartphone on the side of the leg, smartphone on the top of the leg, and the visual method of measurement are positively inflated when compared against the radiographic gold standard and having a statistically significant difference (adjusted $p < 0.001$ for each comparison), which is consistent with the previous observations. Table 4 reveals that there is a difference in the smartphone assessment, with the expected measurements taken on the side of the leg being larger than those taken on the top of the leg (p=0.014).

Tables 2 through 4 show that the goniometer and the smartphone on the top of the leg have the smallest deviations from the radiographic gold standard compared to the smartphone on the side of the leg and the visual assessment. A difference between the goniometer and the smartphone on the top of the leg is observed that may have minimal practical relevance and, given the residual degrees of freedom (Table 1), is not statistically significant (Table 1: p = 0.581; Table 2: p=0.329; Table 3: p=0.996). Table 1 supports these observations through a meaningful interaction between leg type and method.

3.3 Observer experience

A statistically significant difference between PGY 1-3 versus Attend (p = 0.009) with attendings having larger angle assessments, but no statistically significance difference for PGY 4-5 versus Attend (p = 0.295) and PGY 1-3 versus PGY 4-5 (p = 0.741) when conditional on the small leg type. Conditional on the large leg type, there are no statistically significant differences among the different levels of experience: PGY 1-3 versus Attend (p = 0.250), PGY 4-5 versus Attend (p = 0.747), and PGY 1-3 versus PGY 4-5 (p = 0.120). Thus, there is insufficient evidence that measurement assessment will be less reliable for less experienced than experienced observers for large legs. Table 1 supports these observations through a meaningful interaction between leg type and experience.

3.4 Effect of leg size on measurements

When examining the impact of leg girth and considering all four methods of assessment using relative deviation from radiographic measurement, there was insufficient evidence that leg girth is associated with a change in the relative accuracy of knee flexion measurement for visual estimation, smartphone top of leg, and goniometer. There was a statistically significant difference between the large and small leg for the smartphone side of the leg method (p = 0.0003). A sub-analysis, conditional on the use of a smartphone only, indicated that leg girth does have a statistically significant effect on the precision of knee flexion measurement. The smartphone side of the leg measurement had an 8.9% increase in relative deviation with increased leg girth while the top of the leg measurements had only a 4.4% increase in the relative deviation.

3.5 Intraclass Correlation

There was a high level of consistency for any measurement device independent of leg size (small and large) with an ICC = 0.94; 95%, CI 0.91, 0.96.

4. Discussion

The ubiquitous nature of smartphones has led to their rapid adoption into clinical practice. Whether used as a reference tool, risk calculator, or billing device, the use of smartphones in orthopaedic surgery is becoming more commonplace.[8,9] The development of accelerometer technology is being adapted for use in surgical navigation and can also add potential value in the clinical setting.[10] Phase I of this study demonstrated that the optimal positioning of the smartphone was on the top distal third of the femur and top proximal third of the tibia producing the highest agreement among observers. Part II of the study demonstrated that, while there are differences between the measurement techniques when compared to radiographic standards, the smartphone measurement tool is non-inferior to other assessments and does not depend on experience level or size of the measured extremity.

Several other studies have reported on various applications utilizing photographic measurements and angles based on trigonomic function, but none have evaluated the accuracy of these methods compared to radiographic standards and reported the optimal technique for utilizing this new measurement tool. Ferriero et al. utilized a goniometer image overlay tool with a picture of a knee, thereby not directly utilizing the goniometric function of the device.[2] Bedekar et al. utilized only one measurement and calculated the reported angle measurement on assumed constant femur/tibia length ratios; this paper also reported the results of using an application which the authors developed.[3] This evaluation of smartphone based measurements relied on the inherent accelerometer function available on most smartphones and was not influenced by outside programming or mathematical estimation.

In the second portion of the study, there was no significant difference in flexion measurements taken by placing the smartphone on top of the leg or on the side of the leg when measuring the small leg. However, during sub-analysis of smartphone data only, placing the smartphone on top of the leg resulted in a significantly more accurate flexion measurement in the large leg than placing the smartphone on the side of the leg. This finding may have been due to the distorting effects of more tissue present in the larger leg. For both legs, the optimal placement of the smartphone that gave the least deviation from radiographs was the distal femur and proximal tibia.

The second portion of the study revealed that, for measuring knee flexion in both the small and large legs, there was a significant difference between the radiographic measurements and all other measurement methods. Moreover, all the measurement methods were positively biased and overestimated knee flexion measurements. A study by Gogia et al. claimed that the lower limb has demonstrated less interobserver reliability when comparing flexion measurements to radiographic assessment and therefore is consistent with the results observed in the second portion of the study.[11] When comparing the methods for measuring flexion in the small leg, there were no significant differences between both smartphone methods and the goniometer. This finding is consistent with the findings of Ockendon and Gilbert which demonstrated that a smartphone goniometer application showed comparably high intertester reliability when compared to a Lafayette goniometer (a long-arm goniometer).[4] When compared to visual estimation, both smartphone methods were significantly less positively biased which suggests that the smartphone may be more accurate than visual estimation and that visual estimation may be the least accurate method of measurement.

Considering all measuring methods, there was insufficient evidence to indicate that leg girth had a statistically significant effect on measuring knee flexion. Studies have shown conflicting results regarding the impact of leg girth in making accurate flexion measurements. The study conducted by Austin et al. did find leg girth was associated with a significant difference in knee ROM measurements.[12] However, a study conducted by

Edwards et al. showed no correlation between leg girth and the accuracy of goniometric measurements.[1] A sub-analysis considering only the two smartphone methods indicated that there was a significant increase in relative deviation from radiographic measurement for both smartphone methods in measuring flexion of the large leg. These findings may vary depending on the varying girth of the limb and could warrant further assessment. As the radius of the limb increases, the distance from the measured axis will change and could lead to altered data collection.

When examining the impact of observer experience in making knee flexion measurements, there was insufficient evidence to indicate that there was a method of measurement and observer effect when comparing junior residents, senior residents, and attendings.

A limitation to this study was that all measurements were obtained using the same device. The impact of daily use and potential damage to accelerometers is a major confounder not evaluated. Also, the difference between manufacturers of smartphones could potentially influence measurements. Finally, this evaluation was limited to orthopaedic surgeons. The use of the instrument by physical therapists or athletic trainers may produce different results. Although this study was limited to orthopaedic surgeon attendings and residents, to further investigate the effects of observer variability and experience, future studies should also include relevant clinicians such as physical therapists and athletic trainers who also depend on accurate assessment of joint range of motion.

5. Conclusions

The results of this study suggested that the smartphone accelerometer was non-inferior when compared to other measurement techniques, demonstrated similar deviations from radiographic standards, and did not appear to be influenced by the person performing the measurements or the girth of the extremity.

Acknowledgments

Research reported in this publication was supported by the National Institute of General Medical Sciences of the National Institutes of Health under Award Number U54GM104942. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Abbreviations

ROM	range of motion
TKA	total knee arthroplasty
ANOVA	analysis of variance
HSD	Honest Significant Difference
ICC	intraclass correlation
CI	confidence interval
PGY	post graduate year

Attend	attending

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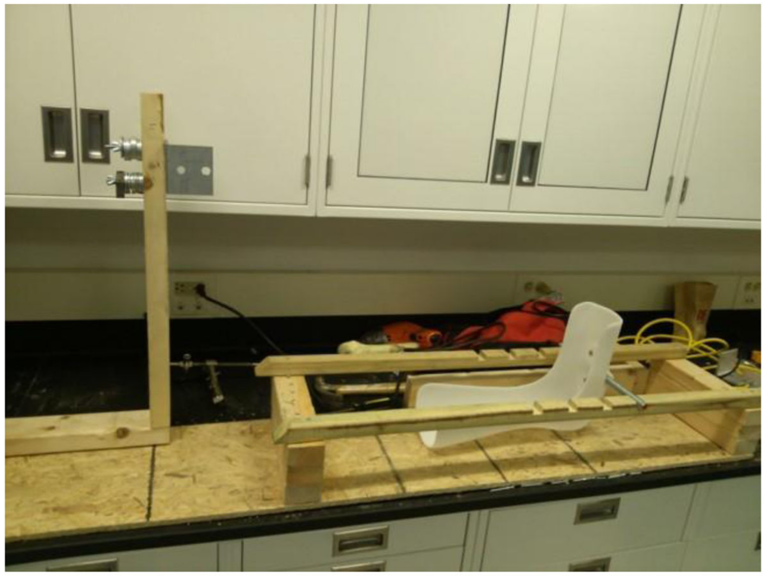

Fig. 1a

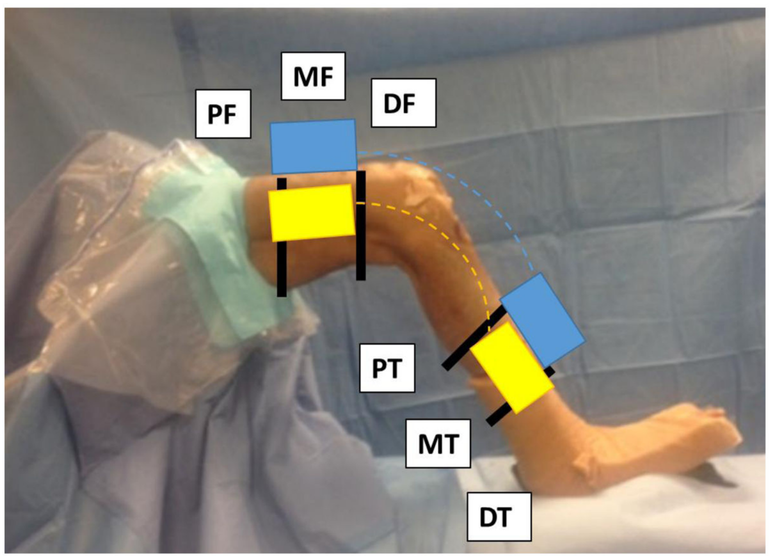

Fig. 1b

Figure 1.

a) Custom device allowing for articulation of the hip around a fixed axis and positioning of the foot to create various flexion angles. b) This device allowed for observation of the leg with an unobstructed view. The femur and tibia were divided into thirds (proximal femur – PF, middle femur - MF, distal femur – DF) and (proximal tibia – PT, middle tibia – MT, distal tibia – DT). The smartphone was either placed on the anterior leg (blue rectangle) or on the side of the leg (yellow rectangle).

Table 1

Sum of squares results from the analysis of the ANOVA study design

Variable[1]	Df[2]	Sum of Squares	P-value
Method	4	16,425	<0.001
Position	2	189,541	<0.001
Leg	1	42,585	<0.001
Experience	2	77	0.272
Method*Position	8	420	0.079
Method*Leg	4	1059	<0.001
Method*Experience	8	140	0.784
Position*Leg	2	216	0.027
Position* Experience	4	127	0.368
Leg*Experience	2	305	0.006
Method*Position*Leg	8	90	0.932
Method*Position* Experience	16	463	0.480
Method*Leg*Experience	8	199	0.567
Position*Leg*Experience	4	426	0.007
Method*Position*Leg*Experience	16	272	0.902
Residuals	510	15,080	

[1]Method refers to the measurement method, position refers to the three variations of leg position (angle), leg refers to the type of leg (small versus large), and experience refers to the surgeon’s level of experience.

[2]Df is the degrees of freedom.

Table 2

Confidence intervals on the differences between measurement devices using Tukey's procedure with a family-wise alpha-level of 0.05.

Comparison[1]	**Difference**	**Confidence Interval**[2]	**Adjusted P-value**[3]
IpSL - Goni	0.82	(−1.10, 2.75)	0.766
IpTL - Goni	−1.03	(−2.96, 0.89)	0.581
Radi - Goni	−12.49	(−14.41, −10.57)	< 0.001
Visu – Goni	1.75	(−0.17, 3.67)	0.094
IpTL – IpSL	−1.86	(−3.78, 0.06)	0.063
Radi – IpSL	−13.31	(−15.24, −11.39)	< 0.001
Visu – IpSL	0.93	(−1.00, 2.85)	0.680
Radi – IpTL	−11.46	(−13.38, −9.54)	< 0.001
Visu – IpTL	2.78	(0.86, 4.71)	0.001
Visu – Radi	14.24	(12.32, 16.16)	< 0.001

[1]IpSL = iPhone side of leg, Goni = goniometer, IpTL = iPhone top of leg, Radi = radiographic, Visu = visual.

[2]The confidence intervals are adjusted to maintain the family-wise alpha level.

Table 3

Confidence intervals on the differences between measurement devices on the small leg using Tukey's procedure with a family-wise alpha-level of 0.05.

Comparison[1]	Difference	Confidence Interval[2]	Adjusted P-value[3]
IpSL - Goni	−1.49	(−4.02,1.04)	0.488
IpTL - Goni	−1.74	(−4.27, 0.80)	0.329
Radi - Goni	−10.47	(−13.01, −7.94)	< 0.001
Visu – Goni	1.81	(−0.73, 4.34)	0.289
IpTL – IpSL	−0.25	(−2.78, 2.29)	0.999
Radi – IpSL	−8.98	(−11.52, −6.45)	< 0.001
Visu – IpSL	3.30	(0.76, 5.83)	0.003
Radi – IpTL	−8.74	(−11.27, −6.20)	< 0.001
Visu – IpTL	3.54	(1.01, 6.08)	0.001
Visu – Radi	12.28	(9.74, 14.81)	< 0.001

[1] IpSL = iPhone side of leg, Goni = goniometer, IpTL = iPhone top of leg, Radi = radiographic, Visu = visual.

[2] The confidence intervals are adjusted to maintain the family-wise alpha level.

Table 4

Confidence intervals on the differences between measurement devices on the large leg using Tukey's procedure with a family-wise alpha-level of 0.05.

Comparison[1]	Difference	Confidence Interval[2]	Adjusted P-value[3]
IpSL - Goni	2.92	(0.05, 5.79)	0.043
IpTL - Goni	−0.40	(−3.26, 2.47)	0.996
Radi - Goni	−14.32	(−17.18, −11.45)	< 0.001
Visu – Goni	1.70	(−1.17, 4.57)	0.482
IpTL – IpSL	−3.32	(−6.18, −0.45)	0.014
Radi – IpSL	−17.24	(−20.10, −14.37)	< 0.001
Visu – IpSL	−1.22	(−4.09, 1.64)	0.769
Radi – IpTL	−13.92	(−16.79, −11.05)	< 0.001
Visu – IpTL	2.10	(−0.77, 4.96)	0.266
Visu – Radi	16.01	(13.14, 18.88)	< 0.001

[1] IpSL = iPhone side of leg, Goni = goniometer, IpTL = iPhone top of leg, Radi = radiographic, Visu = visual.

[2] The confidence intervals are adjusted to maintain the family-wise alpha level.