Original Contribution

A NOVEL SONOGRAPHIC METHOD OF MEASURING PATELLAR TENDON LENGTH

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Abstract—Obtaining accurate and readily repeatable measurements is a prerequisite for using measures of soft tissue structures both clinically and in the research setting. Few studies have evaluated the interrater reliability of ultrasound measurements of tendons. The objective of this study was to determine the accuracy and reliability of a new method of sonographic measurement of patellar tendon length using direct dissection as the gold standard. Four cadaveric knees were sonographically evaluated by two independent investigators. Two custom designed straps with nylon strapping and stainless steel wire were used to firmly mark position on the leg and create an acoustic shadow on the ultrasound image. Anatomic landmarks were the distal patellar pole and the bony ridge on the anterior proximal tibia. After sonographic evaluation, the knee was dissected to expose the patellar tendon, which was measured using digital calipers. Intraclass correlation coefficients (ICC) were used to determine reliability of measurements between observers, where ICC > 0.75 was considered good and > 0.9 was considered excellent. Validity was measured using a Bland-Altman plot, which measures bias between measurement methods as well as variability of scatter. Three sonographic measurements were made by each investigator on each tendon. The length of each of the four tendons based on the mean values of sonographic measurements was 53.8 mm, 53.4 mm, 49.4 mm and 46.8 mm. The length based on visual inspection of the dissected tissue was 54.6 mm, 52.8 mm, 49.8 mm and 46.9 mm. The calculated ICC between raters was 0.96. On the Bland-Altman plot, the bias, or mean difference between sonographic and visual measures, was 0.17 mm, with a standard deviation of 0.71. The 95% limit of agreement was ±1.55 to ±1.22 mm. Measurement of patellar tendon length with ultrasound using adjustable surface markers and calipers is highly accurate and has good interrater reliability. (E-mail: gellhorn@uw.edu) © 2012 World Federation for Ultrasound in Medicine & Biology.

Key Words: Tendon, Tendinopathy, Measurement, Ultrasound, Interrater reliability, Patellar, Patella alta, Infera, Baja.

INTRODUCTION

High resolution sonography is an imaging modality well suited to evaluation of superficial soft tissue structures, with advantages including high axial resolution, wide availability, relatively low cost, relatively short time to conduct the test, real-time image capture, lack of ionizing radiation and capacity to image tissues dynamically. As a typical ultrasound transducer will have an axial resolving power of between 0.04 and 0.2 mm (Grassi and Cervini 1998; Maganaris 2005), this high spatial resolution theoretically makes it ideally suited for the calculation of physical dimensions of soft tissue structures such as tendon length and width. However, the absence of standardized protocols and the operator dependence of scanning technique have limited the wide adoption of ultrasound for this use.

The physical measurements of the patellar tendon are important in both the clinical and research settings. The importance of patellar tendon width and cross-sectional area has been established as an important marker of patellar tendinopathy and ultrasound is well suited to measure this (Davies et al. 1991). The length of the patellar tendon is also important clinically: it is the basis for the diagnosis of both patella alta and patella infera (Lancourt and Cristini 1975) and is also considered an important factor in patellar instability (Neyret 2002). In its use as a graft for anterior cruciate ligament (ACL) reconstruction, the patellar tendon’s length may be an
important determinant of graft suitability, depending on the surgical approach. In a research context, the patellar tendon length is critical for accurate measurement of tendon strain, which is defined as the relative longitudinal deformation of a tendon under an applied load.

Obtaining accurate and readily repeatable measurements is a prerequisite for using measures of soft tissue structures both clinically and in the research setting. Few studies have evaluated the accuracy, inter- and intrarater reliability of ultrasound measurements of tendons. One study evaluating the in vivo measurement of cross-sectional tendon size demonstrated significant variation between observers when assessing a number of tendon measurements (O'Connor et al. 2004). This lack of inter- and intrarater reliability may be due to a number of factors, including operator experience, non-standardized imaging protocols and transducer positioning relative to the tendon under study. Compared with cross-sectional measurements, sonographic calculation of tendon length presents a different type of challenge due to the limited field of view on most ultrasound transducers. While measuring the length of a tendon would be relatively straightforward if the entire tendon could be visualized in a single image, the length of many tendons exceeds the length of the transducer. Therefore, visualization of the entire length of the tendon is often impossible with standard transducers.

Two methods have been proposed to overcome this difficulty and allow measurement of tendon length but neither has been validated with comparison to surgical or cadaveric measurements of the tendon. The first method utilizes extended field of view (EFOV) imaging, which enables generation of images of tendon length when the tendon is longer than the transducer (Pang and Ying 2006). This method relies on specialized software that combines overlapping images to produce a panoramic image, utilizing probe motion estimates; the image is created as the probe is swept manually across a length of the surface skin. Although this method has been evaluated in sonographic imaging phantoms (Weng et al. 1997; Fornage et al. 2000) and dissected animal tissue (Noorkoiv et al. 2010), to our knowledge, no studies of accuracy and reliability have been performed on human tendons. In imaging phantoms, the EFOV technique has been reported to have relative errors of 4% to 5%, which may be unacceptably high for some clinical and research applications. The second method of sonographically measuring tendon length utilizes surface markers, which correspond to the proximal and distal ends of the tendon and which can then be measured manually. The surface markers are usually strands of wire or needles, either manually stabilized or glued to the skin. While these methods have been used to measure tendon displacement in a number of biomechanical studies (Arya and Kulig 2010), the validity of the measurements has been questioned based on substantial movements of the skin markers, with some investigators finding that these methods may introduce measurement error of as much as 35% (Maganaris 2005). In addition to problems with accuracy, gluing markers to the skin may not be practical in many clinical settings where such measurements may be desired.

Our present study investigated a novel method of calculating tendon length using easily adjustable surface tissue markers and calipers. Cadaveric dissection was used as the measurement gold standard. Our primary hypothesis was that measured tendon lengths, as obtained with this technique, have a high level of accuracy compared with cadaveric dissection. Our secondary hypothesis was that these measurements have a high level of interrater reliability.

**MATERIALS AND METHODS**

To test the validity of our patellar tendon length measurement protocol, the patellar tendons from four embalmed cadaver knees were evaluated, first with ultrasound and then by direct dissection. The patellar tendon was chosen for a number of reasons: it is easily accessible, its measurements are important clinically in patellar instability, patella alta and patella infera and it may be useful in screening for graft suitability for ACL replacement. To test interrater reliability, two independent examiners, who were blinded to each other’s results, measured the length of each patellar tendon three times with ultrasound prior to dissection. Institutional review board approval was obtained for all procedures.

Knees were evaluated in 30 degrees of flexion. A Bi-osound MyLab Gold™ ultrasound machine (Esaote, Genoa, Italy) with a 10–18 MHz linear array transducer with a footprint of 40 mm was used for all sonographic imaging. For all images obtained, care was taken to keep the transducer positioned perpendicular to the plane of the patellar tendon. Two custom designed straps with Velcro® closure and 16 gauge stainless steel wire (Fig. 1) were used to firmly mark position on the overlying skin of the leg. Each strap was constructed using two steel D-rings through which nylon strapping was passed; the strap was secured to the flat edge of one ring and could be freely adjusted around the flat edge of the other. Wire was attached securely to the rounded edge of the D-rings. Using this system, the wire could be placed over the anatomic region-of-interest and freely adjusted and secured with a minimum of effort and time using the nylon straps. This system differs from prior studies employing acoustic shadow artifact for measurement, which have either used freehand markers or markers that are glued to the skin (Maganaris 2005;
Anatomic considerations

Repeatability of measurements required determining anatomic landmarks for marking the proximal and distal extent of the tendon. For the patellar tendon, the distal whole nonarticular lower border of the patella in the midline was designated the proximal landmark; preliminary evaluation prior to initiation of the study had suggested that this landmark was robust and easily locatable in different subjects. The distal patellar apex is well visualized with ultrasound as a hyperechoic structure with posterior acoustic shadowing (Fig. 2). The junction between this point and the tendon was considered to mark the proximal patellar tendon. The distal landmark of the patellar tendon was determined to be the bony ridge on the anterior, proximal tibia at the level of the epiphysis, which is at the uppermost aspect of the tibial tuberosity. This is the location where the deepest fibers of the patellar tendon insert (Fig. 3). This ridge is well visualized on ultrasound imaging and also with visual inspection after dissection.

To ensure that measurements were made along the long axis of the tendon, a mark was made in the middle of the patella at its widest point, as well as over the tibial tubercle, and these two points were connected in a straight line, using a flexible straight edge and a skin-marking pen. This line reflected the directional orientation of the underlying patellar tendon, and all subsequent images were made with the transducer aligned along this line.

External skin markers

The portion of the custom designed straps with steel wire were positioned over the anatomic regions of interest and the ultrasound transducer was placed superficial to the wire, using Aquasonic 100 ultrasound transmission gel (Parker Laboratories, Fairfield, NJ, USA) to maximize acoustic coupling. Posterior acoustic shadowing artifact created by the wire was used to adjust each strap to the particular position desired, corresponding to the proximal and distal extent of the tendon (Figs. 4 and 5). Once the acoustic shadow appeared in the ultrasound image at the anatomic site of interest, the strap was tightened to affix the strap securely in place. When both markers had been affixed in position, a digital caliper (Hardwick’s Tools and Hardware, Seattle, WA, USA) was used to measure the distance between the two steel wires along the surface of the skin. Three independent measurements of tendon length were made by each investigator (A.G. and D.M.) using this method, to determine interrater reliability of measurement.
Anatomic dissection

Once the tendon length had been measured, the knee was dissected to expose the patellar tendon (Fig. 6). The proximal tendon was physically marked by inserting a 25 gauge needle into the tendon, beginning approximately 5 mm proximal to the distal pole and slowly marching the needle distally until the needle no longer contacted bone when inserted vertically through the tendon. This location was taken to correspond to the distal patellar pole visualized sonographically. Distally, the tendon was dissected down to bone at its tibial insertion and the bony ridge at the insertion was noted visually. Again using digital calipers, the distance between this bony ridge and the needle marker was measured and recorded.

Statistical analysis

All statistical calculations were performed using SPSS Version 19.0, Excel version 14.1 and R version 2.13 (SPSS, Inc., Chicago, IL, USA).

Reliability

To determine reliability of measurements between observers, the interobserver reliability was calculated using intraclass correlation coefficients (ICC) (3,1), using a two-way mixed effects model (Shrout and Fleiss 1979). An ICC value of ≥0.75 was considered good and ≥0.9 was considered excellent (Portney and Watkins 2009).

Validity

A Bland-Altman plot (Bland and Altman 1999) was constructed to graphically analyze the agreement between the sonographic method and visual method of measurement. The primary application of the Bland-Altman plot is to compare a new method of measurement with a gold standard. This method of displaying data plots the difference between measurements by the two methods for each subject against their mean. The limits of agreement are calculated during Bland-Altman analysis, which is equal to the mean difference ± 1.96 standard deviations of the difference. Based on the 95% limit of agreement, for any future measurement, the difference between measurements using these two measurement techniques will lie within the limits of agreement 95% of the time. Interpretation of a Bland-Altman plot involves determination of the discrepancy, or bias, between methods; whether this bias is large enough to be clinically important; and the degree of variability of the scatter around the bias line.

RESULTS

Each investigator made three sonographic measurements on each patellar tendon as shown in Table 1.
Reliability
In evaluation of the interrater reliability, using the three measurements of each patellar tendon made by each investigator, the calculated ICC between raters was 0.96, (95% confidence interval 0.87 to 0.99).

Validity
In evaluation of the validity of the sonographic measurements based on the Bland-Altman plot, the bias line, or mean difference between the sonographic and visual methods of measurement, was −0.17 mm, with a standard deviation of 0.71 mm (Fig. 7). The 95% limit of agreement was −1.55 to 1.22 mm. The relative error of the sonographic measurement was between 0.2% and 1.5%, with a mean relative error of 0.9%.

DISCUSSION
The present study was designed to test the validity of a novel method of measuring patellar tendon length using ultrasound equipment that is similar to equipment widely available to clinicians and researchers, as well as to evaluate the reliability of these measurements between examiners. Our results indicate a high level of agreement in the length of the patellar tendon measured using ultrasound compared with measurements from dissected patellar tendons, the gold standard for these measurements. The results also demonstrate excellent interrater reliability (ICC = 0.96) for two observers using this technique of sonographic measurement of the patellar tendon.

Clinical relevance
Patella alta, an abnormally high position of the patella relative to the knee joint, is a clinical condition often associated with anterior knee pain and instability (Ward et al. 2007). Patella infera, an abnormally low patellar position relative to the knee joint, is also clinically important, especially following total knee arthroplasty or ACL reconstruction, when it may be associated with decreased knee range of motion, anterior knee pain and poor overall outcomes (Meneghini et al. 2006). Patella alta and infera are frequently determined radiographically using the Insall-Salvati ratio, which is defined as the length of the patellar tendon divided by the length of the patella as seen on lateral radiographs (Insall and Salvati 1971). An Insall-Salvati ratio between 0.8 and 1.2 is considered normal, with a ratio >1.2 consistent with patella alta and a ratio <0.8 consistent with patella infera. Magnetic resonance imaging (MRI) has also been used to determine the Insall-Salvati ratio (Hantes et al. 2007). Although radiographic measurements are widely available, there are inherent inaccuracies related to the magnification and projections of the knee that are used (Adam et al. 2004; Hantes et al. 2007). The present study presents an alternative method to obtain a highly accurate patellar length, without exposure to ionizing radiation and with decreased cost compared with MRI.

Additional clinically relevant application for an accurate measure of patellar length may include determining graft suitability for use in ACL reconstruction. In the transtibial drilling approach used for ACL reconstruction, there is a limited ability to correct any graft-tunnel length mismatch, which increases the importance of a closely matched patellar tendon length. Depending on the surgical approach used, therefore, an accurate measure of patellar tendon length may assist in surgical planning.

In addition to its clinical utility, patellar length is important in the biomechanical determination of patellar tendon strain, which is defined as the relative longitudinal deformation of the tendon under an applied load. An accurate measure of tissue strain has a number of potential clinical and research implications, including predicting tendon rupture, measuring alterations in tendon strength and compliance in the setting of chronic tendinopathy, and evaluating biomechanical differences in pathologic and normal tendon. The patellar tendon is frequently affected by tendinopathy (“jumper’s knee”) and, therefore, represents an important clinical entity. The ability to perform

<table>
<thead>
<tr>
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<th>Sonographic length, mean ± SD (mm)</th>
<th>Sonographic length, mean ± SD (mm)</th>
<th>Direct dissection length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee 1</td>
<td>54.50 ± 0.40</td>
<td>53.09 ± 0.38</td>
<td>54.62</td>
</tr>
<tr>
<td>Knee 2</td>
<td>52.98 ± 0.56</td>
<td>53.77 ± 1.38</td>
<td>53.38</td>
</tr>
<tr>
<td>Knee 3</td>
<td>49.29 ± 0.89</td>
<td>49.59 ± 0.21</td>
<td>49.44</td>
</tr>
<tr>
<td>Knee 4</td>
<td>46.65 ± 0.63</td>
<td>46.93 ± 0.56</td>
<td>46.79</td>
</tr>
</tbody>
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Fig. 7. The Bland-Altman plot shows the mean difference between sonographic and visual measurement methods and the amount of scatter around the mean for each set of measurements. The 95% limit of agreement between the two methods was −1.55 to +1.22 mm.

Table 1. Sonographic and dissected tendon measurements

|                  | Sonographic method of measuring patellar tendon A. C. GELLHORN et al. 723 |
biomechanical evaluations in vivo is only possible if a noninvasive, reproducible and accurate system of measuring small changes in tendon length is established and validated. In fact, in the normal Achilles tendon, a strain of 4.2% has been calculated during a maximal isometric plantarflexion contraction, with a corresponding longitudinal tendon deformation of 2.2 mm (Kongsgaard et al. 2011). Given this small amount of deformation, it is clear that a highly accurate method of determining patellar tendon length is of critical importance in future studies attempting to measure these and other related biomechanical tissue properties in the normal and pathologic patellar tendon.

Measurement accuracy

The bias revealed in the Bland-Altman plot between measurement of the tendon using ultrasound and using direct dissection is likely to be insignificant in nearly all research and clinical settings. Even with the small number of subjects included in the present study, the 95% limit of agreement between techniques was minimal. This suggests that any future measurements of the patellar tendon made using this sonographic technique will fall within −1.55 and 1.22 mm of the gold standard of visual inspection of the dissected tendon.

The ultrasound equipment used in this study is similar to equipment widely used for musculoskeletal imaging in clinical settings. While specialized transducers may be fabricated with larger footprints, these are not in frequent clinical usage, due to the higher costs associated with increased number of piezoelectric arrays necessary to fabricate them. The footprint of the probe used in this study was 40 mm. Probes as long as 100 mm have been used to measure tendons that are longer than standard probes (O’Brien et al. 2010) but to our knowledge these probes are rarely used outside of the research setting. Nonetheless, if available these may represent an alternative way to measure patellar tendon length, though validation of measurements from these probes against anatomic specimens has not been reported. The advantage of the method presented here is that no specialized equipment is necessary to obtain highly accurate patellar tendon measurements.

Our results are notably different from those reported in a cadaveric study using ultrasound to measure the length of the distal biceps femoris tendon (Kellis et al. 2009). In that study, a difference of 5.9 mm was found between the sonographic measurement and the direct dissection measurement, compared with a mean difference of 0.17 mm in our study. This may be partly explained by differences in measurement technique between study designs; the method of externally marking the skin based on ultrasound images is not detailed in that study, and our use of adjustable skin markers and calipers appears to result in a much higher level of accuracy.

An alternative method of measuring tendon length is extended field of view (EFOV) imaging, which produces panoramic images using specialized software to combine overlapping images as the probe is manually swept across a length of surface skin. As mentioned above, this method has been evaluated in sonographic imaging phantoms (Fornage et al. 2000; Weng et al. 1997) where relative error rates are between 4% and 5%. No studies of accuracy and reliability using EFOV have been performed on human tendons to our knowledge, which limits the use of this imaging technology clinically if high levels of accuracy are required. Our relative error rate of 0.9% is superior to the relative error rate reported for EFOV in phantoms. The major applications of EFOV may include showing spatial relationships between anatomic structures and communicating findings to colleagues (Lin et al. 1999).

Another emerging technology that may have an application in the measurement of tendons is three-dimensional ultrasound (3-D US). Although this technology requires a specialized probe and additional postprocessing, 3-D US has demonstrated promising results with accurate and reproducible measures of large muscle volumes such as the medial gastrocnemius (Barber et al. 2009). Using this technique, errors in length measurements for this large muscle were approximately 2%, although error rates for smaller structures such as hand muscles have been found to be as high as 10% (Delcker 1999), which may be unacceptable depending on the context and the structure being measured.

Reliability of ultrasound measurement between observers

The reliability of quantitative ultrasound measurements has been a subject of some disagreement and ultrasound is frequently described as an operator dependent imaging modality (Wakefield et al. 2005). Few studies exist evaluating intraobserver, interobserver and intermachine reliability measurements with respect to physical tendon measurements. Due to the ease of imaging tendons in cross-section, most prior studies evaluating reliability have focused on measurement of tendon cross-sectional area or width. Probe positioning and angle of transducer orientation are a source of variability when obtaining images; small positioning deviations may result in imaging significantly different anatomic planes and few well established anatomical reference points exists around which to base tendon measurements. O’Connor evaluated cross-sectional areas of six tendons and found a statistically significant difference between two raters in five out of 12 measurements, concluding that a single observer
should be used in longitudinal studies, to minimize inter-observer variation (O’Connor et al. 2004). In another study, interrater reliability of biceps and supraspinatus thickness was reported to be good when using a standardized protocol but only moderate for other quantitative measures such as echogenicity (Collinger et al. 2009). Interestingly, a high level of interrater reliability has been reported when measuring the cross-sectional area of the median nerve at the level of the distal radius (dependability coefficient $\phi = 0.93$, where $>0.75$ signifies good reliability) but only moderate ($\phi = 0.63$) at the level of the hamate and poor ($\phi = 0.33$) at the level of the pisiform (Impink et al. 2010). These results highlight the importance of protocol designs in ultrasound imaging and suggest that measures of the same anatomical structure may have higher levels of interrater reliability when measured in reference to particular anatomic markers.

This is the first study to our knowledge that has assessed interrater reliability in ultrasound measurements of tendon length. By using a consistent protocol with well-defined anatomical landmarks, we were able to achieve a high level of interrater reliability.

**Limitations**

The main limitation to the study is its small sample size, with only four patellar tendons. Two main potential sources of error exist in this type of study design: first is the inaccuracy of individual measurements by each examiner and second is inaccuracy in approximating the true tendon length. However, even with this small sample size, both of these sources of error can be accounted for. Regarding the inaccuracy of individual measurements, the standard deviation of each measurement is presented in Table 1, with values between 0.2 and 1.4 mm. We believe these are acceptably low rates of error. The second potential source of error is in approximating true tendon length and the potential problems with repeatability in the setting of a small N. To test a new measurement technique, to our knowledge, the most appropriate statistical method is the Bland Altman plot, with analysis of the 95% limit of agreement. This method takes into account the overall N such that measurements that have low repeatability will result in a high value for the 95% limit of agreement. The 95% limit of agreement includes calculation of the standard deviation of the differences, which in turn relies on the number of samples included in the calculation. Given a 95% limit of agreement between $-1.5$ and $+1.2$ mm, we believe this is an acceptable level for our purposes. A larger study sample would increase the confidence of our calculated accuracy.

Additionally, this study does not directly compare our measurement technique with alternate measurement techniques such as EFOV imaging. However, the relative measurement errors for EFOV using phantoms have been found to be significantly higher than the relative errors found with the present technique and would likely be similar or more pronounced if used in an *in vivo* or cadaveric setting rather than in idealized tissue phantoms. Nonetheless, a future study may be helpful to directly compare the accuracy of the two techniques.

**CONCLUSIONS**

These study findings suggest that measurement of patellar tendon length with ultrasound using adjustable surface markers and calipers is both highly accurate and has excellent interrater reliability, when following a specific protocol. These results have positive implications for the reliable and accurate measurement of clinical and biomechanical properties of the patellar tendon in the future.

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