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A Hybrid Method for Computing Achilles Tendon Moment Arm Using Ultrasound and Motion Analysis

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Abstract

In this article, we outline a method for computing Achilles tendon moment arm. The moment arm is computed from data collected using two reliable measurement instruments: ultrasound and video-based motion capture. Ultrasound is used to measure the perpendicular distance from the surface of the skin to the midline of the tendon. Motion capture is used to determine the perpendicular distance from the bottom of the probe to the ankle joint center. The difference between these two measures is the Achilles tendon moment arm. Unlike other methods, which require an angular change in joint position to approximate the moment arm, the hybrid method can be used to compute the moment arm directly at a specific joint angle. As a result, the hybrid method involves fewer error-prone measurements and the moment arm can be computed at the limits of the joint range of motion. The method is easy to implement and uses modalities that are less costly and more accessible than MRI. Preliminary testing using a lamb shank as a surrogate for a human ankle revealed good accuracy (3.3% error). We believe the hybrid method outlined here can be used to measure subject-specific moment arms in vivo and thus will potentially benefit research projects investigating ankle mechanics.

Keywords

tendon excursion; center of rotation; lever arm; ankle joint; line of action

Developing accurate estimates for muscle-tendon parameters is important for use in biomechanical studies. The muscle moment arm is one such parameter transforming the force developed by a muscle into a moment about a joint. Current methods for estimating muscle-tendon moment arm (MA) include the tendon excursion method (An et al., 1984) and the center-of-rotation method (Rugg et al., 1990), the latter of which is based on the method of Reuleaux (1875). These methods have been adapted for in vitro and in vivo MA studies of the lower extremity (Rugg et al., 1990; Spoor et al., 1990; Ito et al., 2000; Maganaris et al., 2000, 2004; Lee & Piazza, 2008).

The tendon excursion method is based on the principle of virtual work, which relates tendon excursion and the angular change in joint position. This requires two measurements of tendon length for each moment arm that is computed. Similarly, the center-of-rotation method requires multiple image-based geometric measurements to determine the moment arm at a specific joint angle. Although in theory the angular change should be small to approximate the instantaneous moment arm, in practice, however, large displacements are generally used to overcome the influence of measurement error on the resulting moment arm. For example, Maganaris and colleagues used a 15-degree angular change in joint position when approximating the Achilles tendon moment arm using the tendon excursion method, and a 30-degree change when using the center-of-rotation method (Maganaris et al., 2000). In doing so, the moment arm is more representative of an average value rather than a specific value at particular joint angle. An obvious limitation of using a large angular change

is that it is not possible to determine the moment arm at the limits of a joint's range of motion. This is particularly relevant at the ankle since plantar flexion strength is greatest when the ankle is dorsiflexed (Sale et al., 1982; Orishimo et al., 2008).

In this paper we present a hybrid method for computing the Achilles tendon moment arm. The hybrid method uses two reliable measurement instruments: ultrasound and video-based motion analysis. The method requires fewer error-prone measurements than tendon excursion and center of rotation, and the moment arm can be determined directly at any angle, even at the limits of the ankle range of motion. In addition, the use of ultrasound is less costly, time consuming, and more readily available than magnetic resonance imaging and consequently it has the potential to be a useful tool for those investigating ankle mechanics and tendon function in vivo. The hybrid method was tested using a lamb shank, and the results of validation trials are presented.

Methods

Overview

Briefly described, the hybrid method uses ultrasound to determine the distance from the surface of the skin to the midline of the tendon. Retro-reflective markers are placed on the transducer so that its position is known relative to a fixed inertial reference. Retro-reflective markers are also placed over the medial and lateral malleoli. The ankle joint center is defined as the midpoint between the malleoli markers, and it is also known in the same reference as the position and orientation of the transducer. The algorithm then resolves the perpendicular distance from the midline of the tendon to the ankle joint center (i.e., the moment arm). This is depicted schematically in Figure 1. Each step involved in determining the moment arm will be described in sections to follow. Specifics pertaining to the ultrasound and motion analysis methods are intended as guidelines only, with actual sampling and processing methods determined by the individual laboratory.

Ultrasound

Real-time, B-mode ultrasound images in our laboratory are sampled using a 60-mm linear transducer at a scanning frequency of 10 MHz (Aloka SSD-5000, Tokyo, Japan). Two retro-reflective markers are placed on the top of the probe and positioned to coincide with the scanning limits of the transducer (see Figure 2). The transducer is aligned with the line of action of the Achilles tendon and placed directly over the ankle joint center. It is important that the markers on the probe markers are on either side of the joint (i.e., proximal and distal) when the image is recorded. Although the joint center is not visible on the ultrasound image, spanning the joint in this manner ensures it will be between the left and right edges of the sonogram. Images are saved in DICOM format and postprocessed as described later. It is necessary to establish a temporal correspondence between the sonogram and the motion capture data. This can be done by taping a pressure-sensitive contact switch to the image acquisition button on the ultrasound console. Pressing the save button generates a 5-V square wave that is sampled by an A/D board synchronized with the motion capture system. The leading edge of the square wave is used to synchronize the ultrasound and motion capture data.

Video-Based Motion Capture

Retro-reflective markers are attached to the ultrasound probe and over the malleoli. The midpoint between the markers over the malleoli is used to approximate the ankle joint center. The markers attached to the ultrasound probe are used to track its position in the same reference frame as the ankle joint center. In our laboratory we sample the marker trajectories and analog contact switch data at the same rate (i.e., 30 Hz) for convenience of

synchronization. Marker trajectories are filtered using a fourth-order phase-lag corrected Butterworth digital filter with a cutoff frequency of 6 Hz. The analog frame corresponding to the onset of the 5-V square wave is used to identify the precise video frame the ultrasound image is saved. Marker coordinates corresponding to this frame are extracted and used for further analysis.

Moment Arm Determination

The position of the ankle joint center in a fixed inertial reference was determined from markers on the malleoli. The perpendicular distance from the ankle joint center to the line formed by the markers on the probe is then computed. Identifying where this intersection lies along the line connecting the probe markers is an important step in the method. Recall that the markers were placed on the probe so they coincided with left and right edges of the sonogram. The distance measurement tool on the ultrasound console is used to move the cursor along the top edge of the sonogram to the point of intersection. The joint center, although not visible on the ultrasound image, lies beneath this point at a depth determined from the markers on the probe and over the malleoli. This distance is labeled P on Figure 1. The distance from the top of the sonogram to the midline of the tendon directly below the point of intersection is measured using the ultrasound console measurement tool and is labeled T in Figure 1. The distance from the line formed by the markers on the top of the probe and the recording surface is the constant value, C , (see Figure 1). The moment arm can then be calculated per Equation 1:

$$MA = P - C - T \quad (1)$$

Note that use of a gel standoff pad will create a void at the top of the ultrasound image as seen in Figure 2. This does not affect the moment arm calculation since the added height is accounted for when measuring the distance from the bottom of the probe to the midline of the tendon (i.e., distance T in Figure 1).

Validation Experiment

The hybrid method was tested using an animal model. A lamb shank was chosen because it has a superficial Achilles tendon and the intermalleolar distance is similar to that of a human. The lamb shank was fixed in a jig exposing the posterior of the leg for ease of ultrasound imaging. Markers were placed over the medial and lateral malleoli and on the scanning limits of the ultrasound probe. A gel standoff pad was used to improve acoustic coupling. B-mode ultrasound images of the tendon were recorded at 10 MHz using a 60-mm linear transducer (Aloka SSD-5000, Tokyo, Japan). A six-camera motion analysis system (Qualisys ProReflex, Gothenburg, Sweden) was used to capture the spatial location of markers on the probe and over the malleoli. The Achilles tendon moment arm was computed as described in the preceding sections. A total of five trials were collected and the average value, referred to as MA_{hybrid} , was used for analysis.

An additional set of trials was collected using only the motion capture system. The markers on a digitizing pointer were used to identify a point along the midline of the tendon that was proximal to the joint center. A point distal to the joint center was also digitized (Figure 3). A line connecting the proximal and distal digitized points was used to define the tendon midline. The perpendicular distance from the midline to the ankle joint center was computed and was defined as the measured moment arm, MA_{measured} . The process was repeated and an average MA_{measured} was calculated. The MA_{hybrid} and MA_{measured} were compared with assess the accuracy of the hybrid method. Inherent in this approach was the assumption that MA_{measured} was an accurate estimation of the Achilles tendon moment arm.

Results

The moment arm computed by digitizing the midline of the tendon (i.e., MA_{measured}) was 38.8 ± 0.05 mm. Moment arm estimates were highly repeatable as indicated by the small standard deviation associated with these measures. The moment arm computed using the hybrid method had an average value of 37.5 ± 0.5 mm, also with good repeatability. The MA_{hybrid} and MA_{measured} estimates were in close agreement, with only a 3.3% difference between the two measures. Computing the moment arm using the hybrid method is a simple matter requiring no more than a couple of minutes. This is in stark contrast to methods that use magnetic resonance imaging to estimate the moment arm, thus requiring the significant image processing and high expense associated with scanning the subject.

Discussion

The purpose of this article was to outline a new technique for computing Achilles tendon moment arms. The hybrid method was designed specifically to overcome limitations of existing methods. Namely, the hybrid approach requires fewer error-prone measurements and the moment arm can be measured directly at the joint angle of interest, even at the limits of the ankle's range of motion. In addition, the method is easy to implement and the choice of joint center can be specified according to modeling practices used by a particular laboratory. For example, in our laboratory we define the ankle joint center to lie at the midpoint between markers over the malleoli. Other laboratories may define the joint center differently (e.g., functionally based). The advantage of a user-defined joint center is that moment arms computed using the hybrid method will be consistent with the anatomical reference frame used during gait analysis.

One limitation of the hybrid method is that incorrectly placing the markers over the malleoli will directly affect the moment arm estimate. For example, if the markers are placed anterior to the apex of the medial and/or lateral malleoli, the moment arm will be overestimated. Likewise, if positioned posteriorly, the moment arm will be underestimated. Care must be taken when placing the malleoli markers to avoid such errors. This is also true of typical gait analyses and a well-recognized consideration during such studies. Another potential source of error is the subjective nature, in which the tendon midline is identified. We believe this error is small, however, given that the Achilles tendon is only approximately 5 mm thick (Pang & Ying, 2006; Du et al., 2007). Thus, even if the midline is misidentified by 20%, the resulting error on the estimated moment arm would only be approximately 1 mm.

The purposes of this article were twofold. Firstly, we outlined a new approach for measuring Achilles tendon moment arm. The method was designed to circumvent limitations of existing methods and uses common laboratory instruments (i.e., ultrasound and motion analysis). The second goal was to evaluate the accuracy of the hybrid method using a lamb shank as a surrogate for a human ankle. Excellent agreement was noted during the validation experiment (i.e., 3.3% difference). Although we recognize that this was for a single specimen and at one joint angle, it is nonetheless a promising result for the in vivo application of the method in human subjects. Applying the hybrid method for the estimation of Achilles tendon moment arms in vivo throughout the ankle range of motion at rest and during maximal isometric voluntary contractions will be the focus of future work.

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Sagittal plane schematic of a hybrid method for computing Achilles tendon moment arm. MA = moment arm, C = constant distance from line between markers on probe to recording surface of the ultrasound transducer, P = perpendicular distance from line between markers on probe and ankle joint center approximated from markers over the malleoli, T = distance from bottom of transducer to tendon midline. Gel pad to improve acoustic coupling.

Figure 2.

Sonogram of the lamb Achilles tendon used during testing. The markers on the ultrasound probe were positioned to correspond with the scanning limits of the transducer. The dark space beneath the outline of the transducer is the acoustically inert gel pad used for coupling. The Achilles tendon is located below the dark space and appears on the image as a uniformly striated echo.

Figure 3. Lamb shank used for hybrid method testing. Note the gel pad beneath the ultrasound transducer. Markers attached to the digitizing wand were used to define the midline of the tendon (see text). Similarly, the midline of the tendon was determined from the sonogram as depicted in Figure 1.