Rectus Femoris Knee Muscle Moment Arms Measured *in Vivo* During Dynamic Motion With Real-Time Magnetic Resonance Imaging

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Moment arms represent a muscle's ability to generate a moment about a joint for a given muscle force. The goal of this study was to develop a method to measure muscle moment arms in vivo over a large range of motion using real-time magnetic resonance (MR) imaging. Rectus femoris muscle-tendon lengths and knee joint angles of healthy subjects ($N=4$) were measured during dynamic knee joint flexion and extension in a large-bore magnetic resonance imaging (MRI) scanner. Muscle-tendon moment arms were determined at the knee using the tendon-excursion method by differentiating measured muscle-tendon length with respect to joint angle. Rectus femoris moment arms were averaged across a group of healthy subjects and were found to vary similarly during knee joint flexion (mean: 3.0 (SD 0.5) cm, maximum: 3.5 cm) and extension (mean: 2.8 (SD 0.4) cm, maximum: 3.6 cm). These moment arms compare favorably with previously published dynamic tendon-excursion measurements in cadaveric specimens but were relatively smaller than moment arms from center-of-rotation studies. The method presented here provides a new approach to measure muscle-tendon moment arms in vivo and has the potential to be a powerful resource for characterizing musculoskeletal geometry during dynamic joint motion. [DOI: 10.1115/1.4023523]

Keywords: quadriceps, joint motion, magnetic resonance imaging, musculoskeletal geometry, real-time measurement

Introduction

Accurate descriptions of muscle-tendon moment arms are needed to characterize musculoskeletal function, because moment arms represent a muscle's ability to produce a joint moment for a given muscle force. Assessment of muscle moment arms has historically been by study of cadaveric specimens [1–6]. While cadaveric studies have provided a means to measure *ex vivo* moment arms and serve as a valuable resource for input into musculoskeletal models, they lack the ability to study active muscle contraction during dynamic motion and make interpretation with respect to *in vivo* conditions difficult or impossible.

Recent advances in ultrasound and magnetic resonance (MR) imaging have permitted *in vivo* assessment of moment arms for muscles crossing various joints, including the ankle [7], knee [8], and shoulder [9]. Ultrasound studies generally utilize the tendon-excursion method and track only the musculotendon junction during passive joint rotation [10], though this methodology lacks the ability to account for tendon stretch due to active muscle contraction [11]. Static MR studies are able to determine muscle-tendon moment arms with the tendon-excursion method or by directly measuring the distance between a line of action and a joint axis of rotation [12]; however, results from static measurement techniques are not necessarily representative of musculoskeletal geometry during dynamic joint motion. In particular, static measurements would not take into account the effects of muscle activation on moment arms and any dynamic effects of joint motion. For previous dynamic MR studies, range of motion inside the scanner has remained a limiting factor, and the cine MRI sequences used require many precise repetitions inside the scanner bore [13].

The goal of this study was to develop a method to measure muscle moment arms *in vivo* during dynamic activity, over a large range of motion, and without the need for precise repetitions in the MR scanner, which has not been accomplished by any previous study to our knowledge. The approach makes use of recent advances in real-time MRI and the advent of large-bore MRI scanners to measure moment arms with the tendon-excursion method. In contrast to previous studies that utilized the tendon-excursion method, the current study measures the length of the muscle belly and the distal tendon; therefore, the work associated with the length change in the muscle and distal tendon was accounted for in a combined musculotendon length measurement. To investigate the tractability of this approach, we measured muscle-tendon moment arms for the rectus femoris muscle during knee motion.

Methods

Four healthy female subjects (age: 32 (SD 13) years, height: 161 (SD 4) cm) provided informed consent and were scanned in accordance with the National Institutes of Health's Institutional Review Board guidelines. All subjects were free of lower extremity joint pain and chronic conditions that would affect knee joint motion.

Subjects were placed in the left lateral position in a 1.5-T Siemens Espree MR scanner (Siemens Medical Solutions, Erlangen, Germany) in a position that permitted the maximum knee joint angle range of motion inside the 70-cm diameter scanner bore (Fig. 1). Knee flexion-extension motions were performed at a self-guided comfortable rate of approximately one-half cycle (flexion or extension) every 3 seconds. The series with the highest image quality, the least imaging artifact, and the largest range of motion was analyzed. Range of motion and speed were 85 (SD 13) deg and 10 (SD 2) cycles min^{-1} , respectively, averaged across all subjects. A platform was placed underneath the subject's leg to maintain the flexion-extension motion in the sagittal imaging plane. In addition, an ankle brace was placed on the foot such that a rope and pulley system raised and lowered a small weight (1.1 kg) during flexion and extension, respectively.

A sagittal imaging plane was defined through the rectus femoris muscle, patella, patellar tendon, and patellar tendon insertion on the tibia. Images were acquired continuously during flexion and extension with a real-time spoiled gradient-recalled echo sequence with the following parameters: $400 \times 300 \text{ mm}^2$ field-of-view, 256×104 imaging matrix (reconstructed to 256×192), 7-mm slice thickness, 331 ms per frame, TR/TE 3.18/1.4 ms, and flip angle 8 deg. Prior to analysis, planar motion was verified by inspection of each sagittal image series. In an additional acquisition, real-time images were acquired in an orthogonal transverse imaging plane in the middle of the rectus femoris muscle to verify minimal through plane motion. The rectus femoris muscle was outlined on all transverse images, and the location of the muscle segmentation's centroid was used to assess medial-lateral displacement. Maximal medial-lateral displacement of the center of the rectus femoris muscle was found to be 1.1 (SD 0.4) cm (averaged across all subjects), which was less than one-third of the average muscle width (3.8 (SD 0.8) cm). The amount of medial-lateral displacement relative to the width of the muscle suggests that the muscle-tendon stayed within the sagittal plane image, such that measurement will not be biased by through-plane motion and an accurate measurement of muscle-tendon length can be made on each image.

Moment arms were determined via the principle of virtual work and the tendon-excursion method [14], where moment arm is defined as the change in muscle-tendon length (L) with respect to joint angle (θ), or $\partial L / \partial \theta$. Knee flexion angle and length measurements were collected by manually digitizing the axes of the femur and tibia bones and the centerline of the muscle-tendon unit (Fig. 2(a)). Angle and length measurements were acquired with image analysis software OsiriX [15]. The axes of the femur and tibia bones were identified by drawing a line parallel the long axis

of each bone. For the tibia, the line was perpendicular to the tibial plateau and parallel to the shaft. Due to restriction in the field-of-view, the distal portion of the tibia was not visible in the sagittal imaging plane; as such, the line for the tibia axis was drawn parallel to the shaft of the tibia that was visible in the imaging plane. The shaft of the tibia bone was present in all images. Furthermore, the origin of the rectus femoris' proximal tendon on the anterior inferior iliac spine in the hip was not visible in all images. The muscle-tendon unit length was measured from the insertion site on the tibial tubercle, along the patellar tendon, and to the most superior point (in the muscle or proximal tendon) that was visible in all images. This point was identified initially by visual inspection of all images. To verify the point as the most superior, a line was drawn across the muscle at the point and copied to all images. To assess measurement precision, angle and length measurements were repeated by the same observer, and the change in knee joint angle and the change muscle-tendon length were averaged over an entire series of images. Any length or angle change measurements that were below these precision values (2.5 deg and 1.3 mm) were neglected in the analysis. On average, 1.3 images (11%) were removed per flexion or extension cycle. These cases occurred at the beginning and end of the motion cycle, when there was very little movement.

Measured length versus knee flexion angle relationships were fit with a third order polynomial (Fig. 2(b)), which was then differentiated to determine moment arms over the subject's entire range of motion (Fig. 2(c)). The third order polynomial was found to fit the measurements adequately (all fits had $R^2 > 0.95$). A polynomial fit was used to avoid potential issues from numerical differentiation of noise in muscle-tendon length and angle measurements. Moment arms were averaged at each angle and reported over the angle range achieved by all subjects (40–107 deg), though it should be noted that individual subjects were able to achieve a greater range-of-motion in the large-bore MR scanner. Moment arms were not normalized due to the small variation in subject heights (161 (SD 4) cm) and the female-only subject population. Moment arm measurement repeatability was assessed by comparing moment arms' mean and maximum across the same group of subjects as determined by two independent observers. In addition, a fourth order polynomial fit was used to assess the dependence of moment arms on the order of the polynomial fit, and no larger than a 4% difference was found for average or maximum moment arm.

A paired t-test was used to test for significant differences between moment arms during flexion and moment arms during extension. A difference was considered significant at $\alpha = 0.05$. Comparisons were made for mean moment arm and maximum moment arm, as these measures are representative of the subjects' moment arm over the entire range of motion and the largest achievable moment arm during flexion and extension.

Results

Rectus femoris moment arms were measured during dynamic knee motion and over a knee joint angle of 67 degrees

Fig. 1 Experimental setup. The subjects were placed in the left lateral position in a 70-cm wide bore MR scanner (view of the front face of the scanner) (a). A platform was used to maintain the knee joint flexion-extension motion in the sagittal plane (view from the back of the scanner) (b). A weight (1.1 kg) at the end of a pulley system provided a small amount of resistance to the motion (view of the back face of the scanner) (c).

a - Example MR images during knee motion with representative measurements

b - Example length measurements during flexion

c - Moment arms for measurements in B

Fig. 2 Analysis technique. Muscle-tendon paths were digitized and joint angles measured on sagittal images during flexion and extension (a). Length measurements (circles) were fit with a third order polynomial (line) for flexion and extension motions separately (b). Moment arms were determined by taking the derivative of the polynomial fit with respect to joint angle [14] (c).

a - MAs measured during flexion

b - MAs measured during extension

Fig. 3 Rectus femoris knee muscle moment arms. Average rectus femoris muscle moment arms (solid line) plotted over joint angle with shaded standard deviation measured during flexion (a) and extension (b). Data from published cadaveric measurements during dynamic joint motion [1] (dashed line) are plotted over the same range for comparison. Note that cadaver data were averaged across multiple flexion and extension motions.

(40–107 deg) using the tendon-displacement method. Intrauser variability between measurement trials was found to be 2.5 deg and 1.3 mm or an average of 14% and 17% of the image-to-image change in angle and muscle-tendon length, respectively. Rectus femoris moment arms were similar when measured during knee flexion and extension (Fig. 3), as no significant difference was

observed in mean moment arms or maximum moment arms. The mean and maximum moment arms were 3.0 (SD 0.5) cm and 3.5 (SD 0.4) cm during flexion and 2.8 (SD 0.4) cm and 3.6 (SD 0.6) cm during extension, where the standard deviation represents intersubject variability. Cadaveric moment arms that were found with the tendon-excursion method during dynamic knee extension

[1] were generally smaller than but always within one standard deviation of those measured with this *in vivo* technique. The moment arms determined from the second observer were similar to the first observer's results, with the overall mean moment arm differing by 0.3 cm and the maximum moment arm by 0.6 cm.

Discussion

Moment arms are a major determining factor in how muscle forces generate joint moments that produce motion, and an accurate assessment of moment arms is a necessity for understanding musculoskeletal function. In this study, we developed a technique to measure muscle moment arms *in vivo* for the rectus femoris muscle, as determined from a real-time MR scan in the thigh during dynamic activity. Rectus femoris muscle moment arms were found to be similar to those found with the same tendon-excision method in cadaveric specimens during dynamic joint motion [1].

The moment arm measurements in this study were lower than those found with a center-of-rotation method (distance between the muscle-tendon's line-of-action and joint center of rotation) in cadavers [4,16]. This has traditionally been the case when comparing tendon-excision measurements to center-of-rotation measurements. Direct comparison of the two methods in the ankle joint found that the Achilles tendon moment arm was 25% greater with the center-of-rotation method than the tendon-excision method [17]. The tendon-excision method's underestimate was attributed to the underlying assumptions associated with the principle of virtual work, which include the inability to account for force generation in the musculotendon unit when tracking the myotendinous junction (MTJ). In the present study, however, the length of the patellar tendon and muscle belly was tracked instead of the MTJ only; therefore, the work associated with forces in the musculotendon unit would be accounted for by tracking the change in length.

Many previous *in vivo* moment arm measurements in the knee relied on static scans after incremental joint angle changes [12,18,19]. Without active muscle contraction and dynamic knee motion, static scans may not accurately reflect muscle moment arms during dynamic activity; however, a study comparing moment arms during dynamic motion and passive motion is required to confirm this assertion. Cine-MR techniques collect images during dynamic motion and allow for three-dimensional moment arm measurement by calculating the distance between the line of action and instantaneous screw axis of rotation [8]; however, they require minutes of precise repetitions to produce a single series of images and integration of velocity data to determine the instantaneous axis of knee joint rotation [20]. Similar to the center-of-rotation studies on cadavers, rectus femoris moment arms determined from cine-MR imaging are greater than those presented in this study [13].

The primary advantages of the technique presented here are that moment arms are determined *in vivo*, during dynamic activity, without the need for numerous repetitions in the MR scanner, and over a large range of motion. Unlike many studies that used the tendon-excision method by tracking the displacement of the muscle-tendon junction only, the current study measured the length of muscle and tendon, taking into account force generation and length change in the muscle fibers and tendon. In addition, the images with the technique presented here are acquired in real time; therefore, only one flexion or extension motion is required to determine moment arms over the full range of motion. It should be noted that subjects repeated the motion to acquire multiple series of images, though multiple repetitions were not necessary to measure moment arms over the full range of motion. Future studies could characterize motions under higher loading conditions and for patients with difficulty precisely repeating joint motions in the MR scanner. Moreover, by placing subjects in the left-lateral position in a wide-bore scanner, the technique presented here allowed for an average of 85 degrees of joint motion.

Musculoskeletal models have generally relied on cadaver-based literature values for muscle moment arms [21], which can be

problematic because moment arms determine explicitly to what extent a muscle's force generates a joint moment in forward dynamic computer simulations. Because the accuracy of dynamic simulations of the musculoskeletal system can depend largely on the accuracy of moment arms in the model [22], musculoskeletal models could potentially benefit from *in vivo* moment arms measurement during dynamic activity. For example, subject-specific musculoskeletal model simulations calculate moment arms during joint motion, and the moment arms measured with dynamic MR technique presented here could be used to validate the moment arms calculated with a musculoskeletal model. In addition, musculoskeletal models use the same moment arm at a given joint angle, regardless of the direction of movement (e.g., flexion versus extension, abduction versus adduction, etc.). The technique presented here can test this assumption. The data presented in this study show that the mean and maximum rectus femoris moment arms do not differ significantly between flexion and extension, though this result could change for other muscles and joint motions. The method presented here could also detect differences in the shape of the moment arm curves for different directions of motion, which could be caused by changes in muscle geometry that accompany active contraction and/or alternative paths of the joint center location taken during flexion versus extension, for example. A future study is required to quantify how (dis)similar dynamic *in vivo* moment arm measurements are from those used in cadaveric models.

A limitation to the approach presented here is that it is unsuitable for muscles that cannot be tracked with two-dimensional imaging. More complex deformations and geometries would require a three-dimensional imaging sequence. When a muscle's length and joint angle change can be accurately tracked in a single imaging plane during dynamic motion, however, the real-time technique presented here shows much promise for determining subject-specific muscle moment arms for muscles crossing the ankle, knee, hip, shoulder, and elbow. For example, the following muscles provide a potential target for future investigations—tibialis anterior, vastus intermedius, erector spinae, deltoids, and biceps brachii—as long as the joint motion is permitted in the MR scanner and two-dimensional musculotendon motion is verified prior to analysis. Furthermore, two-dimensional imaging yields moment arms about a single axis of rotation only, and real-time imaging may result in blurring image artifacts at faster joint angular velocities. Additionally, to provide the maximum joint angle range, subjects were placed on their left side, which may produce different results from weight-bearing or antigravity activity.

Additional limitations to the current study accompany the tendon-excision method. While the work associated with force generation and tendon stretch are accounted for in the length change of the patellar tendon and muscle belly, stretch in the proximal tendon attached to the hip, whose angle was fixed, was not included due to field-of-view restrictions and MR field inhomogeneity. Any length change not accounted for will result in an underestimate of the moment arm. Furthermore, any friction or energy dissipation in the tibiofemoral and patellofemoral joints would lead to underestimation of the muscle moment arms. In addition, the sample size of the study was limited to four adult female subjects who were close to the same size. Future investigations with a bigger variation in subject size are required to relate the moment arms result to a larger population. Moreover, a larger subject pool will allow for a more robust analysis of potential methodological errors, in addition to multiple imaging sessions for each subject [23]. Lastly, the moment arms in this study were only compared directly to a cadaveric study using the same technique, because no gold standard exists for measuring muscle moment arms *in vivo* during dynamic activity. While the cadaveric study used the same technique, it should be noted that the cadaveric study imposed dynamic motion by moving the knee manually against gravity. The current study measured moment arms while the subject was actively moving their knee in the left lateral position; as such, the results might differ if passive motion

was studied and/or the knee was flexed and extended against gravity. A future investigation should measure differences in moment arms between dynamic joint motion and passive joint motion and, if differences exist, quantify the magnitude change in muscle moment arms with dynamic joint motion.

In summary, we developed a method to measure muscle moment arms *in vivo* during dynamic activity and over a large range of motion using real-time MR imaging. This method offers a valuable resource for measuring musculotendon moment arms and providing musculoskeletal data on clinically relevant populations.

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