Tendinous movement of a human muscle during voluntary contractions determined by real-time ultrasonography

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Tendinous movement of a human muscle during voluntary contractions determined by real-time ultrasonography. J. Appl. Physiol. 81(3): 1430–1433, 1996.—The degree of shortening or lengthening of muscles during joint actions has not been clarified in humans, although such information is essential in understanding human muscle functions. In this study, the tendinous movement of a muscle was determined by real-time ultrasonography during voluntary contractions. The tibialis anterior muscle (TA) was tested in five healthy men who performed dorsi- and plantar flexion movements (shortening and lengthening of TA) at two frequencies (0.1 and 1.5 Hz). The insertion point (q) of fascicles onto the aponeurosis was clearly visualized on the ultrasonogram, and its position relative to a fixed marker moved proximally and distally according to dorsi- and plantar flexion of ankle joint. The movement of q occurred in phase with the angular change of ankle joint, giving high correlations (r = 0.93 to 0.97) between the displacement of q and the angle. The displacement of q for one radian of joint angle change, 46.5 ± 1.7 (SD) mm, was comparable to the reported moment arm of TA. The present method has many potential applications in the field of muscle physiology and biomechanics in humans.

CONTRACTIONS OF MUSCLE FIBERS result in movements of the tendon that produce joint motions. Because muscle contraction cannot be observed easily, in vivo functions of muscle fibers in humans have been estimated from joint actions through measurements of torque and angular velocity. However, this procedure has some limitations and sometimes gives inaccurate estimates of muscle fiber behavior. One cannot get information on how much muscle shortening or lengthening occurs during joint actions because joint actions are the results of various interactions among anatomic factors such as fascicles, aponeuroses or tendons of the muscle, and muscle relative to the joint (1). By using a simple anatomic model, the force-velocity relationship of human elbow flexor muscles has been reported to be similar to that of muscle fibers (12), but that similarity is controversial if one considers the multiple factors lying between muscle fibers and a joint. Especially in pennate muscles in which fascicles are arranged diagonally to the line of pull of the muscle, it is impossible to know the behavior of a muscle tendon unit from observation of a joint movement. Information on the relationship between joint angles and tendinous movement of the muscle helps the understanding of physiological characteristics of human muscles such as force-velocity and force-length relationships.

Previous studies (2, 3) have presented estimates of the movement of contracting human elbow flexor muscles by using X-ray photography or needles inserted into the muscles, but these methods are invasive in nature and applicable only to parallel-fibered muscles. Recently, Henriksson-Larsen et al. (4) and Kawakami et al. (5) have shown that fascicles and aponeuroses in human muscles can be visualized by the use of ultrasonography. The purpose of the present study is to quantify tendinous movements of in vivo human muscles during dynamic voluntary actions by real-time ultrasonography and to determine the relationship between joint angles and the movement of the tendon.

METHODS

The subjects of this study were five healthy men. Their physical characteristics are presented in Table 1. Informed consent was obtained from each subject before the study began. The muscle tested in this study was the tibialis anterior (TA), a bipennate muscle with fascicles attached obliquely onto the central (distal) aponeurosis.

The ultrasonic apparatus (model SSD-2000, ALOKA) was used with an electronic linear array probe of 7.5-MHz wave frequency. The scanning head was coated with water-soluble transmission gel, which provided acoustic contact without depressing the dermal surface. The transducer was placed perpendicular to the tissue interface and parallel to the tibia located at a point 50% distal from the proximal end of the tibial bone. The experimenter visually confirmed the echoes reflected from the aponeurosis and from interspaces among fascicles (5). The point at which one fascicle was attached to the aponeurosis (q) was visualized on the ultrasonogram (Fig. 1, top).

Each subject lay supine on a bed and was requested to perform dorsi- and plantar flexion movements (shortening and lengthening of TA) for 10 s at two different frequencies (0.1 and 1.5 Hz), with no additional load. Real-time ultrasonic images during contraction were continuously recorded on a videotape at 40 Hz, synchronized with recordings of a clock timer every 1 ms and angles of the ankle joint (θ) measured by an electrogoniometer. Frame-by-frame ultrasonic images recorded on the tape were printed every 25 ms onto image
Table 1. Physical characteristics of subjects

<table>
<thead>
<tr>
<th>Subj. No.</th>
<th>Age, yr</th>
<th>Height, m</th>
<th>Weight, kg</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>26</td>
<td>1.65</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>1.67</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>29</td>
<td>1.71</td>
<td>68</td>
</tr>
<tr>
<td>4</td>
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<td>91</td>
</tr>
<tr>
<td>5</td>
<td>39</td>
<td>1.82</td>
<td>83</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>34 ± 11</td>
<td>1.73 ± 0.07</td>
<td>75 ± 12</td>
</tr>
</tbody>
</table>

recording paper. The displacement (6X) of η during shortening and lengthening was determined as the tendinous movement between two consecutive images. A marker made of a fish bone and an acoustic standoff (κ in Fig. 1) was placed between the skin and the probe as a landmark to confirm that the probe did not move during measurement. To test the reproducibility of the measurement, 6X was measured three times for two subjects. The intertest variability was <1 mm for the dorsiflexion of 0.18 rad, and the coefficient of variation was 6%.

A simple linear regression analysis was applied to the relationships between 6X and θ and between estimated moment arms and physical measurements such as body height and tibial length. In all cases, the level of significance was set at P < 0.05.

RESULTS

Figure 1 shows successive ultrasonic images at three different values of θ during dorsiflexion. It was observed that η moved by 15 mm proximally with a dorsiflexion of 0.35 rad. Figure 2 shows an example (1 subject) of 6X and θ during dorsiflexion at two frequencies. 6X appeared to synchronize with the changes in θ both at low and high frequencies. Highly significant correlations were observed between 6X and θ (Fig. 3) in all subjects (r = 0.93–0.99).

DISCUSSION

Through a comparison of ultrasonic measurements with direct measures on human cadavers, the ultrasonic echoes have been confirmed to be from the aponeuroses and fascicles of muscles (5). 6X in the present study is thus considered to be the movement of a point on the central aponeurosis; i.e., tendinous movement, resulting from shortening and lengthening of fascicles. The methods that have been proposed so far
Joint motions. In this way, the length-tension relationship can be studied with these methods. The present technique involves insertion of needles into a muscle (3) and X-ray cine recordings of injected markers into the muscle-tendon junctions (2), both of which test the biceps brachii muscle. These methods have some drawbacks; for example, in the former it is not clear whether the position of the tips of the needle remained unchanged in the muscle, especially when the muscle is voluntarily tensed, and in the latter a limitation exists for the allowable duration of X-ray exposure. In addition, pennate muscles in which fibers are arranged diagonally to the longitudinal direction of the muscle cannot be studied with these methods. The present technique is noninvasive in nature, and one can observe the actual movement of aponeuroses of pennate muscles during contraction in a real-time fashion.

\[ \eta \] moved proximally during dorsiflexion and distally during plantar flexion. This implied that TA shortened and lengthened in phase with dorsiflexion and plantar flexion, respectively. Amis et al. (2) also reported that there was no detectable phase shift between intramuscular joint displacements during voluntary elbow flexion-extension movements with no additional load. The muscle-tendon unit consists of elastic and contractile components, and a major part of the elastic component is occupied by tendinous tissues that are lengthened by a tension applied to them (12). Because no additional load other than the mass of the foot was applied to the muscle-tendon unit in this study, the lengthening of the elastic component was negligible. This could explain the lack of a phase shift of \( \delta \lambda \) from joint movements, although it is possible that the present method was not sensitive enough to detect the small phase shift that might have occurred. At other intensities of contraction, the tendinous movement might shift from the joint motions. In this way, the length-tension relationship of the tendon could be determined in vivo by using the present method. However, as discussed below, it should be noted that the present results are limited to a certain point on the aponeurosis of muscle.

Because TA is a bipennate muscle with its proximal fibers attached to the tibial bone, it is reasonable to assume that the proximal attachment does not move during contraction. Thus displacement of the central aponeurosis, i.e., \( \delta \lambda \) in this study, is considered to be equivalent to the movement of the distal tendon. It therefore follows that the slope of the regression lines (\( \delta \lambda/\theta \)) represents the average moment arm length of TA for this joint range (10). The values ranged from 44 to 48 mm among subjects, which were highly correlated with the body height (\( r = 0.98 \)) (Table 2) and were comparable to direct measurement by using magnetic resonance imaging (8). Longer tibias mean there are more sarcomeres in series. Subjects with longer tibias have more sarcomeres and thus larger, and possibly faster, muscle excursions to account for the longer moment arms.

Some methods have been proposed to measure moment arms of human muscles; most of these are based on measurements on cadaver specimens. One study (10) that used a similar (tendon travel) method to the present one determined moment arms of the cadaver quadriceps muscles. In that study, tendinous movement of the muscles in situ was measured and related to the joint angles to give average moment arms. The present technique is similar, but it enables determination of the moment arm length in vivo. However, the moment arms determined in this manner are the average values over the joint range of motion, and it has been shown that the moment arm length changes at different joint angles (8). By studying the tendinous movement over a small joint angle range, changes in the moment arms over a whole range of motion could be determined and compared with the anatomically determined values.

The tendinous movement observed in this study was presumably caused by the change in length of muscle fibers. However, as noted above, the tendinous movement might also include elongation of the aponeurosis. Furthermore, it has been shown (7) that the fibers do not run from origin to insertion but taper within fascicles. Elasticity of the attachments between tapering fibers might affect the tendinous movement. The present study cannot distinguish what amount of the measured tendinous movements is muscle and what amount is tendon in origin. In addition, the present results are based on the measurements of the movement of one certain point on the aponeurosis. It has

![Graph of \( \lambda \) vs. \( \theta \)](image)

**Table 2. Estimated moment arms of tibialis anterior muscle from relationships between tendinous movement and joint angles**

<table>
<thead>
<tr>
<th>Subj. No.</th>
<th>Moment Arm, mm</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>44.4</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>46.2</td>
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<tr>
<td>5</td>
<td>46.4</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>46.5 ± 1.7</td>
</tr>
</tbody>
</table>
been shown in rat muscles that there is some variability in the elasticity over the aponeurosis (13). Such a heterogeneity may exist in human muscles, in which case the movement of separate areas on the aponeurosis might not be the same. Considering also that the pennation angle changes during contraction, the present measurements do not correspond to the muscle movement but are limited to the movement of a certain point on the aponeurosis. These uncertainties could be investigated with the present method in future studies.

This method could also have other applications in the field of muscle physiology and biomechanics in humans. Quantification of changes in fascicle length and pennation angles in a contracting muscle, which is currently under investigation, is an example. Force-velocity and force-length relationships in human muscles could also be determined in human muscles in vivo.

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REFERENCES