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SHORT COMMUNICATION

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Measurement of muscle and tendon stiffness in man

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Abstract Human first dorsal interosseous muscle was stimulated tetanically using several levels of percutaneous electrical current which produced forces in the muscle-tendon complex of between 30% and 100% of maximum. During the tetanus the muscle was subjected to a small fast stretch. The ratio of the force response to the displacement of the muscle-tendon complex gave a measure of the stiffness of the total complex. An adaptation of the method of Morgan (1977) allowed the stiffness to be separated into two components the stiffness of the muscle fibres and the stiffness of the tendon. The results showed that at full activation the stiffness of the muscle fibres and the tendon are approximately the same. The normalised stiffness values obtained in the experiments compared well with animal data.

Key words Muscle · Human · Stiffness · Tendon

Introduction

The studies of Alexander and colleagues have made it clear that tendons are not just inextensible straps (Bennet et al. 1986). They clearly have an elasticity which plays an important role in movements. Thus, to understand the mechanics and physiology of natural movements the properties of both muscles and tendons must be considered. Muscle-tendon complexes are responsible for joint movements and have properties which depend both on the mechanics of active muscle (e.g. the force velocity relationship) and on the elasticity of the complex. Elasticity is usually measured as stiffness (force change/length change) or as its reciprocal, compliance. The mechanical behaviour of the muscle-tendon complex will vary considerably with its total compliance. We have recently shown that the total compliance of human muscle-tendon complexes has important effects on the mechanics of eccentric muscle concentrations (Cook and McDonagh 1995), and others have illustrated their importance in stretch-shortening cycles in animal muscle (Ettema et al. 1992).

In addition to the total compliance an estimate of the separate compliances of muscle and tendon is also important. Muscle and tendon are arranged in series; therefore the total compliance of the complex is equal to the compliance of the tendon (including aponeurosis) added to the compliance of the muscle. The part of the complex which has the highest compliance will show the greatest extension when the complex is subjected to an external force. Thus a knowledge of these separate compliances enables a calculation of the relative length changes in each which accompany a force change. The tendon compliance is normally constant at higher forces. The muscle compliance decreases as more of the muscle is activated because much of the muscle stiffness depends on crossbridge formation. Thus the total compliance of the muscle tendon complex can be altered by altering the compliance of the muscle. This alteration can be achieved by varying the neural control signals sent to the muscle component.

Several techniques have been used to estimate the relative contributions of muscle and tendon elasticity to muscle-tendon complexes. Most are unsuitable for work on intact humans as they involve dissection (e.g. Ettema and Huijing 1990) or removal of the tendon, or they give data which is only valid at low forces (Joyce and Rack 1969). However, one elegant method appears suitable.

Morgan (1977) modelled the muscle-tendon complex as two springs connected in series: one spring with constant stiffness was assigned to the tendinous structures, while the other, with a stiffness proportional to force, was assigned to the cross-bridges. By means of this model, the stiffness of the entire complex measured by fast length changes can be separated into tendon and fibre stiffness.

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We have used the Morgan technique to determine the relative stiffness of muscle and tendon in a muscle-tendon complex of human subjects.

Methods

Subjects

The experiments were performed on five subjects (four males aged 24, 25, 27, 45 and one female aged 23). Six to eight similar experiments were performed on each subject on separate days. Informed consent was obtained from all the subjects and the approval of the local Ethical Committee was obtained for all procedures.

Apparatus

The details of the apparatus muscle stimulation and signal processing have been given in a previous publication (Cook and McDonagh 1995). In brief the apparatus consisted of a moving coil actuator which could produce rapid abduction and adductions of the index finger of a human volunteer. A shortening of the first dorsal interosseus muscle (F.D.I.) produces abduction of the index finger. Thus adduction of the index finger by the apparatus stretches the interosseus muscle tendon complex. Incorporated into the set-up were a force transducer and a length transducer. From these signals the responses to a rapid controlled stretch could be used to determine muscle stiffness.

The first dorsal interosseus muscle of the subject's right hand was stimulated percutaneously using a pulse width of 50 μs and a frequency of 100 pulses per second. The duration of the tetanic contractions was 1.4 s. The level of activation (and hence size of the isometric force) was controlled by varying the stimulating current. A two minute rest period was allowed between contractions to prevent fatigue (Cook and McDonagh 1995). The skin temperature above the FDI muscle was 30.5 °C. This predicts a muscle temperature for the human FDI muscle of 27.6 °C (Cook and McDonagh 1995).

Protocol

The muscle was tetanised and after the plateau of the isometric tension was reached a small stretch was applied to the muscle (Fig. 1 inset). This stretch was 2.6 mm at the finger and 0.58 mm at the muscle tendon complex. All forces and displacements quoted in this paper forces are those at the attachment of the finger to the apparatus. Force in the tendon is 4.5 times larger and displacements are 4.5 times smaller (Cook and McDonagh 1995). The initial finger position was set such that the FDI was at the plateau of its length tension curve and thus the small stretch used to determine stiffness did not take the muscle length off the plateau. The level of muscle activation was varied by adjusting the stimulating current. This allowed the total complex series elastic stiffness to be determined at a variety of force levels. To calculate stiffness, force was measured on the isometric plateau and after 1.32 mm of the 2.6 mm stretch. The difference between these forces divided by the length change gave values for the total stiffness of the complex. The stimulating current was varied to provide force levels from 30–100% of the maximum isometric force. Contractions were continued at two minute intervals until as even spread of force levels over the desired range was achieved. This took 18 to 25 contractions. Successive contractions were performed in a random order with respect to the size of the stimulating current. A comparison of the force of maximal contractions before and after this protocol revealed no evidence of fatigue.

Principle of the method to separate the stiffness components

The Morgan technique separates the muscle-tendon complex stiffness into two components: variable muscle stiffness being proportional to muscle force and constant tendon stiffness over the range of forces examined. When two materials are joined in series

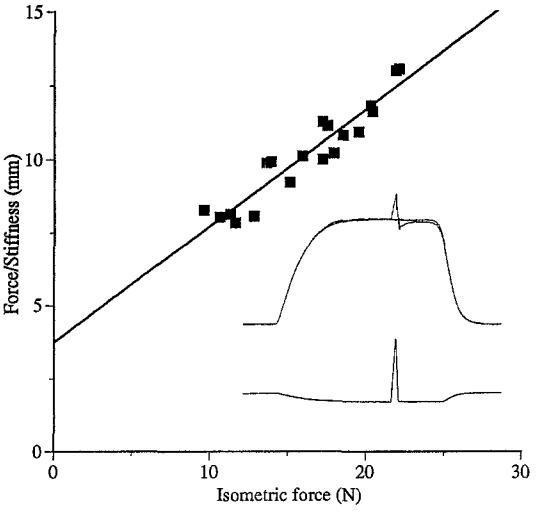

Fig. 1 Force/stiffness plotted for a range of isometric forces. A plot of force/stiffness against isometric force from a single experiment on subject no 1. Each point represents one concentration at an isometric force given by its x coordinate. The intercept on the ordinate gives the value of ao. The slope gives the value of 1/tendon stiffness. The linear regression line has the equation $y=0.397x+3.374$ with an R value of 0.945. The inset shows an original myogram of a 1.4 s isometric tetanus of 13.8 N (upper trace) on which a stretch of 2.6 mm (lower trace) was superimposed. Forces and displacement values are those measured at the apparatus attachment to the finger

the total compliance is the sum of the two individual compliances (compliance = 1/stiffness). Tendon stiffness is defined as a constant k

$$\text{Muscle stiffness (M) is defined as } M=\text{force}/a \quad (1)$$

where a is a constant.

Using the above assumptions for the muscle-tendon the following equation is obtained for the total stiffness of the muscle and tendon unit:

$$1/\text{Total complex stiffness} = 1/\text{Tendon stiffness} + 1/\text{Muscle stiffness} \quad (2)$$

$$1/\text{Total complex stiffness} = 1/k + a/\text{force} \quad (3)$$

Equation 3 is not very useful in this form. However, if the equation is multiplied by force an equation in the form

$Y=mX+c$ is obtained: $\text{force}/\text{Total complex stiffness} = (1/k)\ \text{force} + a \quad (4)$

For each level of activation the isometric force and total complex stiffness was measured as described under *protocol* above. Then the isometric force divided by total stiffness was plotted on the y-axis vs isometric force on the x-axis. An example of one of these plots is shown in figure 1. The method of least squares was used to fit a straight line to the data. From equation 4 the gradient of this line is the reciprocal of the tendon stiffness and the intercept on the y-axis is the constant a defined above. Knowing the value of a it is possible to calculate the muscle stiffness at each isometric force from equation 1. The measured gradient and intercepts were then averaged from different experiments to give mean values for each subject.

Cadaver dissection

We obtained an independent estimate of tendon stiffness by dissecting the FDI muscle of a cadaver which had a muscle similar in size to those of our subjects. For the tendon cross-sectional area six sections were taken through the muscle tendon unit over a 25 mm distance near the distal end of the FDI. This was done to see if the tendon cross-section varied with its position within the mus-

Table 1 Mean values ± S.E. of the maximum isometric force, total complex stiffness, muscle stiffness and tendon stiffness for each subject

Subject	SN	SH	MS	CC	MM	Mean
No. of experiments	7	6	6	7	7	6.6
Fmax (N) at tendon	106	133	150	133	118	128
Total stiffness at Fmax (N/mm) and (S.E.)	68.5 (3.1)	84.2 (5.1)	89.5 (5.7)	65.0 (6.7)	56.5 (4.9)	72.7
Tendon stiffness (N/mm) and (S.E.)	134.5 (7.8)	147.8 (8.2)	179.5 (11.6)	155.4 (14.4)	87.0 (3.7)	140.8
a (mm) and (S.E.)	0.76 (0.025)	0.68 (0.042)	0.84 (0.053)	1.19 (0.131)	0.73 (0.071)	0.84
Muscle stiffness at Fmax (N/mm) and (S.E.)	139.5 (4.6)	195.6 (12.1)	178.6 (11.3)	111.8 (12.3)	161.6 (15.7)	157.4

cle. To distinguish muscle and tendon all of the sections were stained with haematoxylin and three were further stained with the connective tissue stain van Gieson. The stained sections were mounted on slides and magnified 13 times by a documenter. The tendon regions were traced onto graph paper and the squares counted to obtain the total cross sectional area.

Results

The results shown in Table 1 yielded a range of tendon stiffness of 87.0–179.5 N/mm with a mean of 140.8 N/mm. Muscle stiffness at full activation was 111.8–195.6 N/mm with a mean of 157.4 N/mm.

The tendon cross sections from the cadaver revealed no trend in tendon cross sectional area along the axis of the muscle. The mean cross-sectional area was 6.22 mm^2 with SD 0.98 mm^2. The tendon length was 50 mm. The mean value for the Young's modulus of tendon obtained from the literature Bennett et al. (1986) is 1.2 GPa (range 0.6–2.0 GPa). Tendon stiffness = Young's modulus (cross-sectional area/length). So in this case tendon stiffness was 149 N/mm.

Discussion

The results for tendon stiffness obtained from the Morgan method and from the cadaver dissection are in very good agreement. At full activation muscle and tendon stiffness are approximately equal. At lower activations and forces the complex becomes more compliant because of the fall in muscle stiffness. The stiffness values obtained by the Morgan method can be compared to values obtained on the cat soleus (Proske and Morgan 1984). Stiffness depends on length and cross-sectional area. Tendon cross-sectional area is usually proportional to maximal isometric muscle force. Therefore to provide a comparison, the tendon stiffness has been divided by maximal isometric force in each case. This gives a range of normalised tendon stiffness values for FDI of 0.74–1.20 mm^{-1} and a range of 0.47–0.61 mm^{-1} for the cat soleus. The a values are 0.68–1.19 mm and 0.58–0.72 mm respectively. This is encouraging since the length of the fibres and of the tendon in the cat soleus is similar to those lengths in the FDI. The data we provide here for human subjects has one advantage over the animal data. Each of the subjects in our study was retested several times, so we could assess the within subject variability which is small as shown in Table 1.

There is increasing research interest in the role of elastic structures in movement. They substantially alter the shape of the shortening force velocity curve recorded under isokinetic conditions (authors unpublished observations). Also these structures not only absorb energy in landing and braking movements but can release some of this energy during a subsequent shortening (Ettema et al. 1992). These stretch-shortening cycles occur in many natural movements (e.g. running jumping and throwing). Both the power output and efficiency of such movements are dependent one the energy returned by elastic structures. If the separate compliances of the muscle and tendon are known then the work done by the each can be calculated. In natural stretch-shortening movements the use of muscles with long tendons, can be very efficient as the muscle fibres contract almost isometrically while the stretched tendon returns much of its stored energy on recoil.

The methods used in this study to obtain estimates of muscle and tendon stiffness could be easily adapted for use with other human muscle-tendon complexes.

References

Bennett MB, Ker RF, Dimery NJ, Alexander RMcN (1986) Mechanical properties of various mammalian tendons. J Zool Lond (A) 209:537–548

Cook CS, McDonagh MJN (1995) Force responses to controlled stretches of electrically stimulated human muscle-tendon complex. J Exp Physiol 80:477–490

Ettema GJC, Huijing PA (1990) Architecture and elastic properties of the series elastic element of a muscle-tendon complex. Multiple Muscle Systems: biomechanics and Movement Organisation. Winters JM, Woo SL-Y (eds). Springer, New York, pp 57–68

Ettena GJC, Huijing PA, de Haan A (1992) The potentiating effect of prestretch on the contractile performance of rat gastrocnemius medialis muscle during subsequent shortening and isometric contractions. J Exp Biol 165:121–136

Joyce GC, Rack PHM (1969) Isotonic lengthening and shortening movements of cat soleus muscle. J Physiol 204:475–491

Morgan DL (1977) Separation of active and passive components: short-range stiffness of muscle. Am J Physiol 232:C45–C49

Proske U, Morgan DL (1984) Stiffness of cat soleus muscle during activation of part of muscle. J Neurophysiol 52:459–468

Rack PHM, Westbury DR (1984) Elastic properties of the cat soleus tendon and their functional importance. J Physiol 347:479–495