Tendon conditioning: artefact or property?

Constantinos N. Maganaris

Centre for Biophysical and Clinical Research into Human Movement,
Manchester Metropolitan University, Alsager ST7 2HL, UK
(c.n.maganaris@mmu.ac.uk)

Recd 08.01.03; Accptd 05.02.03; Online 18.03.03

Isolated tendons subjected to cyclic tensile loads higher than those experienced in the tendons' recent history exhibit 'conditioning', i.e. gradually increasing elongations upon loading and gradually increasing residual elongations after unloading in the first few loading-unloading cycles. The present study examines whether this behaviour is a measurement artefact or an actual time-dependent property. The gastrocnemius tendons of six men who refrained from rigorous physical activities prior to the experiment were loaded cyclically by 10 repeated isometric plantarflexion contractions at 80% of the moment generated during plantarflexion maximal voluntary contraction (MVC). In each contraction, the elongation of the gastrocnemius tendon at 80% of MVC and the residual tendon elongation after relaxation were obtained from the analysis of sonographs recorded during the test. The tendon elongation during activation and the residual tendon elongation after relaxation increased by *ca.* 5 mm from the first contraction to the tenth contraction, with no changes obtained after the fifth contraction. The behaviour of the tendon in the first five contractions indicates the presence of conditioning. It is therefore concluded that conditioning is a relevant property and not an artefact associated with *in vitro* testing. This has implications for joint kinematics and muscle excursion.

Keywords: creep; tendon viscoelasticity; *in vivo*; ultrasound

1. INTRODUCTION

When applying to *in vitro* tendons oscillating tensile forces higher than those that the tendons have been exposed to in their recent history, the first few loading-unloading cycles yield gradually increasing tendon elongations (Viidik 1973; Ker 1992; Pollock & Shadwick 1994). This phenomenon is referred to as 'conditioning'.

The origin of conditioning remains obscure. If it applies only in isolated-specimen testing, it could be an artefact associated with ineffective clamping (Ker 1992). If, however, conditioning occurs *in vivo*, it is a relevant property associated with creep and may have potential functional implications. The extra tendon length generated by the initial loading would have to be taken up so that the tendon remains taut and capable for transmitting tensile forces. This would necessitate a greater joint extension and/or flexion or an extra shortening in the in-series muscle and a shift in the excursion range of its fibres.

In the present study, I sought to determine the origin of tendon conditioning. I have examined the behaviour of the intact human gastrocnemius tendon. This tendon was selected owing to its physiological oscillating loading and functional importance in locomotion.

2. MATERIAL AND METHODS

(a) Subjects, conditions of testing and body positioning

Six healthy male volunteers (age, 23 ± 2 years; body height, 174 ± 4 cm; lower leg length, 40 ± 2 cm; body mass, 73 ± 4 kg; mean $\pm$ s.d.) gave their consent to participate in the experiments. The study was approved by the institutional ethics committee. Testing was performed relatively soon after (2–4 h) the subjects woke up in the morning; hence, they were instructed to refrain from rigorous physical activities (e.g. running or jumping) between awakening and testing. Measurements were taken in the right leg, with the body placed in the prone position on the bench of an isokinetic dynamometer (Cybex Norm, USA) set in the isometric ankle plantarflexion mode. The knee was placed between mechanical stops to prevent it from shifting in the mediolateral direction. The lateral malleolus was then aligned with the dynamometer footplate, and the foot was fixed at an angle of 5° plantarflexion (0° : the sole of the foot at right angles to the tibial axis) on the dynamometer footplate with straps. The position examined generated no passive plantarflexion moment.

(b) Application of the tendon load

The gastrocnemius tendon was loaded cyclically with successive isometric plantarflexion voluntary contractions at 80% of the moment generated during plantarflexion maximal voluntary contraction (MVC) at an ankle angle of 0° . This level of moment was selected because it would generate tendon forces exceeding the habitual forces that the plantarflexor tendons of the subjects examined here would have been exposed prior to testing (e.g. tendon forces during walking *ca.* 50% of those during MVC; Maganaris & Paul 2002). I considered that a constancy in the measured absolute plantarflexion moment between repeated contractions would correspond to a respective constancy in the force acting along the gastrocnemius tendon. I will return to this point in § 4. Two sets of contractions were elicited (set A and set B), with each set containing 10 contractions. The two sets were separated by a rest period of 15 min. In either set, each contraction was elicited by requesting the subject to increase the plantarflexion moment gradually over a 3 s period until target moment was reached. The subject was then asked to maintain that moment for 1 second before relaxing the contracting muscles, reducing the moment generated to zero. After 1 second of rest, the next contraction was elicited. Surface EMG recordings verified the absence of muscle activity between consecutive contractions. Audio-visual feedback of the moment generated and time elapsed was provided. A familiarization trial was held 2–4 days before the experimental trial to establish the MVC moment and ensure that each subject could complete the test.

(c) Measurement of tendon origin displacement

The displacement of the gastrocnemius tendon origin in the myotendinous junction (the site where the aponeurosis becomes free tendon) was measured in the contractions of set A by ultrasonography. Previous studies have shown that ultrasonography is accurate and reproducible in locating human collagenous tissue and measuring its longitudinal deformation (Narici *et al.* 1996; Maganaris & Paul 1999, 2000). In the present study, a linear, 7.5 MHz B-mode probe (Esaote Biomedica, Florence, Italy) was used. First, the axis of traction of the Achilles tendon was identified and drawn on the skin. Next, the scanning probe was displaced along this axis to locate the distal myotendinous junction of the gastrocnemius muscle. Over this point, the probe was fastened with a clamp fixed on the dynamometer bench. The recordings of the ultrasound and dynamometer were synchronized and the 10 contractions were then performed. In the scans produced, the displacement of the echo generated by the endpoint of the gastrocnemius tendon origin was measured along the gastrocnemius tendon (figure 1).

(d) Measurement of tendon insertion displacement

To quantify displacements in the gastrocnemius tendon insertion occurring during the test owing to inevitable heel movements, additional measurements were taken in the contractions of set B, again by ultrasonography. The rest period administered between sets A and B (15 min) is much longer than that required to resume the properties of tendon after loading (*ca.* 5 min; Viidik 1973); therefore, I considered that set B would yield results independently of the loading applied in set A. In set B, the ultrasound probe described was

Figure 1. Sagittal-plane sonographs. The arrows in (a–e) point to the proximal edge of the calcaneal posterior surface. The arrows in (f–j) point to the gastrocnemius tendon origin in the myotendinous junction. (a) and (f) were recorded at rest before the first contraction, (b) and (g) were recorded at 80% of MVC in the first contraction, (c) and (h) were recorded at 80% of MVC in the third contraction, (d) and (i) were recorded at 80% of MVC in the fifth contraction, and (e) and (j) were recorded at 80% of MVC in the tenth contraction. (k) The structures scanned.

placed in the sagittal plane over the proximal edge of the calcaneal posterior surface, where it was fixed with the clamp used earlier. The recordings of the ultrasound and dynamometer were synchronized and the 10 contractions were then performed. In the scans produced, the displacement of the echo generated by the proximal edge of the calcaneal posterior surface was measured along the Achilles tendon. This displacement was assumed to represent the displacement of the gastrocnemius tendon insertion (figure 1).

(e) Data analysis

In each contraction, the displacements of the tendon origin (set A) and tendon insertion (set B) relative to their resting-state positions before the first contraction were measured: (i) at the target moment of 80% of MVC; and (ii) at the end of relaxation when the moment returned to zero. For each subject, contraction number and moment

level examined in either set, two to three scans with the best available quality in the structures seen were analysed and average displacements were further considered. All displacements were measured by digitization. The elongation of the gastrocnemius tendon in each cycle was calculated by subtracting the displacement of the tendon insertion from the displacement of the tendon origin. One-way ANOVA was used to test differences between contractions in the variables examined. Tukey's tests were used for *post hoc* analysis where appropriate. The statistical significance was set at $p < 0.05$ and values are reported as means $\pm$ s.d.

3. RESULTS

The plantarflexion moment generated by each subject varied non-systematically from 80% to 82% of MVC between contractions. The displacement of the tendon origin at 80% of MVC (108 ± 9 Nm) increased from 15 ± 3 mm in the first contraction to 20 ± 3.1 mm in the tenth contraction ($p < 0.001$), with no differences ($p > 0.05$) obtained after the fifth contraction (figure 2a). A residual displacement in the tendon origin (relative to the resting-state position before the first contraction) was obtained after relaxation in each contraction. This displacement increased from 2.3 ± 0.6 mm in the first contraction to 7.5 ± 1.5 mm ($p < 0.001$) in the tenth contraction, with no differences ($p > 0.05$) obtained after the fifth contraction (figure 3a).

In contrast to the tendon origin, the displacement of the tendon insertion at 80% of MVC ranged between 3.5 ± 1.3 mm (sixth contraction) and 4 ± 1.1 mm (fourth and eighth contractions), with no differences ($p > 0.05$) obtained between the 10 contractions (figure 2b). A residual displacement in the tendon insertion (relative to the resting-state position before the first contraction) was obtained after relaxation in each contraction. This displacement ranged between 0.1 ± 0.4 mm (seventh contraction) and 0.5 ± 0.4 mm (second and sixth contractions), with no differences ($p > 0.05$) obtained between the 10 contractions (figure 3b).

Similarly to the tendon origin, the entire tendon exhibited an increasing elongation during activation and an increasing residual elongation after relaxation, as a function of contraction number. The tendon elongation at 80% of MVC increased from 11.2 ± 1.8 mm in the first contraction to 16.3 ± 2.9 mm in the tenth contraction ($p < 0.001$), with no differences ($p > 0.05$) obtained after the fifth contraction (figure 2c). The tendon residual elongation (relative to the resting-state length before the first contraction) increased from 2.2 ± 0.7 mm in the first contraction to 7 ± 1.2 mm in the tenth contraction ($p < 0.001$), with no differences ($p > 0.05$) obtained after the fifth contraction (figure 3c).

4. DISCUSSION

In the present experiment, the intact human gastrocnemius tendon was loaded cyclically 10 times with contractile forces exceeding the tensile forces that the tendon would have been exposed to before the measurements. A reproducible tendon elongation was taken only in the last five loading–unloading cycles. By contrast, in the first five cycles, the tendon elongation upon loading and its residual elongation after unloading increased gradually as a function of contraction number. The possibility that these length changes reflect a reduction in the slack of the tendon at rest can be safely excluded because any such slack would not require repeated contractions to be taken up.

Figure 2. Summarized displacements at 80% of MVC as a function of contraction number. (a) Tendon origin displacement; (b) tendon insertion displacement; (c) tendon elongation. The '0 mm' value corresponds to the resting state before the first contraction. * $p < 0.001$, ** $p < 0.01$ and *** $p < 0.05$, compared with the tenth contraction. Values are means $\pm$ s.d. ($n = 6$).

By contrast, the present results indicate the presence of conditioning. Therefore, it is concluded that conditioning is a relevant time-dependent property resulting from creep in the material of the tendon (Cohen *et al.* 1976)—not an artefact as previously suggested (Ker 1992).

The use of surgically implanted transducers has enabled the quantification of *in vivo* human tendon forces (Komi 1990). This technique, however, is highly invasive and inapplicable to anatomically indistinct tendons. Such an example is the gastrocnemius tendon, whose path and action to the calcaneum is mediated by the presence of the soleus tendon. Here, I have assumed that the gastrocnemius tendon would be loaded equally in all contractions because the absolute plantarflexion moment produced was the same. However, it may be argued that the gastrocnemius tendon force could decrease as a function of contraction number owing to fatigue, with the net

Figure 3. Summarized displacements after relaxation as a function of contraction number. (a) Tendon origin displacement; (b) tendon insertion displacement; (c) tendon elongation. The '0 mm' value corresponds to the resting state before the first contraction. * $p < 0.001$, ** $p < 0.01$ and *** $p < 0.05$, compared with the tenth contraction. Values are means $\pm$ s.d. ($n = 6$).

moment measured remaining at the constant level required by recruiting more fibres from the fibre type I predominant and therefore more fatigue-resistant soleus muscle (Johnson *et al.* 1973). The resultant force increase along the soleus tendon might affect its length, but this would hardly alter the gastrocnemius tendon length because

- (i) the collagenous linkages between the gastrocnemius and soleus tendons would not be fully stretched since the two tendons pull simultaneously during contraction; and
- (ii) the gastrocnemius tendon is much longer than the soleus tendon (Cummins *et al.* 1946).

None the less, a change in the force contributions made by the gastrocnemius and soleus muscles in our tests

would indicate that in the absence of fatigue (i) more pronounced tendon elongations might be seen; and (ii) more contractions might be required to generate a steady tendon behaviour. Alternatively, muscle potentiation might produce the opposite effects of fatigue. However, it is unlikely that potentiation occurred to a substantial extent in our experiments because the high forces examined would not be affected by increases in either Ca^{2+} sensitivity or myoplasmic Ca^{2+} concentration in response to the repeated contractions elicited (MacIntosh & Willis 2000).

The present results have implications for the function of the intact muscle–tendon unit. To maintain the tendon taut and therefore capable for tensile force transmission, the residual tendon length generated in the initial loading–unloading cycles would have to be taken up. In a physiological situation involving repeated loading of the gastrocnemius tendon after a period of unloading, for example, in the first steps taken after awakening in the morning, the extra stretch needed could be obtained by further dorsiflexing the ankle and/or further extending the knee at push-off. For average Achilles and quadriceps femoris tendon moment arm lengths of 50 and 40 mm, respectively (Visser *et al.* 1990; Maganaris *et al.* 2000), the ankle and knee rotations required to take up a 5 mm extra tendon length (present study) separately would be *ca.* 6°. However, the gastrocnemius tendon may be also called upon to withstand higher loads than habitual ones with the ankle and knee maintained fixed, for example, in a test involving repeated plantarflexions of maximal effort to study fatigue-related phenomena (Kawakami *et al.* 2000). In such experimental situations, a residual tendon elongation could only be taken up by an equivalent shortening in the in-series muscle. The gastrocnemius muscle operates in the ascending limb of the force–length relationship (Herzog *et al.* 1991; Maganaris 2003), which indicates that fibre shortening would shift the average sarcomeric length away from its optimal value, thereby decreasing the force obtained by contraction. For an average fibre length of 34 mm and an average number of 19 500 in-series sarcomeres in the gastrocnemius muscle (Huijing 1985; Kawakami *et al.* 1998), a 5 mm extra tendon length would reduce the average sarcomeric length from *ca.* 1.7 to 1.5 μm , which according to the theoretical force–length relationship obtained from the results of Walker & Schrodt (1973) might reduce the force-generating potential by *ca.* 10%. Such large force reductions could be mistaken for evidence of neuromuscular fatigue. A decrease in the rate of force development could also be observed owing to the time that the additional muscle shortening would take to occur. This, in turn, could be mistaken for a contraction slowing associated with fatigue-induced changes in the excitation–contraction coupling (Fitts 1994). To avoid such misinterpretations, fatiguing tests should therefore be

performed after the tendons of the studied muscles have been conditioned.

To conclude, I showed that conditioning is an actual property because intact human tendons are liable to it. This has implications for some locomotory activities and *in vivo* studies on neuromuscular fatigue.

Acknowledgements

The author thanks Professor R. McN. Alexander and three anonymous referees for their comments on this work.

- Cohen, R. E., Hooley, C. J. & McCrum, N. G. 1976 Viscoelastic creep of collagenous tissue. *J. Biomech.* **9**, 175–184.
- Cummins, E. J., Anson, B. J., Carr, B. W., Wright, R. R. & Hauser, E. D. W. 1946 The structure of calcaneal tendon in relation to orthopedic surgery. *Surg. Gynecol. Obstet.* **83**, 107–116.
- Fitts, R. H. 1994 Cellular mechanisms of muscle fatigue. *Physiol. Rev.* **74**, 49–94.
- Herzog, W., Read, L. J. & ter Keurs, H. E. D. J. 1991 Experimental determination of force–length relations of intact human gastrocnemius muscles. *Clin. Biomech.* **6**, 230–238.
- Huijing, P. A. 1985 Architecture of the human gastrocnemius muscle and some functional consequences. *Acta Anat.* **123**, 101–107.
- Johnson, M. A., Polgar, J., Weightman, D. & Apleton, D. 1973 Data on the distribution of fibre types in thirty-six human skeletal muscles. An autopsy study. *J. Neurol. Sci.* **18**, 111–129.
- Kawakami, Y., Ichinose, Y. & Fukunaga, T. 1998 Architectural and functional features of human triceps surae muscles during contraction. *J. Appl. Physiol.* **85**, 398–404.
- Kawakami, Y., Amemiya, K., Kanehisa, H., Ikegawa, S. & Fukunaga, T. 2000 Fatigue responses of human triceps surae muscles during repetitive maximal isometric contractions. *J. Appl. Physiol.* **88**, 1969–1975.
- Ker, R. F. 1992 Tensile fibres: strings and straps. In *Biomechanics—materials* (ed. J. F. V. Vincent), pp. 75–97. New York: Oxford University Press.
- Komi, P. V. 1990 Relevance of *in vivo* force measurements to human biomechanics. *J. Biomech.* **23**, 23–34.
- MacIntosh, B. R. & Willis, J. C. 2000 Force–frequency relationship and potentiation in mammalian skeletal muscle. *J. Appl. Physiol.* **88**, 2088–2096.
- Maganaris, C. N. 2003 Force–length characteristics of the *in vivo* human gastrocnemius muscle. *Clin. Anat.* (In the press.)
- Maganaris, C. N. & Paul, J. P. 1999 *In vivo* human tendon mechanical properties. *J. Physiol.* **521**, 307–313.
- Maganaris, C. N. & Paul, J. P. 2000 Load–elongation characteristics of *in vivo* human tendon and aponeurosis. *J. Exp. Biol.* **230**, 751–756.
- Maganaris, C. N. & Paul, J. P. 2002 Tensile properties of the *in vivo* human gastrocnemius tendon. *J. Biomech.* **35**, 1639–1646.
- Maganaris, C. N., Baltzopoulos, V. & Sargeant, A. J. 2000 *In vivo* measurement-based estimations of the human Achilles tendon moment arm. *Eur. J. Appl. Physiol.* **83**, 363–369.
- Narici, M. V., Binzoni, T., Hiltbrand, E., Fasel, J., Terrier, F. & Cerretelli, P. 1996 *In vivo* human gastrocnemius architecture with changing joint angle at rest and during graded isometric contraction. *J. Physiol.* **496**, 287–297.
- Pollock, C. M. & Shadwick, R. E. 1994 Relationship between body mass and biomechanical properties of limb tendons in adult mammals. *Am. J. Physiol.* **266**, R1016–R1021.
- Viidik, A. 1973 Functional properties of collagenous tissues. *Int. Rev. Connective Tissue Res.* **6**, 127–215.
- Visser, J. J., Hoogkamer, J. E., Bobbert, M. F. & Huijing, P. A. 1990 Length and moment arm of human leg muscles as a function of knee and hip-joint angles. *Eur. J. Appl. Physiol.* **61**, 453–460.
- Walker, S. M. & Schrodt, G. R. 1973 I-segment lengths and thin filament periods in skeletal muscle fibers of the Rhesus monkey and the human. *Anat. Record* **178**, 63–82.