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► **To cite this version:**

Alexandre Fouré, Christophe Cornu, Antoine Nordez. Is tendon stiffness correlated to the dissipation coefficient?. *Physiological Measurement*, 2012, 33 (1), pp.N1-N9. 10.1088/0967-3334/33/1/N1 . hal-02130769

HAL Id: hal-02130769

<https://hal.science/hal-02130769>

Submitted on 5 Sep 2024

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NOTE

Is tendon stiffness correlated to the dissipation coefficient?

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Received 19 July 2011, accepted for publication 2 November 2011

Published 7 December 2011

Online at stacks.iop.org/PM/33/N1

Abstract

The assessment of Achilles tendon mechanical properties *in vivo* has received much attention in the literature. Many studies investigated mechanical properties by assessing tendon stiffness. Despite tendon dissipative properties being representative of a storage-recoil process, its determination has received minimal attention in the literature. The aim of this study was to determine if Achilles tendon stiffness is associated with dissipative properties. The cross-sectional area, stiffness and dissipation coefficient of the Achilles tendon were measured in 35 subjects. No significant correlation was found between stiffness and the dissipation coefficient, irrespective of stiffness normalization with cross-sectional area ($P > 0.05$). Thus, it appears that both stiffness and dissipative properties must be assessed to determine the storage-recoil process capacities of the Achilles tendon in order to precisely characterize changes in the tendon mechanical properties after chronic interventions or rehabilitation programs.

Keywords: dissipative properties, elastic energy, hysteresis, stiffness, cross-sectional area

1. Introduction

Since tendon mechanical properties are significantly involved in muscle tension transmission and the storage-recoil process of potential elastic energy, tendon mechanical properties have been assessed *in vivo* with ultrasonography over the past 15 years (e.g. Arampatzis *et al* 2005, 2007a, 2010, Fukashiro *et al* 1995, Karamanidis and Arampatzis 2007, Kongsgaard *et al* 2005, 2011, Maganaris and Paul 1999, 2000, 2002, Magnusson *et al* 2008). Characterization of tendon mechanical properties is essential for understanding those mechanisms that enable to optimize the functional behavior of the muscle–tendon complex (MTC) for an increase in movement performances (Alexander and Bennet-Clark 1977, Bosco and Rusko 1983, Bosco *et al* 1982, Komi 1992). Also, it was shown that Achilles tendon mechanical properties are potentially associated with several pathologies and injuries (Arya and Kulig 2010, Hess 2010,

Kongsgaard *et al* 2011, Magnusson *et al* 2008). By means of the assessment of tendon mechanical properties, information can be obtained concerning tendon functional ability following a lesion (Arya and Kulig 2010, Zhao *et al* 2009). On the basis of the tendon force–length relationship determined during isometric loading and unloading of the tendon, stiffness and energy (i.e. stored, restored and dissipated) can be assessed (Maganaris and Paul 2000, 2002).

Several studies have determined the Achilles tendon stiffness in several populations (Burgess *et al* 2009a, 2009b, Karamanidis and Arampatzis 2007, Rosager *et al* 2002, Westh *et al* 2008). In addition, many authors concentrated on the effects of different kinds of training on tendon stiffness (Burgess *et al* 2007, Fouré *et al* 2010, Kubo *et al* 2001, 2002a, 2002b, 2003, 2004, 2007). In contrast, few studies have assessed the dissipative properties of the Achilles tendon across stored and restored energy during the tendon loading–unloading cycle. Yet, the ability of the tendon to dissipate energy (i.e. area of the hysteresis of force–length relationship) might have a major effect on MTC efficiency. Although this parameter seems particularly important in determining tendon functional behavior, and especially in the assessment of chronic intervention effects, few studies have concurrently assessed both stiffness and dissipation coefficient (DC). The measurement of the DC would not be essential if both parameters are correlated, indicating that the stiffness measurement could provide an indirect assessment of the DC. Yet, no study has determined whether or not these parameters (i.e. Achilles tendon stiffness and DC) are correlated, when determined during an isometric contraction under standardized conditions of tendon loading/unloading rates.

Therefore, the aim of this study was to assess whether there is an actual correlation between Achilles tendon stiffness and DC during an isometric plantar flexion. Interesting insight on tendon's functional mechanics assessed *in vivo* could be provided. In addition, a non-significant correlation argues for the fact that both parameters are independent suggesting that both should be measured to provide a complete assessment of tendon behavior.

2. Materials and methods

2.1. Subjects

Thirty-five subjects were tested (20.9 ± 2.8 years, 177.5 ± 5.9 cm, 70.0 ± 7.0 kg). All subjects were sport science students involved in regular (9.6 ± 6.1 h/week) sport practices (e.g. basketball, tennis, soccer, volleyball). Subjects were fully informed about the nature and the aim of the study before signing a written consent form. This study was conducted according to the Helsinki Statement and has been approved by the local ethics committee. Data from a previous study determining the effects of 14 weeks of plyometric training on tendon stiffness and DC were also included (Fouré *et al* 2010).

2.2. Achilles tendon geometric parameters

Measurement of the Achilles tendon cross-sectional area (CSA) was accomplished with ultrasonographic imaging scans (Philips HD3, Philips Medical Systems, Andover, MA, USA) with an electronic linear array probe (7.5 MHz wave frequency; L9-5, Philips Medical Systems, Andover, MA, USA) as described previously (Fouré *et al* 2010). Subjects were positioned in a prone position on an examination couch with legs fully extended, with the ankle angle at 90° . A stand-off pad was placed over the posterior aspect of the ankle. CSA measurements were carried out in the transverse plane with the transducer perpendicular to the Achilles tendon at the level of the medial *malleolus* (Ying *et al* 2003).

2.3. Achilles tendon mechanical properties

A Biodex system 3 research[®] (Biodex Medical, Shirley, NY, USA) isokinetic dynamometer was used to measure the external torque, ankle joint angle and ankle joint angular velocity during a muscular contraction. Subjects were positioned prone with their legs fully extended. Thighs, hips and shoulders were secured by adjustable lap belts and were held in place as previously described (Fouré *et al* 2010). The right ankle joint was securely strapped to a footplate connected to the arm of the dynamometer. The input axis of the dynamometer was carefully aligned with the supposed rotational axis of the right ankle joint. External torque and ankle angle were sampled at 1000 Hz using an A/D converter (National Instrument, Delsys[®] Inc., Boston, MA, USA), and stored on a hard drive using EMGWorks 3.1 software (Delsys[®] Inc., Boston, MA, USA) for further analysis.

The session assessing the mechanical properties of Achilles tendon included the following protocols: (i) a warm up consisting of constant submaximal isometric plantar flexion. (ii) Two maximal voluntary isometric contractions in plantar flexion with the knee fully extended at an ankle angle of 90°. The maximal isometric torque in plantar flexion (MVC) was then determined as the maximal value of the two trials. (iii) Familiarization trials to perform a constant increase in isometric torque in plantar flexion, from a relaxed state to 90% of MVC within 5 s, followed by a constant decrease in isometric torque, from 90% of MVC to the rest state within 5 s. Visual feedback was used to regulate and train the subjects for this task. (iv) Five trials of constant isometric torque development in plantar flexion as described in point (iii) were then performed by each subject with 2 min of rest between each trial. The best trial of each subject was retained for analysis. The displacement of the distal myotendinous junction of the *gastrocnemii* was measured during the test using ultrasonography. The linear array probe mounted on an externally fixed bracket was strapped onto the skin of subjects to obtain longitudinal ultrasonic images of the distal myotendinous junction of the *gastrocnemii*.

Ultrasonographic videos were recorded on a hard drive at 25 Hz. To synchronize the torque signal and ultrasonographic images from the videos, the signal of the switch used to start the video was also recorded using the Delsys[®] system. A selection of 40 images comprising 20 images equally spaced from both the loading and unloading phases of torque development were collected from each trial. Displacements of the myotendinous junction were quantified from these 40 images using Matlab (The Mathworks, Natick, USA).

The ankle joint torque (T) measured by the dynamometer was converted to tendon force (Ft) using the following equation (Arya and Kulig 2010):

$$Ft = \frac{T}{m_g}, \quad (1)$$

where m_g is the moment arm length of *gastrocnemii* at 0°, which was estimated from the limb length of each subject (Grieve *et al* 1978). Myotendinous junction displacement determined during isometric contraction was corrected for the passive displacement attributed to joint rotation alone (Arampatzis *et al* 2007b, Magnusson *et al* 2001). The ratio of the calculated tendon force (Ft) to the corrected elongation (ΔL) (i.e. the displacement of myotendinous junction) was used to calculate the stiffness of the Achilles tendon.

The Ft - ΔL relationship is classically curvilinear, consisting of an initial region (toe region), characterized by a large increase in ΔL with increasing force and a linear region after the toe region. In this study, the Ft and ΔL values from the ascending curve between 50% and 90% of MVC were fitted to a linear regression equation, the slope of which was defined as the Achilles tendon stiffness (S_{LOAD}) (Kubo *et al* 2002a). S_{LOAD} was also normalized with the CSA. Although the determination of the loading curve slope is the most commonly used method to assess tendon stiffness in the literature, other definitions of tendon stiffness were

Table 1 Measured variables in this study and data from a previous study assessing the effects of 14 weeks of plyometric training (Fouré *et al* 2010).

	Present study ($n = 35$)	Effects of 14 week plyometric training ($n = 9$)	
		Before	After
S_{LOAD} (N mm ⁻¹)	239.4 ± 109.0	224.7 ± 92.2	284.3 ± 139.0**
S_{LOAD}/CSA (N mm ⁻³)	4.12 ± 2.10	4.40 ± 2.47	5.54 ± 3.74**
S_{UNLOAD} (N mm ⁻¹)	400.0 ± 178.2	431.5 ± 174.4	391.5 ± 162.0
S_{MEAN} (N mm ⁻¹)	284.0 ± 125.1	299.9 ± 130.5	326.7 ± 139.2
DC (%)	32.1 ± 12.8	36.9 ± 11.3	23.6 ± 9.3**

S_{LOAD} , S_{UNLOAD} and S_{MEAN} : Achilles tendon stiffness determined from loading, unloading and global loading/unloading curves, respectively; CSA: Achilles tendon cross-sectional area; DC: dissipation coefficient.

** : significant effect of plyometric training ($P < 0.05$).

also determined. Slopes of the unloading curve (S_{UNLOAD}) and of the global loading/unloading curve (S_{MEAN}) were then calculated.

Areas under the ascending and descending phases of the curve were calculated, and represent the potential elastic energy stored (E_S) and recoiled energy (E_R), respectively (Maganaris 2002, Nordez *et al* 2008a, 2008b). On the basis of these parameters, a DC was calculated using the following equation:

$$DC = \frac{(E_S - E_R)}{E_S}. \quad (2)$$

2.4. Statistics

Descriptive data included means and standard deviation. To assess the relationships among measured parameters, the Pearson product–moment correlation was computed. Correlations between DC and S_{LOAD} , DC and S_{LOAD}/CSA , DC and S_{UNLOAD} , and DC and S_{MEAN} were determined. The level of significance was set to $P < 0.05$.

To determine if outcomes of DC– S_{LOAD} , DC– S_{LOAD}/CSA and DC– S_{MEAN} correlations were essentially affected by the precision of the measurement methods, numerical simulations were performed on initially perfectly correlated sets of variables ($r^2 = 1$, RMSE = 0), with controlled random errors mimicking the experimental uncertainties. The simulation used a synthetic set of 35 data corresponding to the number of subjects. The values of standard error of the mean (SEM) and variation coefficient (CV) for DC (SEM: 4.3%, CV: 23.1%), S_{LOAD} (SEM: 8.1 N mm⁻¹, CV: 3.4%) and S_{MEAN} (SEM: 38.5 N mm⁻¹, CV: 12.4%) used in the model correspond to the variability found in the reproducibility assessment (Fouré *et al* 2010). The correlation coefficient was then computed for 10 000 realizations of the synthetic data set. The 95% confidence interval for r was then calculated (Grimal *et al* 2009).

3. Results

Descriptive data on the measured variables in this study and the data from a previous study (Fouré *et al* 2010) concerning the effects of plyometric training on the stiffness and dissipative properties of Achilles tendon are summarized in table 1. The mean Achilles tendon force–length relationship ($n = 35$) is shown in figure 1.

There were no significant correlations between S_{LOAD} and DC ($r = -0.13$, $P > 0.05$) even when stiffness was normalized with the CSA ($r = -0.09$, $P > 0.05$) (figures 2(A) and (B)). No significant correlation between DC and S_{MEAN} was determined ($r = 0.17$, $P > 0.05$) while a

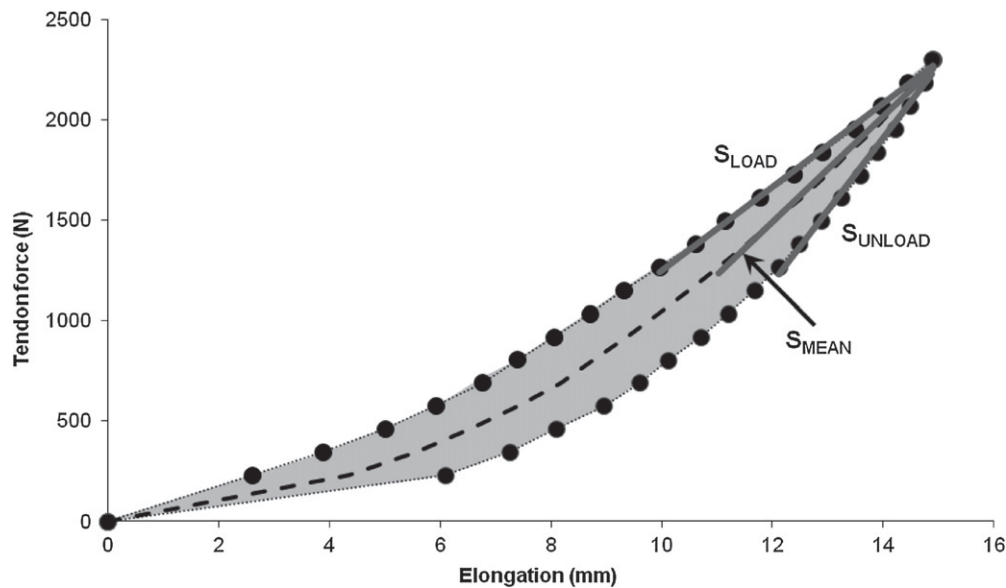


Figure 1. Mean relationship between the Achilles tendon force and elongation ($n = 35$). Tendon stiffness was defined as the slope of the linear regression for tendon forces higher than 50% of the maximal isometric force (i.e. the bold line) for loading, unloading and global loading/unloading (the dashed line) curves (S_{LOAD} , S_{UNLOAD} and S_{MEAN} , respectively). Hysteresis was characterized as the area between loading and unloading curves (i.e. the gray area). Error bars were removed for clarity.

significant correlation between DC and S_{UNLOAD} was found ($r = 0.44$, $P < 0.001$). Furthermore, there was no significant correlation between changes in tendon stiffness, normalized tendon stiffness and DC ($R^2 = 0.07$ and $R^2 = 0.04$ respectively, $P > 0.05$) (figures 2(C) and (D)).

The 95% confidence intervals were [0.89–0.96], [0.29–0.74] and [0.87–0.95] for DC– S_{LOAD} , DC– S_{LOAD}/CSA and DC– S_{MEAN} correlations, respectively. Since $r = -0.13$, $r = -0.09$ and $r = 0.17$ fall out interval, it was concluded that the measurement uncertainties cannot explain the lack of correlation between DC– S_{LOAD} , DC– S_{LOAD}/CSA and DC– S_{MEAN} .

4. Discussion

The results of this study showed no significant correlation between tendon stiffness and dissipative properties. Similarly, changes in these parameters after chronic interventions were not correlated.

A previous study showed a moderate negative correlation between tendon stiffness and hysteresis when determined during hopping (Farris *et al* 2011). However, the shape of the tendon force–length curve is quite different during hopping with a decrease in stiffness for high force values which indicates that experimental conditions strongly influence stiffness and hysteresis measurements. For instance, the contribution of other muscle groups in force production depends on ankle joint angle during measurements and also data analysis (e.g. lever arm characterization, assessment in muscle–tendon unit length change) differed between studies performed during isometric contraction and hopping.

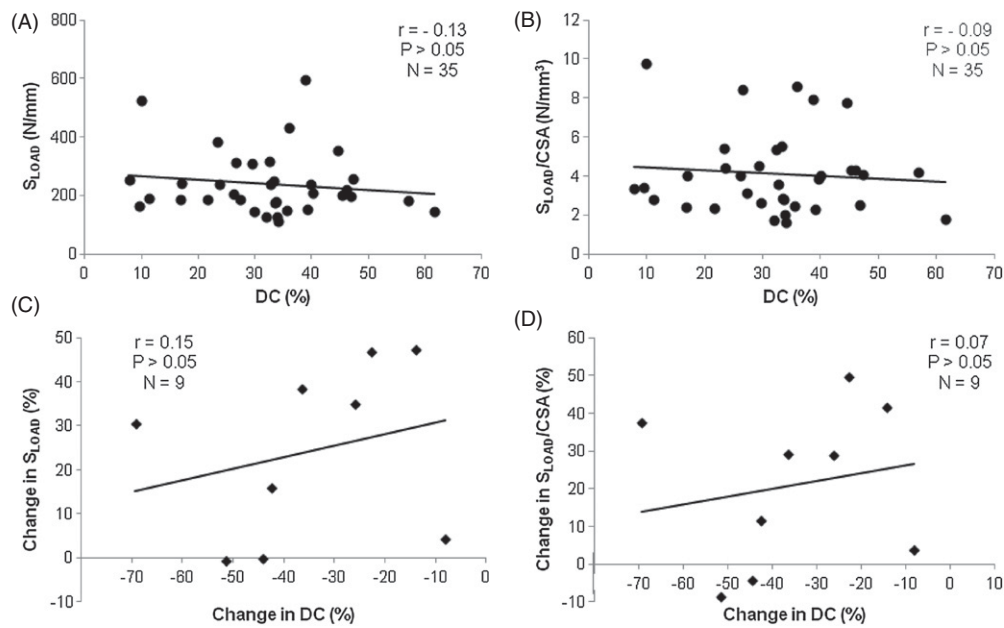


Figure 2. Relationships between Achilles tendon DC and Achilles tendon stiffness (S_{LOAD}) and Achilles tendon stiffness normalized to the CSA (S_{LOAD}/CSA) ((A) and (B), respectively, $n = 35$). Relationships between changes (data from Fouré *et al* 2010) in DC and S_{LOAD} , and between DC and S_{LOAD}/CSA ((C) and (D), respectively, $n = 9$).

Stiffness and DC values found in this study (mean: 239.4 ± 109.0 N mm⁻¹) were in accordance with those of other studies (range: 129–375 N mm⁻¹) performed under the same conditions (i.e. during isometric voluntary contraction) (e.g. Arya and Kulig 2010, Kubo *et al* 2007, Rosager *et al* 2002). Our DC values are higher ($32.1\% \pm 12.8\%$) in comparison with previous study performed on Achilles tendon [17–26%] (e.g. Kubo *et al* 2002a, Lichtwark and Wilson 2005, Maganaris and Paul 2000, Wu *et al* 2010). Yet, Reeves *et al* (2003) found similar values of hysteresis in patellar tendon of humans ($33\% \pm 5\%$). In addition, tendon hysteresis may depend on the rate of loading and unloading. In the present study, the constantly increased isometric contraction was accurately assessed to obtain the same rate of loading and unloading on the tendon which is difficult to supervise during hopping and which was not always controlled in comparable studies. Considering other definitions of tendon stiffness, a significant correlation was found between DC and S_{UNLOAD} . Therefore, it seems that the slope of the unloading curve has more influence than that of the loading curve on the DC. Results found in this study allow a better understanding of the functional behavior of the Achilles tendon.

Stiffness and DC seem to be dependent on various physiological structures and/or mechanisms. The collagen synthesis–degradation process (Heinemeier and Kjaer 2011, Langberg *et al* 1999, 2001, 2007) and change in extracellular matrix (Kjaer 2004, Kjaer *et al* 2006, 2009) were classically evoked to explain the change in intrinsic mechanical properties of the tendon material (Heinemeier and Kjaer 2011, Kjaer *et al* 2006, 2009, Magnusson *et al* 2003a, 2008) as hypothesized after plyometric training (Fouré *et al* 2010). Nevertheless, other authors speculated that damping could take place in the non-collagenous material in the inter-fibrillar space (Eliasson *et al* 2007). Compositional changes in ground substance

might significantly alter the mechanical properties of myotendinous complex (Magnusson *et al* 2003b), which was previously hypothesized to explain the effects of plyometric training on tendon mechanical properties *in vivo* (Wu *et al* 2010). The change in tendon stiffness and DC observed after plyometric training seems to be due to adaptation of several physiological mechanisms within different components of the tendon.

In summary, no significant correlation was found between Achilles tendon stiffness classically calculated as the slope of the loading curve (S_{LOAD}) and DC. Thus, determining the tendon stiffness alone does not provide a complete assessment of tendon mechanical properties and rather the unloading curve of the tendon force–length relationship should be characterized in order to determine the tendon dissipative coefficient. Both parameters are of relevance with respect to clinical studies interested in the effects of ageing, training protocols or neuromuscular pathologies on tendon mechanical properties.

Acknowledgments

This study was supported by grants from the AFM (Association Française contre les Myopathies, grant no 13923), Nantes Métropole and the RSPDL network (Recherche et Sport en Pays de la Loire). The authors would like to thank Jennifer Wegrzyk for English editing.

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