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# Commentaries on Viewpoint: On the hysteresis in the human Achilles tendon

## INFERRING TENDON MECHANICAL PROPERTIES USING ULTRASOUND IMAGING

TO THE EDITOR: Ultrasound imaging has provided an invaluable tool for investigating muscle and tendon mechanics, particularly for measuring tissue strain. However, as Finni and colleagues (1) argue, some physiological measurements are not as consistent or of the magnitude we would expect from isolated tissue preparations. Although tendon hysteresis is often not reported in studies of tendon mechanical properties using ultrasound, the analysis presented in this Viewpoint demonstrates some important technical limitations of combining stress and strain measurements using this technique. Unusually large hysteresis values (>10%) determined through loading and unloading of tendons are likely to be a problem related to the technique rather than a physiological property of the tendon. Although Achilles tendon hysteresis has not been directly calculated from isolated mechanical testing, research by Wren et al. (2) clearly demonstrates low levels of hysteresis in this tendon (<7%) that are consistent with tests on other tendons. Temporal differences between stress and strain measurements can be easily determined, for example, by generation of an event that can be visualized with B-mode imaging and also detected simultaneously by other measurement devices, e.g., A/D converter. However, other factors are more difficult to control, particularly those pertaining to the estimation of tendon force from joint torque measurements that are influenced by neural control of both agonist and antagonist muscle activity, intramuscular force transmission, and changes in moment arm. We must therefore be cautious when making conclusions about changes in tendon stiffness or hysteresis across or within groups when using ultrasound methods.

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## THE HYSTERESIS OF TENDON, IN VITRO AND IN VIVO

TO THE EDITOR: In vitro measurements, of which I have experience, complement the in vivo measurements surveyed in the Viewpoint (1). Ultimately, in vitro and in vivo must agree. Different problems are faced, although both involve the difference between two larger quantities, which increases variability.

In vitro, energy losses occur within the clamped region, so hysteresis tends to be overestimated. An extensometer helps by excluding the clamps from the region of measurement. However, optical extensometers look at the surface only, where,

with imperfect clamping, strains may differ from those in the core. Strains are incompletely shared laterally, because each tendon fascicle is largely independent of its neighbors (3). Ker (2) used an extensometer with pins to penetrate the interior. The most amenable tendons are long, thin, and uniform. Worst of all is the Achilles tendon, for which, in my experience, in vitro measurements are impossible. The literature, unintentionally, confirms this. No Achilles results give me confidence. It is best to use data obtained with mammalian tendons having comparable functions: 10% is unlikely to be seriously wrong.

With hysteresis, lost mechanical energy becomes heat. Temperature rise has been measured in vitro (2) and in vivo for galloping horses (4). Both underestimate hysteresis because some heat is lost. Allowing for this, the measured heating agrees with hysteresis of 7% (2) or 10% (4). High hysteresis, say >20%, would result in denaturation of the Achilles tendon after a few minutes of vigorous exercise. Some of the in vivo values cited in the Viewpoint (1, see Fig. 1) are not plausible!

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## COMMON PROBLEMS IN THE MEASUREMENT OF HUMAN TENDON HYSTERESIS IN VIVO

TO THE EDITOR: Finni et al. (1) suggest that the higher tendon hysteresis values in vivo may be a consequence of synchronization errors between force and displacement recordings. It is unlikely that one experimenter would consistently analyze desynchronized data in the same direction, and it is therefore unlikely that this factor alone can explain the discrepancy between in vivo and in vitro tests. In vivo values of human tendon hysteresis include the frictional resistance offered by surrounding structures and are subject to several potential errors, mainly in the calculated forces. These errors may be larger than the sensitivity required to detect a true biological effect (e.g., adaptation) when questionable assumptions are made about the contribution of different muscles to the joint moment measured or the force acting in one common tendon. Common oversimplifications for force-sharing issues can often, but not always, be avoided, for example by electrical stimulation (2), by selecting tendons with two bony ends (3) and by joint angle manipulation to isolate biarticular muscle tendons (4). It would be insightful to quantify the measurement improvement made by such approaches, so that an evidenced-based decision can then be made as to whether simpler and less demanding approaches are worth pursuing.

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## VIEWPOINT: ON THE HYSTERESIS IN THE HUMAN ACHILLES TENDON

TO THE EDITOR: Mechanical hysteresis of tendon tissue is one important and maybe underappreciated property since tendon involvement in the economy of locomotion is based on the ability of the tendon to store and efficiently return energy. The viewpoint by Finni et al. (1) is therefore relevant, and we agree that this property is poorly understood and that there are noteworthy methodological challenges to overcome. In addition to the synchronization issues, it is also important that the loading follows a uniform period (preferably sinusoidal), which is difficult to achieve with voluntary contractions in vivo. In addition, hysteresis is a measure of the phase difference between load and deformation, which in principle can be derived from just a single cycle, but the relatively large noise associated with this type of ultrasound measurements can introduce sizeable uncertainty in the data. Recording a series of several periods would greatly alleviate this issue and enable analysis by methods commonly used for periodic functions, e.g., Fourier analysis. Some of the difference observed between in vivo and in vitro hysteresis may be ascribed to the aforementioned methodological issues. In addition, it is important to keep in mind that parameters such as hydration, perfusion, temperature, and preload are altered when the tendon is removed from the body, which adds to the overall variability. As described by Finni et al. (1), hysteresis is an underreported parameter, and more studies are therefore warranted; however, a reliable and standardized methodological approach must first be established before useful results can be obtained.

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## ON THE HYSTERESIS IN THE HUMAN ACHILLES TENDON: INFLUENCE OF THE LOADING RATE AND MUSCLE COORDINATION

TO THE EDITOR: We agree with most of the comments of Finni et al. (2) on the hysteresis measurement of human Achilles tendon. Although this parameter has received much less attention than stiffness, it seems very relevant from a functional point of view (2, 3).

We think that the rate of increase/decrease in isometric torque is also a key factor that could influence a desynchronization between force and displacement. Thus slower contractions could be recommended [e.g., 5 s for each phase (4)] and the torque rate should be controlled by providing a feedback (4, 5).

As the loading rate has been shown to influence the response of the tendon (5), it could explain some differences between animal and human studies identified in the Viewpoint (2). Indeed, the loading rate was generally slow in animal studies (from 5 to 10 mm/min at a constant elongation rate), while it was significantly faster in human studies (from 2 to 4 mm/s at an approximately constant rate in torque). Therefore, the validation study proposed in the Viewpoint (2) should be performed with the same loading rates during in vivo and in vitro hysteresis measurements.

The coordination between muscles may also influence the findings. Indeed, a recent study showed changes in the load sharing between synergist muscles during isometric elbow flexion with ramped torque (1). Such changes may have influenced the myotendinous junction displacement, and it remains to be determined whether the assumption of a constant relative contribution of plantar flexors remains valid during the loading and the unloading phases.

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## COMMENTARY ON VIEWPOINT

TO THE EDITOR: Finni et al. (3) report that synchronization uncertainty between dynamometer and ultrasound signals affects the in vivo calculation of human Achilles tendon hysteresis. Although this might technically be solved in the midterm, other relevant issues are harder to work out. On the basis of their data (3) ( $F_{max} = 2,000$  N,  $L_{max} = 10$  mm), we can approximate the tendon's force-length ( $F/L$ ) curve by  $F = kL^2$ ,

$k = F_{max}/L_{max}^2$  (2). Consequently maximal strain energy would be  $E = 1/3 kL_{max}^3$ . For  $\sim 10\%$  hysteresis, as reported by most animal studies (3) the energy difference between loading and unloading condition would be  $\sim 0.67$  J, and the average length difference at the same tendon force would be  $< 0.5$  mm, a quite challenging requirement for the actual methodology.

At noninvasive studies, the human Achilles tendon force is estimated using the resultant ankle joint moment (sum of the moments of agonist and antagonist muscles, ligaments, and bony contact forces) and the tendon's lever arm. The contribution of synergistic muscles beyond the triceps surae to the resultant moment remains unknown and can differ between loading and unloading. Furthermore, to compare the measured tendon elongation at the same tendon force during loading and unloading, the same geometry of the ankle and knee joints (equal length of the muscle tendon unit) is required and almost impossible to achieve in vivo (1). All these inaccuracies affect the tendon  $F/L$  curve during loading-unloading trials and thus tendon hysteresis calculations. Therefore, accurate tendon force and elongation measurements as well as total lower leg geometry control are necessary to correctly assess Achilles tendon hysteresis.

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#### STIFFNESS AND HYSTERESIS OF HUMAN TENDONS

TO THE EDITOR: Transmission of muscle force to the joint through the tendon and recoil of elastic energy from it results

in body movement. The two properties of tendons that are relevant to the movement are stiffness and hysteresis (5). Although both of these factors are important, hysteresis along with the elastic energy recoil of the tendon contributes to the type and quality of the movement. Authors of the Viewpoint (2) mentioned that there are more reports on stiffness than hysteresis. Bipedal locomotion of humans is consistent with the stiffness of muscles and tendons. This might have led researchers to publish a greater number of reports on stiffness than on hysteresis. There are reports showing that in vivo hysteresis in tendons is independent of physiological function and loading (3). Hopping animals showed a higher capacity to store and release elastic energy per unit of contractile work than nonhopping animals. Furthermore, small animals appear to utilize the storage and release of elastic energy to a far lesser extent than larger animals (1). From an injury rehabilitation point of view, lower hysteresis is advantageous than stiffness. Because hysteresis, whether or not biological, is highly non-linear (4) and nonreciprocal, ordinary linear models cannot fully characterize it in tendons, much less permit a quantitative analysis. Although one might agree that the degree of hysteresis is higher in humans than in other animals, to ascertain its influence in Achilles tendons, a universal standard has to be laid down for measurement protocols, including latency in the observed response.

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