J Musculoskelet Neuronal Interact 2023; 23(1):84-89

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Effect of relaxation time on hysteresis of human tendon *in vivo*

Shuhei Sasajima, Ayaka Yasuda, Takehiro Kosaka, Keitaro Kubo

Department of Life Science, The University of Tokyo, Meguro, Tokyo, Japan

Abstract

Objectives: The purpose of this study was to investigate the effect of relaxation time on tendon hysteresis. **Methods**: Subjects exerted isometric plantar flexion torque from rest to maximal voluntary isometric contractions within around 0.5 s, followed by relaxation with six different times (0.3, 0.5, 0.7, 1, 3, and 5 s). During each trial, tendon elongation in the medial gastrocnemius muscle was measured by ultrasonography. The area within the exerted torque–tendon elongation loop, as a percentage of the area beneath the curve during ascending phase, was calculated as tendon hysteresis. **Results**: Between the 0.3 and 1 s relaxation time conditions, the hysteresis values were significantly greater for the shorter relaxation time conditions (except between the 0.5 and 0.7 s conditions). In contrast, no significant differences in tendon hysteresis were found between 1 and 5 s of relaxation time conditions. Furthermore, the relationship between relaxation time and tendon hysteresis showed a significantly negative correlation under 1 s or less of relaxation time, but no significant correlation was observed under conditions of 1 s or more. **Conclusion**: These results suggest that relaxation time greatly affects tendon hysteresis under condition that relaxation time was less than 1 s.

Keywords: Elongation, Medial Gastrocnemius Muscle, Plantar Flexion, Tendon Relaxation, Ultrasound

Introduction

The mechanical properties of tendons are known to be important for stretch-shortening cycle exercises[1,2]. For the two decades, several studies have used ultrasonography to determine the effects of the mechanical properties (stiffness and hysteresis) of human tendons on the performance and efficiency (i.e., the ratio of work output to work input during exercises) during stretch-shortening cycle exercises[3-7]. Tendon hysteresis, i.e., the area within the loop of tendon force-elongation relationship, represents the energy loss as heat, and the area under the unloading curve is the energy reused in the elastic recoil[8]. Therefore, tendon hysteresis is theoretically thought to be related to exercise efficiency, although no studies have experimentally shown a relationship between tendon hysteresis and efficiency during running and jumping exercises. In fact, when comparing repeatability of measurement within the same study, most studies showed that the measurement of tendon hysteresis was less reproducible than tendon stiffness[4,9-11]. Finni et al.[12] pointed out that the hysteresis values of human tendons previously reported varying greatly among individuals and cited the difficulty of controlling muscle strength during the relaxation phase as one of the reasons for large individual differences.

Relaxation time is one of the indicators of control of muscle strength during the relaxation phase of the measurement of tendon hysteresis. So far, the relationship between relaxation time and tendon hysteresis has been poorly investigated, including in animal and human experiments[11,13-15]. Regarding the effect of relaxation time on the hysteresis of human tendons *in vivo*, we previously reported no differences in tendon hysteresis values of relaxation time from 1 to 10 s[11,15]. More recently, we have demonstrated that tendon hysteresis measured during ballistic contraction (relaxation time was around 0.5 s) is much greater than that during ramp contraction (relaxation time was around 5 s)[9,10,16]. To date, the effect of relaxation time on tendon hysteresis is

The authors have no conflict of interest.

Corresponding author: Keitaro Kubo, Ph.D., Department of Life Science (Sports Sciences), The University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan
E-mail: kubo@idaten.c.u-tokyo.ac.jp

Edited by: G. Lyritis
Accepted 13 November 2022

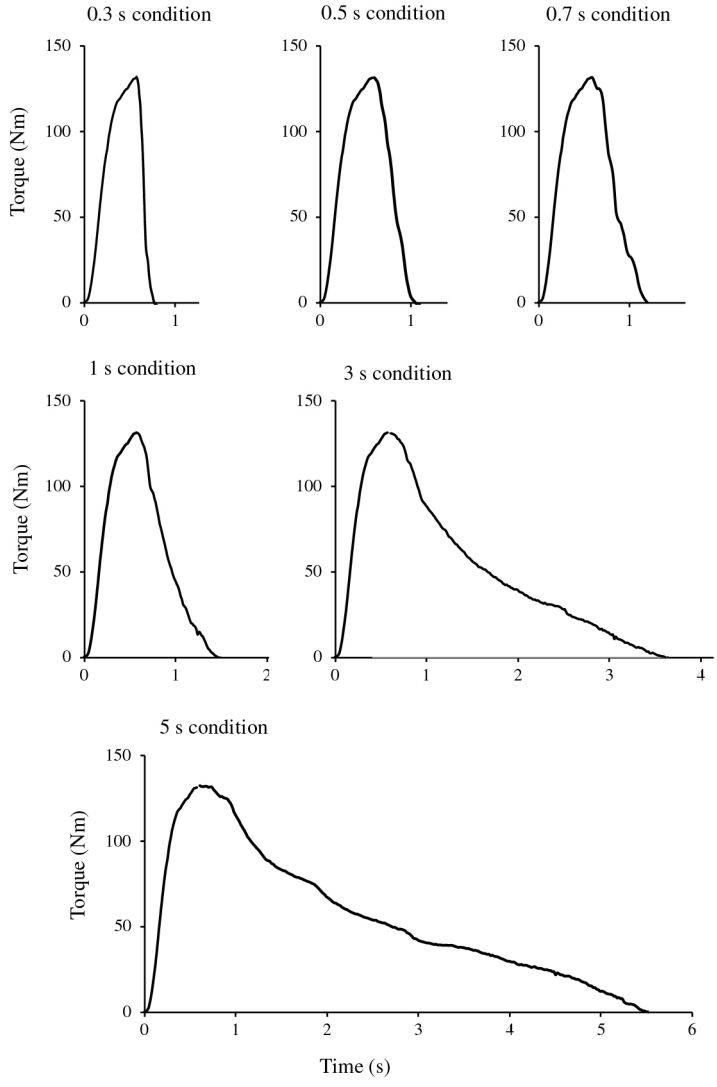

Figure 1. Typical examples of the exerted torque during six different relaxation time conditions.

unknown under the relaxation time condition of less than 1 s. An aqueous ingredient in the tendon is highly related to its viscosity and may significantly affect tendon hysteresis[8,16-18], especially if the relaxation time is less than 1 s.

The purpose of this study was to investigate the effect of relaxation time on tendon hysteresis *in vivo*. Based on the previous findings cited earlier, we hypothesized that the relaxation time up to 1 s would not affect the tendon hysteresis, but if it was less than 1 s, the shorter the relaxation time, the greater the tendon hysteresis.

Materials and Methods

Participants

Seventeen healthy males (age: 23.0±2.8 yrs, height: 173.6±6.4 cm, weight: 66.3±12.2 kg, mean±SD) volunteered for this study. They were fully informed of the procedures to be utilized, as well as the purposes of the study.

Stiffness and hysteresis of tendon structures

Participants lay prone on a specially designed dynamometer (Applied Office, Tokyo, Japan). Their right foot was tightly secured to the footplate of the dynamometer with two straps. The axes of the ankle and the footplate were aligned as close as possible. The right ankle joint was set at a neutral anatomical position (0 deg) with the knee joint at full extension. The measurements began with a standardized warm-up (including static stretching) and submaximal contractions to habituate to the tests. In the present study, they were asked to exert isometric plantar flexion torque from rest to maximal voluntary isometric contractions (MVC) within around 0.5

Table 1. Contraction time, relaxation time, MVC, ankle angle and maximal tendon elongation at MVC during the measurements Mean (SD), MVC; maximal voluntary isometric contraction.

	0.3 s	0.5 s	0.7 s	1 s	3 s	5 s
Contraction time (s)	0.50 (0.1)	0.57 (0.1)	0.56 (0.1)	0.63 (0.1)	0.60 (0.1)	0.62 (0.1)
Relaxation time (s)	0.35 (0.0)	0.54 (0.1)	0.73 (0.0)	1.16 (0.2)	3.00 (0.4)	4.93 (0.4)
MVC (Nm)	103.3 (21.5)	102.6 (20.8)	102.1 (20.5)	100.2 (20.2)	99.8 (21.6)	99.6 (20.0)
Ankle angle at MVC (deg)	3.3 (1.7)	3.0 (1.5)	3.0 (1.5)	3.2 (1.4)	3.3 (1.9)	3.1 (1.5)
Maximal tendon elongation at MVC (mm)	15.3 (2.0)	15.3 (2.3)	15.7 (2.0)	15.7 (2.5)	15.6 (2.7)	16.0 (2.5)

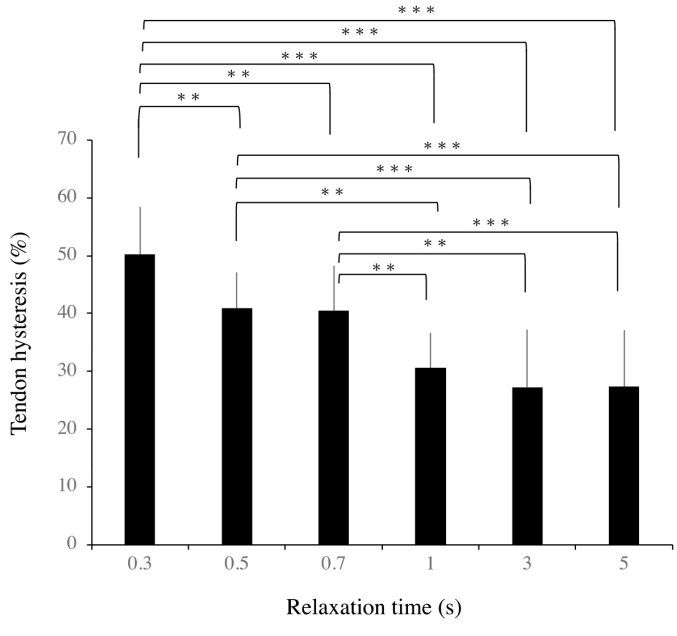

Figure 2. Tendon hysteresis of six different relaxation time conditions. Significant difference among the conditions: ** p<0.01, *** p<0.001.

s, followed by relaxation with six different times (0.3, 0.5, 0.7, 1, 3, and 5 s) (Figure 1). Torque data were collected at a sampling rate of 1 kHz. Firstly, participants performed two 3-s MVC of the plantar flexor muscles with a 2-min rest period between trials. After that, they practiced performing the six conditions as mentioned above. In the present study, contraction times at all conditions were the same (around 0.5 s from rest to MVC) in order to concentrate on adjusting the instructed relaxation time. The measurement was repeated twice for each condition with at least 2-min between trials in random order. The measured values that were shown below were the means of two trials. In the present study, however, one trial was excluded for each of the 0.7 s condition for 1 male, the 0.3 s and 5 s conditions for 2 males, the 0.5 s and 1 s conditions for 3 males, and the 3 s condition for 4 males due to unclear ultrasound images.

During an isometric contraction, ultrasonic images of the medial gastrocnemius muscle (MG) at the level of 30% of lower leg length were obtained using the ultrasonic apparatus (SSD-3500, Aloka, Tokyo, Japan). Ultrasonic images were recorded on a videotape at 60 Hz, synchronized with recording of a clock timer for subsequent analyses. To assess the tendon elongation, we measured the movement of the point at which one fascicle was attached to the aponeurosis. However, angular joint rotation occurred in the direction of ankle plantar flexion even during an isometric contraction[19]. An electrical goniometer (Penny and Giles, Newport, UK) was placed on the lateral aspect of the ankle in order to measure angle joint during an isometric contraction. Additional measurements were performed under passive conditions to correct the measurements taken for the tendon elongation. The movement of the point at which one

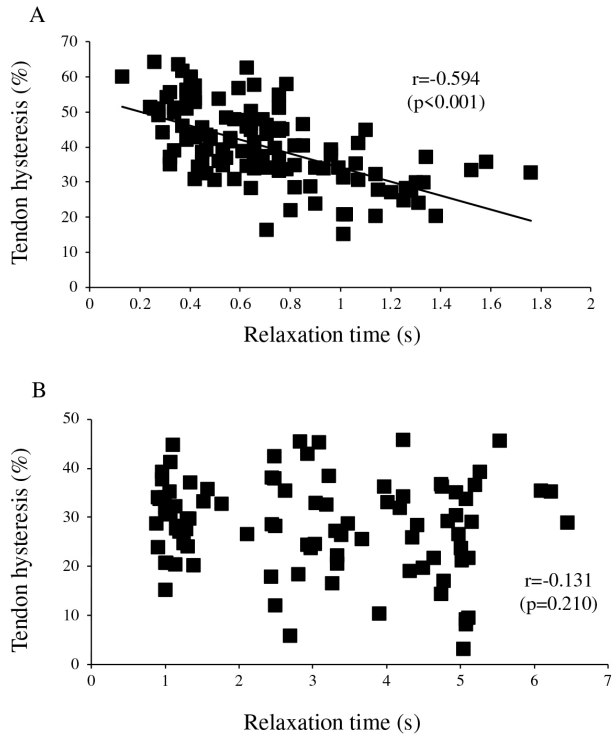

Figure 3. Relationship between the relaxation time and tendon hysteresis in each trial under 1 s or less (A) and 1 s or more (B) of relaxation time.

fascicle was attached to the aponeurosis for the influence of rotating the ankle from 0 to 9 deg was measured and was subtracted from the measured tendon elongation during an isometric contraction[5,19]. The area within the exerted torque–tendon elongation loop, as a percentage of the area beneath the curve during the ascending phase, was calculated as tendon hysteresis[11]. In the present study, we confirmed the repeatability of measurements of tendon hysteresis on the two trials for each condition. The coefficients of variation were 4.2% at 0.3 s, 8.7% at 0.5 s, 10.3% at 0.7 s, 10.1% at 1 s, 14.0% at 3 s, and 14.3% at 5 s conditions, respectively.

Statistical analysis

Descriptive data are presented as means±SD. For the means of two trials for each condition of the six different relaxation times, a one-way ANOVA with repeated measures was used to identify significant differences in the measured variables. In the event of significant values of F in the ANOVA, the Bonferroni post-hoc test of critical differences was used to assess the significance between means. The effect size was calculated using partial eta-squared ($p\eta^2$) for one-way ANOVA. For each trial (but not the means of two trials) of all subjects, a linear regression analysis was performed on the relationship between the relaxation time and tendon hysteresis. The level of significance was set at $p<0.05$.

Results

Under the six relaxation time conditions, the contraction time and relaxation time could be achieved in almost the set time (Tabel 1). There were no significant differences in MVC ($p=0.232$, $p\eta^2=0.081$), displacement of ankle joint angle at MVC ($p=0.561$, $p\eta^2=0.047$), or maximal tendon elongation at MVC ($p=0.143$, $p\eta^2=0.096$) among six relaxation time conditions (Table 1).

Figure 2 showed tendon hysteresis under the six types of relaxation time conditions. The effect of relaxation time on tendon hysteresis was significant ($p<0.001$, $p\eta^2=0.660$). From 1 s to 0.3 s conditions, the shorter the relaxation time, the greater the tendon hysteresis (except between 0.5 s and 0.7 s). Between 1 s and 5 s conditions, no significant differences in tendon hysteresis were found. In each trial of all subjects, the relationship between the relaxation time and tendon hysteresis showed a significantly negative correlation under 1 s or less of relaxation time, but no significant correlation was observed under the condition of 1 s or more (Figure 3).

Discussion

The main result of the present study was that under the condition that the relaxation time was less than 1 s, the shorter the relaxation time, the greater the tendon hysteresis. In contrast, no significant differences in tendon hysteresis were found among 1 s and 5 s conditions of the relaxation time. These results supported our hypothesis.

To date, few studies have examined the effect of relaxation time on tendon hysteresis[11,15], whereas the relationship between contraction time and tendon stiffness has been reported in several studies[11,20-22]. In addition, few *in vitro* studies have attempted to investigate the strain rate on tendon hysteresis[13,14]. These previous studies demonstrated that tendon hysteresis was independent of the strain rate. Regarding the human tendon *in vivo*, we previously reported that tendon hysteresis during ballistic contraction (relaxation time was around 0.5 s) was considerably greater than that during ramp contraction (relaxation time was around 5 s)[9,10,16], whereas there were no differences in tendon hysteresis of relaxation time from 1 s to 10 s[11,15]. The tendon hysteresis measured during ballistic contractions so far was around 35% to 40%, which was almost the same as the values of the 0.5 s (41.0%) and 0.7 s (40.4%) conditions in this study. Furthermore, the tendon hysteresis became even greater (50.3%) when examined in 0.3 s under a shorter relaxation time condition. As discussed in our previous studies[9,10,16], the increase in tendon hysteresis associated with the shortening of the relaxation time under the condition of less than 1 s is considered to be largely related to the viscosity caused by the water content in the tendon.

Previous studies have demonstrated that the relative work of tendons during stretch-shortening cycle exercise in humans is considerably higher[23,24]. In these studies, however, tendon hysteresis has been largely ignored in the calculations of work performed by muscles and tendons according to the results of *in vitro* studies where tendon hysteresis is below 10%[13]. Considering the present result on tendon hysteresis at shorter relaxation time conditions, the amount of elastic energy reused in the tendons by the model calculation may be overestimated as pointed out previously[8]. Previous studies reported that the duration during the push-off phase during running and jumping was around 0.2 s[25,26]. Therefore, we need to acquire tendon hysteresis data under a relaxation condition that is shorter than the 0.3 s condition of this study. In any case, in order to accurately evaluate the tendon work during stretch-shortening cycle exercises, tendon hysteresis data measured under relaxation time conditions close to the actual concentric phase time is required.

As mentioned in the introduction, no studies have experimentally demonstrated the effect of tendon hysteresis on efficiency during stretch-shortening cycle exercises. Furthermore, previous studies using ultrasonography reported that hysteresis of human tendons changed with aging, stretching, resistance training, and inactivity[10,16,27]. However, no studies have tightly controlled relaxation times during the measurement of tendon hysteresis. Based on the results of this study, we may say that it is important to unify the relaxation time, especially in the tendon hysteresis measurement under ballistic conditions, when investigating the relationship between tendon hysteresis and efficiency and conducting an intervention study.

Unfortunately, we did not measure the electromyographic activities of each agonist and antagonist muscles in the present study. In our previous studies[9,15], there were no differences in the relative electromyographic activities of each constituent muscle (to the sum of mEMG of all constituent muscles) and co-activation level during the relaxation phase between ramp (around 5 s) and ballistic (around 0.5 s) contractions. In addition, Kosters et al.[20] reported no differences in co-activation levels during the measurement of tendon properties among the different strain rates. Therefore, we considered that there were no differences in the relative activation levels among the synergist muscles and co-activation levels among the different relaxation time conditions in the present study.

In conclusion, the relaxation time greatly affected the tendon hysteresis under the condition that the relaxation time was less than 1 s. This result indicates that aligning the relaxation time when evaluating tendon hysteresis under a higher strain rate in intervention studies is necessary.

Ethics approval

This study was approved by the Ethics Committee for Human Experiments, Department of Life Science (Sports Sciences), The University of Tokyo (Issue Number: 779, approval date: November 2th, 2021).

Consent to Participate

Written informed consent was obtained from all participants.

Funding

This study was supported by a Grant-in-Aid for Scientific Research (B) (20H04070 to K. Kubo) from the Japan Society for the Promotion of Science.

References

1. Cavagna GA. Storage and utilization of elastic energy in skeletal muscle. Exerc Sport Sci Rev 1997;5:89–129.
2. Dawson TJ, Taylor CR. Energetic cost of locomotion in kangaroos. Nature 1973;246:313-314.
3. Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. Eur J Appl Physiol 2010;110:1037-1046.
4. Kubo K, Kanehisa H, Fukunaga T. Effects of viscoelastic properties of tendon structures on stretch-shortening cycle exercise *in vivo*. J Sports Sci 2005;23:851-860.
5. Kubo K, Miyazaki D, Shimoju S, Tsunoda N. Relationship between elastic properties of tendon structures and performance in long distance runners. Eur J Appl Physiol 2015;115:1725-1733.
6. Stafilidis S, Arampatzis A. Muscle-tendon unit

mechanical and morphological properties and sprint performance. J Sports Sci 2007;25:1035-1046.
7. Wang HK, Lin KH, Su SC, Shin TTF, Huang YC. Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes. Scand J Med Sci Sports 2012;22:e147-e155.
8. Butler DL, Grood ES, Noyes FK, Zernicke RF. Biomechanis of ligaments and tendons. Exer Sport Sci Rev 1978;6:125-181.
9. Kouno M, Ishigaki T, Ikebukuro T, Yata H, Kubo K. Effects of the strain rate on mechanical properties of tendon structures in knee extensors and plantar flexors *in vivo*. Sports Biomech 2021;20:887-900.
10. Kubo K. Effects of static stretching on mechanical properties and collagen fiber orientation of the Achilles tendon *in vivo*. Clin Biomech 2018;60:115-120.
11. Kubo K, Kawakami Y, Kanehisa H, Fukunaga T. Measurement of viscoelastic properties of tendon structures *in vivo*. Scand J Med Sci Sports 2002;12:3-8.
12. Finni T, Peltonen J, Stenroth L, Cronin NJ. Viewpoint: On the hysteresis in the human Achilles tendon. J Appl Physiol 2013;114:515-517.
13. Bennett MB, Ker RF, Dimery NJ, Alexander RMcN. Mechanical properties of various mammalian tendons. J Zoology 1986;209:537-548.
14. Ker RF. Dynamic tensile properties of the plantaris tendon of sheep. J Exp Biol 1981;93:283-302.
15. Yaeshima K, Kubo K, Ikebukuro T, Kanehisa H. Influence of contraction and relaxation time on the mechanical properties of human tendon. Jap J Biomech Sports Exer 2009;13:114-123 (in Japanese).
16. Ishigaki T, Kubo K. Mechanical properties and collagen fiber orientation of tendon in young and elderly. Clin Biomech 2020;71:5-10.
17. Kubo K. Effects of static stretching on mechanical properties and collagen fiber orientation of the Achilles tendon *in vivo*. Clin Biomech 2018;60:115-120.
18. Wang JHC. Mechanobiology of tendon. J Biomech 2006;39:1563-1582.
19. Magnusson SP, Aagaard P, Rosager S, Poulsen PD, Kjaer M. Load-displacement properties of the human triceps surae aponeurosis *in vivo*. J Physiol 2001;531:277-288.
20. Kosters A, Wiesinger HP, Bojsen-Moller J, Muller E, Seynnes OR. Influence of loading rate on patellar tendon mechanical properties *in vivo*. Clin Biomech 2014;29:323-329.
21. McCrum C, Oberlander KD, Epro G, et al. Loading rate and contraction duration effects on *in vivo* human Achilles tendon mechanical properties. Clin Physiol Funct Imaging 2018;38:517-523.
22. Theis N, Mohagheghi AA, Korff T. Method and strain rate dependence of Achilles tendon stiffness. J Electro Kinesiol 2012;22:947-953.
23. Bobbert MF, Huijing PA, van Ingen Schenau GJ. An estimation of power output and work done by the human triceps surae muscle-tendon complex in jumping. J Biomech 1986;19:899-906.
24. Voigt M, Bojsen-Moller F, Simonsen EB, Dyhre-Poulsen P. The influence of tendon youngs modulus, dimensions and instantaneous moment arms on the efficiency of human movement. J Biomech 1995;28:281-291.
25. Hof AL, Van Zandwijk JP, Bobbert MF. Mechanics of human triceps surae muscles in walking, running and jumping. Acta Physiol Scand 2002;174:17-30.
26. Ishikawa M, Niemela E, Komi PV. Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities. J Appl Physiol 2005;99:217-223.
27. Foure A, Nordez A, Cornu C. Plyometric training effects on Achilles tendon stiffness and dissipative properties. J Appl Physiol 2010;109:849-854.