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Plyometric training effects on Achilles tendon stiffness and dissipative properties

Alexandre Fouré, Antoine Nordez, and Christophe Cornu

Université de Nantes, Laboratoire "Motricité, Interactions, Performance," UFR STAPS, Nantes, France

Fouré A, Nordez A, Cornu C. Plyometric training effects on Achilles tendon stiffness and dissipative properties. *J Appl Physiol* 109: 849–854, 2010. First published June 24, 2010; doi:10.1152/jappphysiol.01150.2009.—The aim of this study was to determine the effects of 14 wk of plyometric training on mechanical properties of the Achilles tendon. Nineteen subjects were randomly assigned to trained or control group. Cross-sectional area (CSA), stiffness, and dissipation coefficient of the Achilles tendon were measured before and after the training period. In the trained group, a decrease in dissipation coefficient (-35.0% ; $P < 0.05$) and an upward trend in stiffness ($+24.1\%$) of the Achilles tendon was found, without any changes in Achilles tendon CSA ($P > 0.05$). Plyometric training enhances the muscular tension transmission mainly through a reduction in energy dissipated by the tendon. The lack of changes in the Achilles tendon CSA indicates that changes in mechanical properties would mainly result from a qualitative change in tendinous tissues rather than from changes in the geometry of the Achilles tendon.

hysteresis; energy; cross-sectional area; jump training

PLYOMETRIC TRAINING IS KNOWN to improve vertical jump performances (9, 22). During a plyometric exercise, the mechanical properties of the Achilles tendon, such as stiffness and dissipative properties, underlie the elastic energy storage-recoil process and the transmission of muscular tension (4). These mechanical properties may also play a role in debilitating injuries, including Achilles tendon rupture or tendinopathy (46).

It has been shown that strength and stretch training induce changes in the stiffness and dissipative properties of the Achilles tendon (19, 21). The results of previous studies on the effects of plyometric training on Achilles tendon stiffness remain conflicting. Burgess et al. (6) and Wu et al. (47) found an increase in Achilles tendon stiffness after 6 and 8 wk of plyometric training, respectively, whereas Kubo et al. (22) found no significant change in Achilles tendon stiffness after 12 wk of plyometric training.

Although Achilles tendon stiffness is considered an important mechanical property of the tendon, dissipative properties also influence the functional behavior of the tendon. Thus, during the loading and unloading of the tendon, the force-length relationship of the Achilles tendon classically displays a hysteresis, demonstrating the ability of the tendon to dissipate energy (23). This energy dissipation indicates that the muscular tension is not fully transmitted to the skeleton. Considering the process of plyometric training, if this hysteresis were to be decreased, the efficiency of the storage-recoil process in the tendon structure could be increased after 14 wk of strength

training, as shown by Reeves et al. (37). Surprisingly, changes in dissipative properties of the tendon have received little attention in the literature. To our knowledge, only one recent study has demonstrated that, astonishingly, the hysteresis characteristics of the tendon remained unchanged after 8 wk of plyometric training (47), contrasting with results obtained after 8 wk of combined strength and stretching training (19) (i.e., decrease in hysteresis). The plyometric training period of 8 wk may have been too brief to result in significant changes in the dissipative properties of the tendon. The effects of plyometric training on the dissipative properties of the tendon remain unclear. Hence, it is germane to assess tendon adaptation after a longer training period.

In addition, changes in the mechanical properties of the Achilles tendon after training may be due to changes in qualitative properties of the tendinous tissue (i.e., intrinsic mechanical properties of tendinous tissues) and/or changes in geometric parameters of the Achilles tendon structure (27). A review of the literature has revealed only one study that has investigated changes in Achilles tendon cross-sectional area (CSA) after plyometric training. These authors found no change in tendon CSA after 12 wk of plyometric training (22).

A comprehensive assessment of the geometric properties of the Achilles tendon (i.e., length and CSA) is needed to discuss the nature of the potential physiological mechanisms involved in the changes in mechanical properties after plyometric training.

The aim of the present study was to determine effects of 14 wk of plyometric training on the stiffness, dissipative properties, and geometric parameters of the Achilles tendon.

MATERIALS AND METHODS

Subjects. Nineteen men volunteered to participate in this study and were randomly assigned to the trained group ($n = 9$, 18.8 ± 0.9 yr, 177.3 ± 6.2 cm, 68.4 ± 6.5 kg) or control group ($n = 10$, 18.9 ± 1.0 yr, 179.8 ± 5.4 cm, 73.3 ± 8.0 kg). All subjects were involved in regular sport practices (10.5 ± 6.2 h/wk) and did not change their usual activity during the period of the study. Subjects were fully informed about the nature and the aim of the study before they signed a written consent form. This study was conducted according to the Helsinki Statement and has been approved by the local ethics committee.

Training. The plyometric training program consisted of standardized jumping protocols that have been defined in the literature (7, 36, 42). Specifically, the subjects performed the following: 1) squat jumps (SJ), defined as vertical jumps without prior counter-movement; 2) vertical counter movement jumps (CMJ); 3) drop jumps [i.e., hopping, jumps from either low (40 cm), medium (60 cm), or high (80 cm) platforms]; and 4) a series of jumps over hedges alternating between one foot and both feet. A constant increase in the number of exercises, the number of jumps per exercise, and intensity of the exercises (series of jumps from platforms where the height was increased) was performed. The duration of the training period was 14

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wk and included 34 one-hour sessions for a total of ~6,800 jumps (from 200 to 600 jumps/session).

Experimental design. All of the subjects of the trained group participated in three testing sessions before (pre-tests) and 1 wk after the end of the plyometric training period (post-tests). Untrained subjects were retested 15 wk after their respective baseline evaluation. The three independent testing sessions were performed on different days in a randomized order and were defined as follows: 1) a jump test session to determine performances in SJ, CMJ, and reactive jump (RJ); 2) a session to assess Achilles tendon mechanical properties (i.e., stiffness and dissipative properties) during isometric plantar flexion; and 3) a session to assess Achilles tendon geometric parameters (i.e., CSA and length).

Jump performances. Performances in SJ, CMJ, and RJ were determined for all subjects, using Bosco's jumping mat (Ergojump, Globus Italia, Codogne, Italy). The SJ was performed with a start angle of 90° of knee flexion. The maximal heights in SJ and CMJ were determined from the maximum of three trials. Average height in the eight RJ without knee flexion was also assessed. During all jump tests, subjects were instructed to place hands on their hips to minimize contribution of the arms during the jumps. The test was repeated if the subject did not adhere to the specific jumping protocol.

Achilles tendon geometric parameters. Measurements of the Achilles tendon CSA were performed by ultrasonographic imaging scans (Philips HD3, Philips Medical Systems, Andover, MA) with an electronic linear array probe (7.5-MHz wave frequency; L9-5, Philips Medical Systems, Andover, MA). 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 performed in the transverse plane with the transducer perpendicular to the Achilles tendon at the level of the medial malleolus (48). Images were saved to a hard disk, and CSA was determined using open-source digital measurement software (Image J, NIH, Bethesda, MD). The CSA was averaged over at least three images. Achilles tendon length (L) was defined as the distance between the most distal identifiable portion of the gastrocnemius medialis muscle (23, 39) and Achilles tendon insertion on calcaneum, measured via ultrasonography. L was measured by using a ruler (30).

Achilles tendon mechanical properties. A Biodex System 3 Research (Biodex Medical, Shirley, NY) 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 position as previously described (9, 33). 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, ankle angle, and angular velocity were sampled at 1,000 Hz using an analog-to-digital converter (National Instrument, Delsys, Boston, MA) and stored on a hard drive using EMGWorks 3.1 software (Delsys) for further analysis.

The session that assessed the mechanical properties of Achilles tendon included the following protocols. 1) A warm-up consisting of constant submaximal isometric plantar flexion. 2) Two maximal voluntary isometric contractions in plantar flexion and dorsi 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 for the two trials. The maximal rate of torque development in plantar flexion (RTD_{max}), defined as the maximal slope of the torque-time relationship, was also characterized for the two MVC trials. 4) 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. 5) Five trials of

constant isometric torque development in plantar flexion as described in *point 3* were then performed by each subject with 2 min of rest between each trial. 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 disk 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, comprised of 20 images equally spaced from both the loading and unloading phases of torque development, were collected (Adobe Premiere Elements, Adobe Systems, San Jose, CA) from each trial. Displacements of the myotendinous junction were quantified on these 40 images using open-source digital measurement software (Image J).

The ankle joint torque measured by the dynamometer was converted to tendon force (Ft) using Eq. 1 (3):

$$F_t = T/m_g \quad (1)$$

where T is the ankle joint torque and m_g is the moment arm length of gastrocnemii at 0°, which was estimated from the limb length of each subject (12). Myotendinous junction displacement is classically attributed to both angular rotation and contractile tension, since any angular joint rotation occurs in the direction of ankle plantar flexion during an "isometric" contraction (1, 25). This myotendinous junction displacement determined during isometric contraction is usually corrected by the displacement of the myotendinous junction attributed to joint rotation alone (i.e., during passive stretching on range of motion, between 0 and 20° in plantar flexion) (1, 25). In the present study, corrections were applied using an electronic goniometer (Biopac Systems, Santa Barbara, CA) synchronized with the analog signals and ultrasonic images (24). The ratio of the calculated Ft and the corrected elongation (ΔL) (i.e., displacement of myotendinous junction) were 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 the present study, the Ft and ΔL values from the ascending curve between 50 and 90% of minimal MVC (i.e., determined before and after intervention period) were fitted to a linear regression equation, the slope of which was defined as the Achilles tendon stiffness (S_{AT}) (19). In addition, a stiffness index (SI_{SK}) was determined from a Sten-Knudsen model (34, 43) fitted to the Ft and ΔL values. Thus the SI_{SK} allows the assessment of changes in stiffness, independent of tendon force changes.

The maximal elongation was defined as ΔL_{max}. 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 (23, 32, 35). From these parameters, a dissipation coefficient (DC) was calculated by using Eq. 2:

$$DC : (E_S - E_R)/1 \quad (2)$$

Statistics. After checking the distribution of data, parametric statistical tests were performed using Statistica software (Statsoft, Tulsa, OK). Two-way multivariate ANOVA (group × test) were performed to assess the statistical significance of changes in jump performances, MVC, RTD_{max}, ΔL_{max}, L, CSA, S_{AT}, normalized stiffness (S_{AT}/CSA), SI_{SK}, and DC. A Newman-Keuls post hoc analysis was conducted where appropriate. The critical level of significance in the present study was set at P < 0.05.

Reliability. A pilot study was conducted on seven subjects (25.4 ± 2.4 yr, 178.7 ± 8.8 cm, 72.8 ± 9.9 kg) in conjunction with the present study to assess the reliability of the methods to determine the MVC, the RTD_{max}, and the geometric and mechanical properties of the Achilles tendon. Two repeated testing sessions completed at the same

Table 1. Reliability assessment for each parameters

Day-to-Day Reliability (2,k)	ICC	CV, %	SE
MVC, N·m	0.93	5.7	5
RTD _{max} , N·m/s	0.91	7.2	63
L, mm	0.95	1.9	4
rL _{max} , mm	0.95	4.1	0.7
CSA, mm ²	0.99	2.2	0.8
SI _{SK} , mm ⁻¹	0.98	9.6	0.013
S _{AT} , N/mm	0.98	4.7	17.5
S _{AT} /CSA, N/mm ³	0.99	3.2	0.22
DC, %	0.94	20.0	4.6

Intraclass correlation coefficient (ICC), variation coefficient (CV), and standard error of the mean (SE) were calculated to establish day-to-day reliability for maximal voluntary contraction (MVC), maximal rate of torque development (RTD_{max}), Achilles tendon length (L), Achilles tendon maximal elongation (rL_{max}), Achilles tendon cross-sectional area (CSA), Sten-Knudsen stiffness index (SI_{SK}), tendon stiffness (S_{AT}), and dissipation coefficient (DC) of the Achilles tendon during isometric contraction and relaxation.

time of day with 2 days of rest in between were performed. Intraclass correlation coefficients (ICC) (8) were calculated and are presented in Table 1 (ICC ranged from 0.82 to 1.00). In addition, the standard error of the mean and coefficient of variation associated with each ICC were calculated (Table 1). These results support the reliability of the methods proposed in the present study described herein.

RESULTS

An interaction between “group” and “test” factors was found for SJ, CMJ, and RJ performances ($P < 0.05$). For the trained group, a significant increase in height was shown in the SJ (mean: +11.0%; $P < 0.001$), CMJ (mean: +7.4%; $P < 0.02$), and average performance on eight RJ (mean: +27.7%; $P < 0.001$). A significant increase in MVC was also seen for the trained group (+5.2%; $P < 0.01$), whereas no significant change in RTD_{max} was found ($P = 0.10$) (Table 2). For the control group, no significant changes were observed for any of the considered parameters ($P > 0.05$).

The mean relationships between Ft and ΔL for both groups are presented in Fig. 1. Linear regression and the Sten-Knudsen model applied on individual Ft- ΔL curves showed a very good correlation coefficient (mean $R^2 = 0.98 \pm 0.02$ and 0.99 ± 0.01 , respectively), which allowed the calculation of S_{AT} and SI_{SK}, respectively.

No significant difference was found at baseline between control and trained groups for all the parameters. Interactions

Table 2. Functional performances for trained and control groups

	Trained Group		Control Group	
	Pretest	Posttest	Pretest	Posttest
SJ maximal height, cm	37.5 ± 4.4	41.5 ± 4.2*	34.7 ± 7.8	35.5 ± 8.3
CMJ maximal height, cm	44.5 ± 4.8	47.5 ± 3.8†	40.3 ± 7.8	39.5 ± 6.9
Average height on 8 RJ, cm	32.3 ± 5.1	40.6 ± 3.0*	27.8 ± 2.8	25.2 ± 4.2
MVC, N·m	133 ± 16	141 ± 18‡	131 ± 16	132 ± 15
RTD _{max} , N·m/s	1,389 ± 447	1,490 ± 426	1,448 ± 362	1,386 ± 331

Jump performances (SJ, squat jump; CMJ, counter movement jump; RJ, reactive jump), MVC, and RTD_{max} in trained and control groups before (pretest) and after (posttest) 14 wk of plyometric training. Results are presented as means ± SD. Post hoc test: * $P < 0.001$; † $P < 0.02$; ‡ $P < 0.01$.

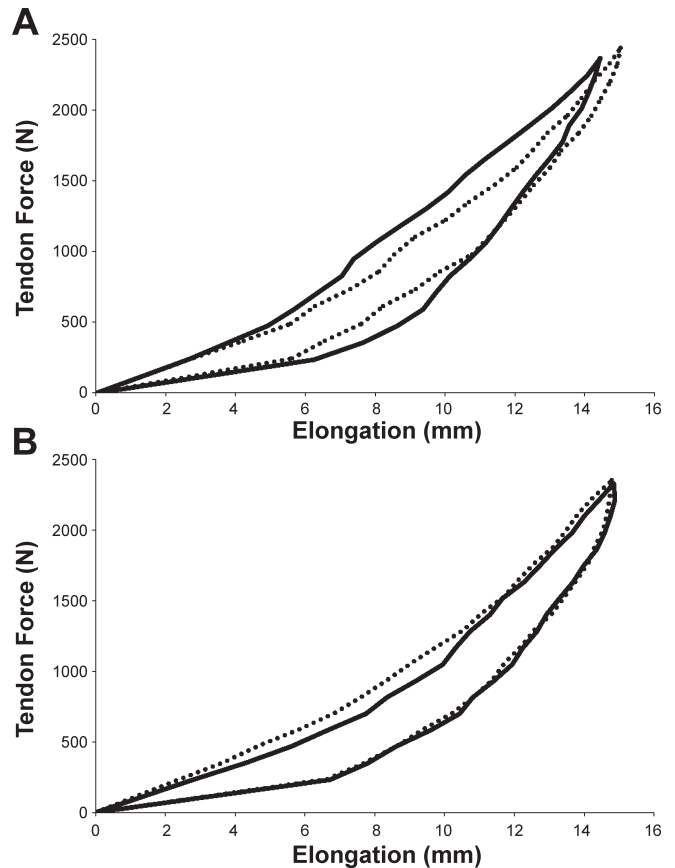


Fig. 1. Mean relationship between the tendon force (Ft) and the Achilles tendon elongation (ΔL) in the trained group (A) and the control group (B) in pretest (solid line) and posttest (broken line). Standard deviation bars were removed for clarity.

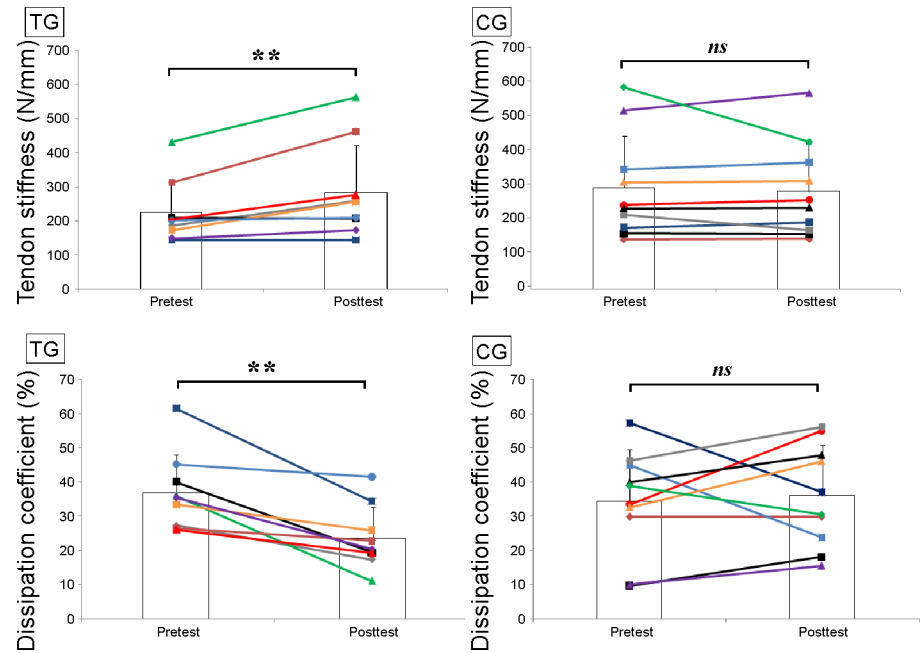
were found between “group” and “test” factors on SI_{SK}, S_{AT}, S_{AT}/CSA, and DC ($P < 0.05$) (Table 3; Fig. 2). Individual changes in S_{AT} and DC are also shown on Fig. 2. Significant increases of 24.1 and 65.2% in S_{AT} and SI_{SK} were found for the trained group ($P < 0.05$). Concerning normalized stiffness (i.e., S_{AT}/CSA), a significant increase of 21.0% was observed ($P < 0.05$), and a decrease of 35.0% in DC was determined for the trained group ($P < 0.05$). There was no significant effect of training on L, ΔL_{max} , and CSA ($P > 0.05$) (Table 3). For the control group, no significant changes were observed, whatever the considered parameters ($P > 0.05$).

Table 3. Tendon geometric and mechanical parameters for trained and control groups

	Trained Group		Control Group	
	Pretest	Posttest	Pretest	Posttest
L, mm	199 ± 24	200 ± 25	198 ± 24	200 ± 25
ΔL_{max} , mm	14.5 ± 2.8	15.1 ± 2.5	14.8 ± 2.1	14.8 ± 2.8
CSA, mm ²	55.6 ± 12.2	57.3 ± 13.1	53.8 ± 9.7	55.3 ± 8.6
SI _{SK} , mm ⁻¹	0.09 ± 0.07	0.11 ± 0.06	0.13 ± 0.07	0.09 ± 0.07
S _{AT} /CSA, N/mm ³	4.40 ± 2.47	5.54 ± 3.74*	5.54 ± 2.25	5.15 ± 2.55

Achilles tendon L, ΔL_{max} , CSA, SI_{SK}, and S_{AT}/CSA before and after plyometric training period for both control and trained groups. Results are means ± SD. Post hoc test: * $P < 0.01$.

Fig. 2. Mean \pm SD and individual values of the tendon stiffness and the dissipation coefficient between pretest and posttest for both trained (TG) and control (CG) groups. ns, Nonsignificant. **Significant difference ($P < 0.05$).



DISCUSSION

The aim of the present study was to determine the effects of 14 wk of plyometric training on the stiffness and dissipative properties of the Achilles tendon. The main results revealed a decrease in the dissipation coefficient of the Achilles tendon (-35.0% , $P < 0.05$) as a result of training without any changes in geometric parameters (i.e., CSA and L ; $P > 0.05$).

The increases in jump performances (between 7.4 and 27.7% according to the respective jump form) and MVC (+5.2%) after the plyometric training for the trained group are in agreement with published results from the literature. For example, a meta-analytic review reported an increase of 4.7 and 8.7% in SJ and CMJ performances, respectively, after 4–24 wk of plyometric training (29). In addition, a 13% increase in MVC has been reported after a similar training protocol (22). The values and change in RTD_{max} assessed in the present study are also in close agreement with other studies (15). The upward trend in RTD_{max} of 12.7% ($P = 0.10$) has been shown to exist after plyometric training (6). Therefore, jumps, MVC, and RTD_{max} results obtained in the present study demonstrate the functional efficiency of the described plyometric training program herein.

Nevertheless, some methodological points of the present study should be discussed before further discussion. First of all, the reliability of the methods proposed to study changes in tendon mechanical properties may limit the ability to detect small changes in some parameters. However, a satisfactory reliability for all of the parameters is reported in Table 1, indicating that they could be used to assess the effects of a chronic intervention.

Second, the relative contribution of muscles other than the triceps surae to active plantar flexion torque is not taken into account in the present study. This is the situation for many other studies determining effects of chronic intervention on Achilles tendon mechanical properties (e.g., Refs. 17–20, 28, 37, 44). Nevertheless, the relative contribution of the triceps surae muscles and other muscles to active ankle plantar flexor

torque could have changed in a different way in subjects who do and do not undertake plyometric training. The contribution of the triceps surae muscles to active plantar flexion torque could be estimated from relative physiological CSA (11). In an additional study, architectural parameters and CSA of the triceps surae muscles (i.e., averaged on three levels of the lower leg length) were assessed using ultrasonography. No significant change was found in pennation angle, fascicle length, and CSA for each muscle of the triceps surae ($P > 0.05$). Architectural parameters and CSA of the other muscles involved in plantar flexion torque were not assessed in the present study, but the contribution of other muscles to plantar flexion torque production is limited to $\sim 20\%$ in our experiments (2, 31, 45). Thus even a significant change of $\sim 10\%$ of the PCSA of the other muscles should have a minor influence on the results of the present study ($\sim 2\%$). Therefore, considering the magnitude of the changes in S_{AT} and DC (i.e., +24 and 35%, respectively, for the trained group), the contribution of other muscles is likely to have a minor influence on the results of the present study concerning the effects of plyometric training.

In addition, due to an increase (i.e., +5.2%) of the MVC after the training period, the force level was not identical before and after the intervention period. Since the stiffness of the Achilles tendon was calculated at the same level of force for both tests, this parameter was not affected by this limit. To determine whether the range of force production has influence on parameters related to DC, a supplementary experiment was performed. Seven subjects (27.7 ± 4.8 yr, 178.0 ± 7.9 cm, 72.0 ± 13.7 kg) volunteered to participate in this experiment to determine the DC during three different isometric contractions from rest, to 90, 84, and 70% of MVC, respectively. The force range excluded, the same protocol as described in MATERIALS AND METHODS was performed. One-way ANOVA revealed no significant effect of the force range (i.e., 70, 84, and 90%) for the DC ($P = 0.48$; 70% of MVC: $16.3 \pm 13.0\%$; 84% of MVC:

18.2 ± 16.1%; 90% of MVC: 18.8 ± 15.1%), indicating that, due to the normalization of the energy dissipated with energy stored, the force range has no significant influence on this parameter. Therefore, this parameter truly represents the ability of the tendon to dissipate potential elastic energy independently from the chosen range of force.

Changes in tendon stiffness after plyometric training remain an issue under debate. A significant increase in S_{AT} was found for the trained group ($P < 0.05$). Nevertheless, a nonsignificant baseline imbalance ($P > 0.05$) in S_{AT} is observed between trained (224.7 ± 92.2 N/mm) and control (301.8 ± 149.8 N/mm) groups (Fig. 2). The baseline imbalance is detrimental for statistical evidence of a training effect (e.g., Ref. 5), and a significant effect in the trained group could then potentially be misleading. Therefore, we conclude that the significant increase in S_{AT} would more appropriately be considered as an upward trend for the trained group. The upward trend in S_{AT} is consistent with most previous studies concerning plyometric training effect on tendon stiffness (10, 22). This upward trend in S_{AT} was not concomitant with an increase in CSA ($P < 0.05$). The lack of change in CSA after training is similar to the findings of Kubo et al. (22).

To our knowledge, only two studies have reported results on tendon elastic energy utilization after a plyometric training period (22, 47). Kubo et al. (22) showed an increase of ~9.5 and 19.6% in maximal tendon elongation and energy stored by the tendon during loading phase, respectively, after 12 wk of training. Wu et al. (47) also found an increase of ~32.5% in energy stored during the loading phase. Although a similar increase in the recoiled energy was found in the study by Wu et al. (47), no change in the hysteresis area (i.e., dissipation coefficient) was determined compared with a control group after 8 wk of plyometric training. In the present study, a significant decrease of 35.0% in the dissipation coefficient without any significant change in energy storage and recoil was characterized as a result of 14 wk of plyometric training. This decrease in dissipation coefficient was also observed after long-term strength training (38). The discrepancy in the dissipative properties of the Achilles tendon change, considering studies dealing with plyometric training effects may be due to training intensity and volume [i.e., ~1,500 jumps in the study of Wu et al. (47) vs. ~6,800 jumps in the present study] and/or duration of training (i.e., 8 wk vs. 14 wk, respectively). It has already been shown in animal models that tendons submitted to high physiological loading levels exhibit lower mechanical hysteresis than tendons subjected to smaller loads (41). The decrease in hysteresis area improves muscular tension transmission and probably partially contributes to the increase in jump performance.

Considering the lack of change in CSA in the present study, changes in S_{AT} and DC mainly result from qualitative change of tendinous tissues (i.e., intrinsic mechanical properties of tendinous tissues) rather than from changes in the geometric parameters of the Achilles tendon structures. Since long-term recreational running in untrained individuals was not sufficient to increase the Achilles tendon CSA (13, 26), the increase in tendon CSA in humans may require prolonged anamnesis of training (14). Nevertheless, it has recently been shown that changes in tendon CSA seem to be inhomogeneous and rather occur near the tendon insertions as observed on the patellar tendon after 9 and 12 wk of knee extension heavy resistance

training (16, 40). Even if our results concerning change in Achilles tendon CSA are similar to those of Kubo et al. (22), it must be considered that change in Achilles tendon CSA could have been undetectable in the present study, considering the measurement of CSA was performed at the middle level of the Achilles tendon.

As described in the present study, appropriate mechanical loading can result in positive changes in the tendinous structures and may lead to improved performance, whereas excessive loading may induce tendon degeneration (28). However, the lack of change in CSA found in the present study combined with the increase in MVC and subsequent tendon stress may predispose the tendon to injuries (i.e., rupture and tendinopathy). In addition, the decrease in Achilles tendon DC would reduce the tendon capacity to protect muscles from mechanical loading and potentially increase risks of muscle or tendon injuries.

In summary, the present study determined the plyometric training effects on the stiffness, dissipative properties, and geometric parameters of the Achilles tendon. Plyometric training enhances the muscular tension transmission and storage-recoil of elastic energy via a decrease in energy dissipated by tendon structures and an upward trend in Achilles tendon stiffness. Thus long-term plyometric training induced changes in mechanical properties of tendinous structures, which partially explain the performance improvements, but may also increase the risk of muscle or tendon injuries.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

REFERENCES

1. Arampatzis A, Monte GD, Karamanidis K. Effect of joint rotation correction when measuring elongation of the gastrocnemius medialis tendon and aponeurosis. *J Electromyogr Kinesiol* 18: 503–508, 2007.
2. Arndt AN, Komi PV, Bruggemann GP, Lukkariniemi J. Individual muscle contributions to the in vivo achilles tendon force. *Clin Biomech (Bristol, Avon)* 13: 532–541, 1998.
3. Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. *J Appl Physiol* 108: 670–675, 2010.
4. Bosco C, Tihanyi J, Komi PV, Fekete G, Apor P. Store and recoil of elastic energy in slow and fast types of human skeletal muscles. *Acta Physiol Scand* 116: 343–349, 1982.
5. Brookes ST, Whitely E, Egger M, Smith GD, Mulheran PA, Peters TJ. Subgroup analyses in randomized trials: risks of subgroup-specific analyses; power and sample size for the interaction test. *J Clin Epidemiol* 57: 229–236, 2004.
6. Burgess KE, Connick MJ, Graham-Smith P, Pearson SJ. Plyometric vs. isometric training influences on tendon properties and muscle output. *J Strength Cond Res* 21: 986–989, 2007.
7. Cornu C, Almeida Silveira MI, Goubel F. Influence of plyometric training on the mechanical impedance of the human ankle joint. *Eur J Appl Physiol Occup Physiol* 76: 282–288, 1997.
8. Fleiss JL. *The Design and Analysis of Clinical Experiment*. New York: Wiley, 1986, p. 186–192.
9. Fouré A, Nordez A, Guette M, Cornu C. Effects of plyometric training on passive stiffness of gastrocnemii and the musculo-articular complex of the ankle joint. *Scand J Med Sci Sports*. In press.
11. Fukunaga T, Roy RR, Shellock FG, Hodgson JA, Edgerton VR. Specific tension of human plantar flexors and dorsiflexors. *J Appl Physiol* 80: 158–165, 1996.

12. **Grieve DW, Cavanagh PR, Pheasant S.** Prediction of gastrocnemius length from knee and ankle joint posture. In: *Biomechanics VI-A*, edited by Asmussen E, Jorgensen K. Baltimore, MD: University Park Press Baltimore, 1978, p. 405–411.
13. **Hansen P, Aagaard P, Kjaer M, Larsson B, Magnusson SP.** Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *J Appl Physiol* 95: 2375–2380, 2003.
14. **Kjaer M.** Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiol Rev* 84: 649–698, 2004.
15. **Klass M, Baudry S, Duchateau J.** Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions. *J Appl Physiol* 104: 739–746, 2008.
16. **Kongsgaard M, Reitelsheder S, Pedersen TG, Holm L, Aagaard P, Kjaer M, Magnusson SP.** Region specific patellar tendon hypertrophy in humans following resistance training. *Acta Physiol (Oxf)* 191: 111–121, 2007.
17. **Kubo K, Akima H, Ushiyama J, Tabata I, Fukuoka H, Kanehisa H, Fukunaga T.** Effects of 20 days of bed rest on the viscoelastic properties of tendon structures in lower limb muscles. *Br J Sports Med* 38: 324–330, 2004.
18. **Kubo K, Kanehisa H, Fukunaga T.** Effect of stretching training on the viscoelastic properties of human tendon structures in vivo. *J Appl Physiol* 92: 595–601, 2002.
19. **Kubo K, Kanehisa H, Fukunaga T.** Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol* 538: 219–226, 2002.
20. **Kubo K, Kanehisa H, Ito M, Fukunaga T.** Effects of isometric training on the elasticity of human tendon structures in vivo. *J Appl Physiol* 91: 26–32, 2001.
21. **Kubo K, Kanehisa H, Kawakami Y, Fukunaga T.** Influence of static stretching on viscoelastic properties of human tendon structures in vivo. *J Appl Physiol* 90: 520–527, 2001.
22. **Kubo K, Morimoto M, Komuro T, Yata H, Tsunoda N, Kanehisa H, Fukunaga T.** Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc* 39: 1801–1810, 2007.
23. **Maganaris CN.** Tensile properties of in vivo human tendinous tissue. *J Biomech* 35: 1019–1027, 2002.
24. **Maganaris CN.** Validity of procedures involved in ultrasound-based measurement of human plantarflexor tendon elongation on contraction. *J Biomech* 38: 9–13, 2005.
25. **Magnusson SP, Aagaard P, Dyhre-Poulsen P, Kjaer M.** Load-displacement properties of the human triceps surae aponeurosis in vivo. *J Physiol* 531: 277–288, 2001.
26. **Magnusson SP, Beyer N, Abrahamsen H, Aagaard P, Neergaard K, Kjaer M.** Increased cross-sectional area and reduced tensile stress of the Achilles tendon in elderly compared with young women. *J Gerontol A Biol Sci Med Sci* 58: 123–127, 2003.
27. **Magnusson SP, Narici MV, Maganaris CN, Kjaer M.** Human tendon behaviour and adaptation, in vivo. *J Physiol* 586: 71–81, 2008.
28. **Mahieu NN, McNair P, Cools A, D’Haen C, Vandermeulen K, Witvrouw E.** Effect of eccentric training on the plantar flexor muscle-tendon tissue properties. *Med Sci Sports Exerc* 40: 117–123, 2008.
29. **Markovic G.** Does plyometric training improve vertical jump height? A meta-analytic review. *Br J Sports Med* 41: 349–355, 2007.
30. **Muraoka T, Muramatsu T, Fukunaga T, Kanehisa H.** Elastic properties of human Achilles tendon are correlated to muscle strength. *J Appl Physiol* 99: 665–669, 2005.
31. **Murray MP, Guten GN, Baldwin JM, Gardner GM.** A comparison of plantar flexion torque with and without the triceps surae. *Acta Orthop Scand* 47: 122–124, 1976.
32. **Nordez A, Casari P, Cornu C.** Effects of stretching velocity on passive resistance developed by the knee musculo-articular complex: contributions of frictional and viscoelastic behaviours. *Eur J Appl Physiol* 103: 243–250, 2008.
33. **Nordez A, Casari P, Mariot JP, Cornu C.** Modeling of the passive mechanical properties of the musculo-articular complex: acute effects of cyclic and static stretching. *J Biomech* 42: 767–773, 2009.
34. **Nordez A, Cornu C, McNair P.** Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. *Clin Biomech (Bristol, Avon)* 21: 755–760, 2006.
35. **Nordez A, McNair P, Casari P, Cornu C.** Acute changes in hamstrings musculo-articular dissipative properties induced by cyclic and static stretching. *Int J Sports Med* 29: 414–418, 2008.
36. **Pousson M, Van Hoecke J, Goubel F.** Changes in elastic characteristics of human muscle induced by eccentric exercise. *J Biomech* 23: 343–348, 1990.
38. **Reeves ND, Narici MV, Maganaris CN.** Strength training alters the viscoelastic properties of tendons in elderly humans. *Muscle Nerve* 28: 74–81, 2003.
39. **Rosager S, Aagaard P, Dyhre-Poulsen P, Neergaard K, Kjaer M, Magnusson SP.** Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports* 12: 90–98, 2002.
40. **Seynnes OR, Erskine RM, Maganaris CN, Longo S, Simoneau EM, Grosset JF, Narici MV.** Training-induced changes in structural and mechanical properties of the patellar tendon are related to muscle hypertrophy, but not to strength gains. *J Appl Physiol* 107: 523–530, 2009.
41. **Shadwick RE.** Elastic energy storage in tendons: mechanical differences related to function and age. *J Appl Physiol* 68: 1033–1040, 1990.
42. **Spurrs RW, Murphy AJ, Watsford ML.** The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 89: 1–7, 2003.
43. **Sten-Knudsen O.** Torsional elasticity of the isolated cross striated muscle fibre. *Acta Physiol Scand* 28: 1–240, 1953.
44. **Urlando A, Hawkins D.** Achilles tendon adaptation during strength training in young adults. *Med Sci Sports Exerc* 39: 1147–1152, 2007.
45. **van Zandwijk JP, Bobbert MF, Harlaar J, Hof AL.** From twitch to tetanus for human muscle: experimental data and model predictions for m. triceps surae. *Biol Cybern* 79: 121–130, 1998.
46. **Witvrouw E, Mahieu N, Danneels L, McNair P.** Stretching and injury prevention: an obscure relationship. *Sports Med* 34: 443–449, 2004.
47. **Wu YK, Lien YH, Lin KH, Shih TT, Wang TG, Wang HK.** Relationships between three potentiation effects of plyometric training and performance. *Scand J Med Sci Sports* 20: 80–86, 2009.
48. **Ying M, Yeung E, Li B, Li W, Lui M, Tsoi CW.** Sonographic evaluation of the size of Achilles tendon: the effect of exercise and dominance of the ankle. *Ultrasound Med Biol* 29: 637–642, 2003.