Effects of ballistic stretching training on the properties of human muscle and tendon structures

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Submitted 26 February 2014; accepted in final form 5 May 2014

Konrad A, Tilp M. Effects of ballistic stretching training on the properties of human muscle and tendon structures. J Appl Physiol 117: 29–35, 2014. First published May 8, 2014; doi:10.1152/japplphysiol.00195.2014.—The purpose of this study was to investigate the influence of a 6-wk ballistic stretching training program on various parameters of the human gastrocnemius medialis muscle and the Achilles tendon. It is known that ballistic stretching is an appropriate means of increasing the range of motion (RoM), but information in the literature about the mechanical adaptation of the muscle-tendon unit (MTU) is scarce. Therefore, in this study, a total of 48 volunteers were randomly assigned into ballistic stretching and control groups. Before and following the stretching intervention, we determined the maximum dorsiflexion RoM with the corresponding fascicle length and pennation angle. Passive resistive torque (PRT) and maximum voluntary contraction (MVC) were measured with a dynamometer. Muscle-tendon junction (MTJ) displacement allowed us to determine the length changes in tendon and muscle, and hence to calculate stiffness. Mean RoM increased significantly from 33.8 ± 6.3° to 37.8 ± 7.2° only in the intervention group, but other functional (PRT, MVC) and structural (fascicle length, pennation angle, muscle stiffness, tendon stiffness) parameters were unaltered. Thus the increased RoM could not be explained by structural changes in the MTU and was likely due to increased stretch tolerance.

stiffness; ultrasound; passive resistive torque; maximum voluntary contraction; range of motion

THE THREE MOST COMMON stretching methods are static, ballistic, and proprioceptive neuromuscular facilitation (PNF) stretching (7, 26, 33, 45). All methods are used for both acute (a single stretching session) and short-term (repeated stretching training for 3–8 wk) stretching and are able to increase the range of motion (RoM) (28, 30, 31, 36). Various authors have reported that repeated static stretching does not affect the torque-angle curve (9, 12, 27, 40) or standardized torque (2, 3, 8, 22) in the pre- and postintervention. Others, however, have identified decreased PRT, and therefore changes in the torque-angle curve, after a short-term static stretching regime (11, 21, 30, 36). Furthermore, there is some evidence that static stretching does not alter maximal isometric torque (MVC, 21) or tendon stiffness (defined as force-length relationship during an isometric ramp contraction with maximal voluntary effort; 21, 30) following a 3- to 6-wk training period. Although there have been several studies on the effects of short-term static stretching on structural parameters (21, 30, 36), similar studies on PNF (20, 31) or ballistic (30) stretching training are scarce. During a ballistic stretch, the joint is placed, similar to a static stretch, at the maximum RoM, where a dynamic “ballistic” movement is applied on the stretched structure at the end of the RoM. To the best of the authors’ knowledge, so far only Mahieu and coworkers (30) have analyzed the effects of a short-term ballistic stretching program on functional and structural muscle-tendon parameters. Mahieu et al. (30) reported an increase in RoM, no changes in PRT, and a decrease in Achilles tendon stiffness. However, several structural parameters that might affect and explain RoM changes, such as muscle and tendon stiffness during passive movements (17, 20), as well as fascicle length and pennation angle (20, 34), were not analyzed by these authors (30). Therefore, the objective of this study was to analyze the effects of a ballistic stretching program on the functional and structural parameters of the ankle plantar flexors. Since tendon, like muscle tissue, undergoes substantial structural changes as a result of a number of chronic processes, such as aging (37, 38), chronic use (5), disuse (6, 39), exercise (41), and static or PNF stretching (17, 20), we also expected changes as a result of the ballistic stretching training.

Due to the findings in the literature, we hypothesized to observe a gain in RoM, a decrease in PRT, but no change in MVC following a 6-wk ballistic stretching training program. Moreover, we expected that the ballistic stretching training would result in structural changes, i.e., more compliant muscle or tendon tissue, as well as longer fascicle length and/or smaller pennation angles.

METHODS

Subjects

Thirty healthy male (mean ± SD: 23.2 ± 2.4 yr, 179.9 ± 6.2 cm, 75.3 ± 6.9 kg) and 18 healthy female (mean ± SD: 22.1 ± 2.7 yr, 170.1 ± 4.1 cm, 61.9 ± 5.9 kg) police cadets participated in this study. Each subject was informed about the testing procedure but not about our hypotheses, and they each gave written consent to participate in the study. Competitive athletes and participants with a history of lower-leg injuries were excluded. The Ethical Committee of the University of Graz approved the study.

Experimental Design

A total of 48 police cadets participated in the study, and they were randomly assigned to a ballistic stretching group (N = 24) and a control group (N = 24) by picking cards in a blind manner. All the subjects were asked to maintain their normal physical activities during the study. Teachers of the police school were informed about the study and were asked to maintain the intensity and extent of physical activities during their lessons (2 per wk). The ballistic stretching group undertook a collective ballistic stretching training program, 5 times/wk for 6 wk in the morning, before education in the police school started. Investigators controlled the stretching training at least once a week by random and unannounced visits to ensure the accomplishment of the stretching training. Furthermore, subjects were asked to keep a diary of their stretching performance by documenting every single stretching session, which was collected at the end of the study.

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In the week before and in the week after the 6-wk intervention, the RoM, PRT, MVC, and several parameters of the muscle (passive muscle stiffness, pennation angle, fascicle length) and tendon structure (active and passive tendon stiffness) of the gastrocnemius medialis (GM) were determined.

**Measures**

To ensure a high scientific standard, all measurements were undertaken by the same investigator. In addition to a written introduction, subjects were personally informed about the procedure. Pre- and posttraining tests were executed at the same time of day, and the temperature in the laboratory was kept constant at ~20.5°C. To avoid any bias, measurements were performed without warm up and in the following order: 1) range of motion (10-min break); 2) passive resistive torque (1-min break); 3) maximum voluntary contraction (see Fig. 1).

**Range of motion (RoM) measurement.** Dorsiflexion RoM was measured with an electronic goniometer (Biovision, Wehrheim, Germany) fixed to the ankle joint with Leukotape (BSN Medical, Vibraey, France). Participants were first instructed to stay upright in a neutral position, with the ankle joint angle at 90°. They were then asked to step back with one leg and bring the ankle joint to maximum dorsiflexion, keeping their heel on the ground. The knee of the tested leg had to remain fully extended, and the knee of the opposite leg flexed. Both feet were kept in a parallel position, and hands could be placed on a wall to ensure balance. Special attention was paid to the appropriate position of the stretched leg during the measurement, to avoid any pronation of the foot. If some pronation was observed, the measurement was repeated. The difference between the maximum dorsiflexion and the position in rest (neutral position) was defined as dorsiflexion RoM. RoM was intentionally not assessed with a dynamometer, to ensure natural behavior of the subjects.

**Passive resistive torque (PRT) measurement.** To investigate PRT, an isokinetic dynamometer (CON-TREX MJ, CMV AG, Duendorf, Switzerland) with the standard setup adjusted for ankle joint movement was used. Subjects lay prone with their knee fully extended on a bench and were secured with a strap on the upper body to exclude any evasive movement. The foot was fixed barefooted with a strap to the foot plate of the dynamometer. The ankle joint was carefully aligned with the axis of the dynamometer and fixed to the plate to avoid any heel displacement. The dynamometer moved the ankle joint from an initial 10° plantar flexion to a dorsiflexion position, which corresponded to 95% of the individual maximum dorsiflexion RoM previously measured in the RoM measurement. During pilot measurements, we recognized a conditioning effect during the first two passive movements, similar to the active conditioning reported by Maganaris (25). Therefore, the ankle joint was moved passively for three cycles, and measurements were taken during the third cycle, to avoid bias related to the conditioning effect. Similar to the studies by Kubo et al. (21) and Mahieu et al. (31), the velocity of the dynamometer was set at 5°/s to exclude any reflexive muscle activity. Participants were asked to relax during the measurements.

**Maximum voluntary contraction (MVC) measurement.** MVC measurements were performed with the dynamometer at a neutral ankle position (90°). Subjects were instructed to perform three isometric MVCs of the plantar flexors for 5 s, with rest periods of at least 1 min between the measurements, to avoid any fatigue. The attempt with the highest MVC value was used for the further analysis.

**Electromyography (EMG).** Muscular activity was monitored by EMG (myon 320, myon AG, Zurich, Switzerland) during PRT and MVC measurements. Surface electrodes (Blue Sensor N, Ambu A/S, Ballerup, Denmark) were placed on the muscle bellies of the GM and the tibialis anterior. In the PRT measurements, the EMG (normalized to plantar flexor MVC) was monitored post hoc to ensure that the subject was relaxed, i.e., did not show any EMG activity. The sample rate was 2,000 Hz. The EMG signals were high-pass filtered (10 Hz, Butterworth), and root-mean-square (RMS, 50 ms window) values were calculated.

**Measurement of elongation of the muscle-tendon structures.** A real-time ultrasound apparatus (mylab 60, Esaote S.p.A., Genova, Italy) with a 10 cm B-mode linear-array probe (LA 923, Esaote S.p.A.) was used to obtain a longitudinal ultrasound image of the GM. During the PRT and MVC measurement, the ultrasound probe was placed on the distal end of the GM (Fig. 2), where the muscle is connected to the Achilles tendon, i.e., the muscle-tendon junction (MTJ, 18). The ultrasound probe was secured with a standard orthopedic stocking to prevent any displacement of the probe, which was tested in pilot measurements. To determine the muscle elongation during PRT measurement, the echoes of the MTJ in the ultrasound videos were manually tracked (16, 18). To determine the tendon elongation during MVC measurement, the echoes of a fascicle insertion at the deep aponeurosis near the MTJ were manually tracked (21).

During RoM measurement, the length of the GM fascicle and its pennation angle with the deep aponeurosis were determined from the ultrasound videos. The ultrasound probe was placed at 50% of the GM muscle length (34). The fascicle length and the pennation angle were measured at a neutral position of the ankle joint (90°) and at maximum dorsiflexion.

The ultrasound images were recorded at 25 Hz, with an image depth resolution of 74 mm. During PRT and MVC measurement, the videos were synchronized with the rest of the data via the signals of a function generator (Volkraft, Hirschau, Germany). The videos were cut and digitized in VirtualDub open-source software (version 1.6.19, www.virtualdub.org) and were analyzed in ImageJ open-source software (version 1.44p, National Institutes of Health).
Subjects of the ballistic stretching group were asked to perform a ballistic stretching training program of their plantar flexor muscles, while the control group did not receive any intervention. The stretching was done 5 times/wk for a 6-wk period. Each subject was informed about the stretching procedure. Subjects were instructed to undertake the stretching of the plantar flexors in a standing wall push position, and to stretch until a point of discomfort was reached. Furthermore, they had to move up and down with the front knee at a frequency of 1 Hz. A stretching intervention consisted of a 30-s ballistic stretch of the lower leg. This procedure was repeated four times during each stretching session, alternating both legs, with no rest in between, resulting in a total stretch period of 120 s for each muscle. This procedure was chosen because Ryan et al. (43) reported that $4 \times 30$ s of static stretching decreases muscle-tendon unit stiffness.

Statistical Analyses

SPSS (version 20.0, SPSS, Chicago, IL) was used for all the statistical analyses. To determine the inter-rater reliability of the muscle-tendon displacement measurements, an intraclass correlation coefficient (ICC) was used. A Kolmogorov-Smirnov test was used to verify the normal distribution of all the parameters. To prove the homogeneity between the baseline characteristics of both groups, $t$-tests were performed. Tendon, muscle, and muscle-tendon stiffness calculations were controlled with Pearson correlation coefficients. To assess the reliability of our methods, paired $t$-tests were performed to test if the mean values of the pre- and postmeasurements of the control group were equal. Subsequently, we performed paired $t$-tests to test the effect of the stretching protocol in the intervention group. An alpha level of $P = 0.05$ was defined for the statistical significance of all the tests.

RESULTS

Data Exclusion and Measurement Quality

There was no significant difference between the groups, except in the “(passive) muscle stiffness” parameter. Due to subject drop-out and the poor quality of the ultrasound videos, three (six) subjects of the RoM measurement, four (nine) subjects of the PRT measurement, and five (four) subjects of the MVC measurement of the ballistic stretching (control) group, respectively, had to be excluded from the study (Fig. 1). The subject drop-outs were all due to injuries. In the ultrasound videos with poor quality, fascicle insertion points at the deep aponeurosis (MVC measurement) or the MTJ (PRT measurement) were not identifiable with the necessary precision. Drop-outs and data exclusion did not change the homogeneity of the groups.

The mean (range) ICC of the ultrasound video analysis of both investigators was 0.99 (0.978–0.998), 0.96 (0.831–0.999), and 0.96 (0.801–1.000) for the RoM, PRT, and MVC measurements, respectively. Values above 0.80 were classified as acceptable (48).

The mean values of the Pearson correlation coefficients of the linear regression were 0.99, 0.96, 0.89, and 0.96, with ranges of 0.88–0.99, 0.81–0.99, 0.76–0.96, and 0.93–0.98, with all $P < 0.05$, for passive tendon stiffness, active tendon stiffness, muscle stiffness, and muscle-tendon stiffness, respectively.

Calculation of Muscle/Tendon Force, Passive Muscle/Tendon Stiffness, Active Tendon Stiffness, and Muscle-Tendon Stiffness

The muscle force of the GM was estimated by multiplying the measured torque by the relative contribution of the physiological cross-sectional area (18%) of the GM within the plantar flexor muscles (21, 30, 31), and dividing by the moment arm of the triceps surae muscle (MA), which was measured individually with a measuring tape as the distance between the malleolus lateralis and the Achilles tendon at rest (neutral position). The mean value of the moment arm was 4.41 cm and the range was 3.0–6.0 cm.

Active tendon stiffness was calculated by linear regression between the difference of active force (0–100% MVC) and the passive force at neutral ankle position (19) and the related tendon length changes during the MVC measurements. Passive tendon stiffness, muscle stiffness, and muscle-tendon stiffness were calculated by linear regression between the passive force (~0–30% MVC) produced from the neutral ankle position (90°) to maximum dorsiflexion, and the related tendon length, muscle length, and joint angle changes, respectively. Please note that the term “passive tendon stiffness” was used for the force-length relationship during PRT measurement and therefore differs from previous studies (30, 31). To distinguish between the force-length relationships from passive measurements performed in our study, we have defined this parameter as “active tendon stiffness” throughout the text. The quality of the linear regressions was assessed with Pearson correlation coefficients.

Fig. 2. Images showing the displacement of the MTJ during a passive movement from neutral position (A) of the ankle joint to maximum dorsiflexion (B).
Table 1. Results of maximum dorsiflexion RoM, as well as changes in fascicle length and pennation angle during RoM measurement; PRT, passive tendon stiffness, muscle stiffness, and muscle-tendon stiffness during passive measurements; and MVC torque and active tendon stiffness during MVC measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ballistic</th>
<th>Control</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>PRE</td>
<td>POST</td>
</tr>
<tr>
<td>Range of motion, °</td>
<td>33.8 ± 6.3</td>
<td>37.8 ± 7.2*</td>
</tr>
<tr>
<td>Fascicle length at rest, cm</td>
<td>6.4 ± 0.7</td>
<td>6.3 ± 0.9</td>
</tr>
<tr>
<td>Fascicle length in stretching position, cm</td>
<td>7.4 ± 0.9</td>
<td>7.4 ± 0.7</td>
</tr>
<tr>
<td>Pennation angle at rest, °</td>
<td>17.2 ± 2.2</td>
<td>17.6 ± 2.1</td>
</tr>
<tr>
<td>Pennation angle in stretching position, °</td>
<td>15.3 ± 1.9</td>
<td>15.3 ± 1.8</td>
</tr>
<tr>
<td>Passive resistive torque, N·m</td>
<td>32.2 0.24</td>
<td>92.7</td>
</tr>
<tr>
<td>Passive tendon stiffness, N/mm</td>
<td>5.3 0.26</td>
<td>20.2</td>
</tr>
<tr>
<td>Muscle stiffness, N/mm</td>
<td>9.2 ± 2.3</td>
<td>9.9 ± 1.8</td>
</tr>
<tr>
<td>Muscle-tendon stiffness, N·m²</td>
<td>0.83 ± 0.22</td>
<td>0.87 ± 0.22</td>
</tr>
<tr>
<td>MVC torque, N·m</td>
<td>85.9 ± 38.3</td>
<td>89.9 ± 32.2</td>
</tr>
<tr>
<td>Active tendon stiffness, N/mm</td>
<td>18.6 ± 3.4</td>
<td>19.8 ± 5.3</td>
</tr>
</tbody>
</table>

Values are means ± SD. RoM, range of motion; PRT, passive resistive torque; MVC, maximum voluntary contraction. *Significant difference between PRE and POST session data.

Range of Motion (RoM) and the Related Structural Muscle Parameters

Following the 6-wk stretching intervention, the ballistic stretching group had a significantly increased dorsiflexion RoM (P = 0.00, see Table 1). Fascicle length and pennation angle did not change in the neutral or maximum dorsiflexion position. No parameter changes were observed in the control group.

Passive Resistive Torque (PRT) and Related Structural Muscle-Tendon Parameters

There was no significant change in PRT at the same maximum ankle joint angle for the pre- and postsession data (Table 1). Figure 3 shows the relationship between ankle joint angle and the corresponding PRT of the ballistic stretching group. No significant differences were observed in any joint angle. Moreover, muscle-tendon stiffness, and passive tendon and muscle stiffness did not change after the ballistic stretching intervention. No parameter changes could be found in the control group.

In Fig. 4, A and B, the elongation of muscle and tendon in relationship to the PRT data is shown in steps of 5° from 0° to 25°. Moreover, Fig. 4, C and D, shows the elongation of the tendon and muscle as a function of the ankle angle.

Maximum Voluntary Contraction (MVC) and Tendon Stiffness

Plantar flexor MVC was the same after the short-term stretching intervention. Tendon stiffness calculated from the MVC measurements did not change in both the ballistic stretching and control groups (see Table 1).

DISCUSSION

The functional parameters investigated in this study were RoM, PRT, muscle-tendon stiffness, and MVC. Similar to previous studies (30, 44), the maximum dorsiflexion RoM increased significantly after the short-term ballistic stretching training in the present study. The RoM increase of 4° was similar to the results of Mahieu et al. (30), who reported a slightly smaller ankle joint range of motion (3.2°) after a 6-wk ballistic stretching training program.

Muscle-tendon stiffness and PRT did not change, which is in accordance with the findings of Mahieu et al. (30), who are the only other researchers to have studied the effects of ballistic stretching training on these parameters. However, the findings do not support our hypothesis of a decreased PRT as a result of a ballistic stretching intervention. Following a single ballistic stretching intervention, some authors (14) reported decreasing PRT and muscle-tendon stiffness, while others (29) determined unchanged muscle-tendon stiffness. Decreasing passive forces were also reported in similar animal studies (46, 47). In summary, the results of muscle-tendon stiffness after a single stretching session are controversial. However, together with the results of the short-term stretching studies, one could speculate that passive forces and PRT rapidly return to the
initial state, and there is no underlying chronic adaptation due to stretching.

As with several other short-term studies of static stretching (11, 21) and PNF stretching (15), an unchanged maximal isometric torque was observed after the ballistic stretching intervention. Thus it appears that ballistic stretching has no detrimental effect on MVC.

In addition to the functional parameters, several structural parameters (muscle stiffness, active and passive tendon stiffness, fascicle length, pennation angle) which might explain the increasing RoM were investigated in this study. To the best of our knowledge, so far only Mahieu et al. (30) have investigated the effect of a 6-wk ballistic stretching training program on active tendon stiffness. In the current study, active tendon stiffness was unaltered after a 6-wk ballistic stretching training program, while Mahieu and colleagues (30) reported decreased active tendon stiffness. Based on the assumptions of McNair et al. (32), Mahieu et al. (30) speculate that as a result of the cycling motion, polysaccharides and water are redistributed within the collagen framework, which leads to a decrease in stiffness. Although the current study and the study of Mahieu et al. (30) both investigated ballistic stretching methods, differences in stretch intensity and amplitude could be one reason for the different results. Mahieu et al. (30) noted that their subjects were instructed to move up and down at a pace of one movement per second with the front knee. Although we instructed our subjects in the same way, we cannot be certain that we achieved the same stretch intensity and amplitude. This might have caused the different results. Other possible explanations for the controversial results in tendon stiffness with similar methods could be the warm-up routine, or the fact that the subjects in the study of Mahieu et al. (30) wore shoes, compared with the subjects being barefooted in the current study.

In their studies of short-term static stretching, both Kubo et al. (21) and Mahieu et al. (30) reported unchanged tendon stiffness. However, studies of short-term PNF stretching have shown controversial results: Konrad et al. (20) detected decreasing tendon stiffness following a 6-wk PNF stretching training program, while Mahieu et al. (30) reported no such changes in the MTU. In summary, the current study and other studies of static stretching (21, 30), which have reported similar adaptations in tendon stiffness, indicate that the tendon structure reacts the same to stretching, regardless of whether it is a sustained or repetitive stimulus.

In addition to tendon stiffness during active conditions, the current study investigated muscle-tendon stiffness and the separate muscle and tendon stiffness during passive movements. As with the measurement of active tendon stiffness, passive tendon stiffness was unaltered after the ballistic stretching intervention in the current study. In their study of ballistic stretching, Mahieu et al. (30) observed constant PRT but decreased tendon stiffness (measured from MVC). They explained this counterintuitive result with the hypothesis that tendon stiffness from active state and PRT are not directly related, due to the different forces associated with the different tests. However, the current study recorded a similar behavior of the tendon in both active and passive conditions, and both in accordance with PRT, which all remained unchanged by the ballistic stretching intervention.

Furthermore, no changes in muscle stiffness or muscle-tendon stiffness were detected, indicating that the muscle belly with the contractile elements and its connective tissues (endomysium, perimysium, and epimysium) were not affected by the ballistic stretching training program. However, our methods do not allow us to exclude an adaptation in the muscle at a cellular level.
Similarly, fascicle length and pennation angle during RoM measurements did not change in the intervention group. Due to the findings on static stretching in animal studies (4), Mahieu et al. (30) hypothesized that changes in RoM might be a result of the increasing number of sarcomeres in series. However, since fascicle length remained unaltered in the present study following the 6 wk of ballistic stretching, we cannot support this hypothesis. Unchanged fascicle lengths were also reported by Nakamura et al. (36) following a 4-wk static stretching training program. Therefore, it seems improbable that static stretching in humans induces similar effects in the muscle structure to those seen in the stretching interventions done in animal studies.

In conclusion, the present study showed an increase in RoM but no significant adaptation in measured structural parameters which could explain the RoM gains. The lack of changes in structural parameters in the lower-leg MTU following a short-term ballistic stretching training program does not support our hypotheses. Hence, a probable explanation for the results of the current study could be that the increased RoM following stretching is due to an altered perception of stretch and pain, or stretch tolerance (12, 13, 26), rather than altered muscular or tendon structures. However, the present study might not have investigated all the structural parameters that affect RoM. A novel study by Akagi and Takahashi (1) investigated the so-called hardness (transverse muscle stiffness) in the gastrocnemius muscle following a 5-wk static stretching training program. The results of this study revealed a decrease in the hardness of the gastrocnemius medialis and lateralis; in other words, a structural adaptation in the muscle. This is in contrast to other studies (21, 30) of short-term static stretching, in which no changes in the structural parameters of the MTU were reported.

A possible bias could have occurred due to the specific subject group of police cadets in this study. Police cadets have to pass a physical exam to enter the police school and have regular lessons of physical activity. However, the exam is not as demanding as an entry exam for sports science at the University, and lessons of physical education are only 2 h/wk. Therefore, the physical state of police cadets is probably slightly above average. Thus we neither expect significantly different muscle-tendon properties in our subject group compared with the general public nor any influence of the general training program on the tested parameters. This was confirmed by the lack of changes also in the control group.

There are some limitations to the current study. First, the persons taking the measurements were not all blind to the intervention. Therefore, a bias in the results cannot be completely excluded, although the interrater reliability was excellent (mean ICC: 0.96–0.99). Second, the method of measuring the moment arm of the ankle joint in vivo was quite simple. However, values obtained in the study were very similar to others using magnetic resonance imaging (MRI) data (42) or ultrasound (23). Third, it is very difficult to standardize amplitude, velocity, and force of the ballistic stretches. An alternative approach would have been to use the dynamometer in the training process. However, in human studies of stretching, this is very complex and has, to date, only been used by Kubo et al. (21) for a small training group (eight subjects) and a short duration (3 wk). Furthermore, such a procedure does not represent the typical stretching training used in practice.

Conclusions

This study has shown that a 6-wk ballistic stretching training program of the lower-leg muscle increases dorsiflexion RoM but has no effect on muscle and tendon tissue. Therefore, altered tolerance to stretching seems to be a plausible explanation for the gains in RoM. However, further studies, including other structural parameters such as muscle hardness which might give an additional explanation for the gain in RoM, should be undertaken. Furthermore, future studies should include follow-up measurements to assess a possible decrease in the RoM following the end of the stretching training.

GRANTS

This study was supported by a grant (Project P23786-B19) from the Austrian Science Fund FWF.

DISCLOSURES

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

AUTHOR CONTRIBUTIONS

Author contributions: A.K. and M.T. conception and design of research; A.K. performed experiments; A.K. and M.T. analyzed data; A.K. and M.T. interpreted results of experiments; A.K. prepared figures; A.K. and M.T. drafted manuscript; A.K. and M.T. edited and revised manuscript; A.K. and M.T. approved final version of manuscript.

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