Effects of static stretching on active muscle stiffness with and without the stretch reflex

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Abstract  The purpose of the present study was to examine acute changes in active muscle stiffness with and without the stretch reflex following static stretching. Before and after static stretching for 10 min, active muscle stiffness was measured according to changes in exerted torque and fascicle length during short-range stretch of faster (peak angular velocity of 250 deg·s⁻¹; without the stretch reflex) and slower (peak angular velocity of 100 deg·s⁻¹; with the stretch reflex) angular velocities. During the measurement of active muscle stiffness, the electromyographic activities of plantar flexor muscles were recorded and averaged over two different phases: just before (mEMGa) and after (mEMGb) stretch. In addition, the mEMGb/mEMGa ratio was used to evaluate the effects of stretch reflex. After 10 min of stretching, the mEMGb/mEMGa ratio tended to decrease under the 100 deg·s⁻¹ condition, but not 250 deg·s⁻¹. Under both conditions, active muscle stiffness did not change after 10 min of static stretching. In conclusion, the prolonged static stretching did not affect active muscle stiffness with or without the stretch reflex, but tended to decrease the stretch reflex. In addition, these results imply that active muscle stiffness measured during contractions was not influenced by the stretch reflex.

Keywords: plantar flexors, EMG, fascicle, ultrasonography

Introduction

It is known that static stretching predominantly results in deficits in force production, jump height, and running economy⁷. Stretching-induced deficits in muscle strength have been widely investigated, and thus changes in central drive to the muscles and the mechanical properties of the muscle-tendon complex were reported as the mechanisms behind this phenomenon²⁻⁵. However, a few studies reported the mechanisms of changes in performance during stretch-shortening cycle exercises, e.g., jumping height, after static stretching⁶⁻⁹. Previous studies demonstrated that the mechanical properties of the muscle-tendon complex influenced performance and efficiency during stretch-shortening cycle exercises⁸⁻⁹. Therefore, it is possible that the stretching-induced deficits in stretch-shortening cycle exercises are related to changes in the mechanical properties of the muscle-tendon complex. Regarding the effects of static stretching on tendon properties, stiffness of tendon structures did not change after static stretching, but their hysteresis significantly decreased⁹⁻¹⁴. On the other hand, previous researchers reported that passive stiffness evaluated based on the slope of the relationship between passive torque and joint angle (or fascicle length) during slow passive stretching significantly decreased after static stretching¹⁵⁻¹⁶. More recently, ultrasound shear wave elastography was used to assess changes in muscle stiffness after static stretching¹⁷⁻¹⁸. However, these measurements were performed under passive conditions. The mechanical properties of muscles need to be investigated under active conditions in order to clarify static stretching-induced changes in performance, especially during stretch-shortening cycle (SSC) exercises such as jumping, etc.

We demonstrated that muscle stiffness during submaximal isometric contractions (i.e., active muscle stiffness) could be determined from changes in torque and fascicle length when the joint begins moving and then 60 ms thereafter¹⁹. In order to avoid any potential stretch reflex, we analyzed the measured variables during this time period¹⁹⁻²⁰. Using this methodology, we noted training-induced changes in active muscle stiffness according to cross-sectional and longitudinal studies²¹⁻²². Furthermore, we recently proposed a method to evaluate active muscle stiffness including stretch reflex according to changes (the duration analyzed was 110 ms) in torque and fascicle length during slower stretch velocity (peak angular velocity was 100 deg·s⁻¹)²³. On the other hand, some previous studies showed that stretch reflex declined following static stretching²⁻²⁴. Therefore, it is likely that changes in active muscle stiffness after static stretching would be different with and without the stretch reflex.

In the present study, we examined acute changes in active muscle stiffness with and without stretch reflex fol-
lowing prolonged static stretching. We hypothesized that static stretching would reduce active muscle stiffness with the stretch reflex, but not without the stretch reflex.

Materials and methods

Subjects. Twelve healthy males (age: 24.5 ± 7.9 yrs, height: 171.8 ± 5.0 cm, body mass: 70.5 ± 10.0 kg, mean ± SD) volunteered for this study. Written informed consent was obtained from all subjects. This study was approved by the Ethics Committee for Human Experiments, Department of Life Science, The University of Tokyo (Issue Number: 565).

Active muscle stiffness. In order to assess active muscle stiffness, a custom-made dynamometer (Applied Office, Tokyo, Japan) was used to measure external torque and ankle joint angles. After a standardized warm-up, subjects performed two or three maximal voluntary isometric contractions (MVC) at 0 degrees (deg) (0 deg was the neutral anatomical position where the sole of the foot was 90 deg to the tibia, with positive values for plantar flexion) of ankle angle with the knee joint at full extension with a 2-min rest period between each trial. Peak torque value within all trials was recorded as MVC value. After a 5-min rest period, measurement of active muscle stiffness was performed using a previously described procedure. A specially designed dynamometer was programmed to apply dorsiflexion stretches from +10 deg plantar flexion to -10 deg (= 10 deg dorsiflexion). In the present study, measurements of active muscle stiffness were carried out at two angular velocities (peak angular velocities of 250 and 100 deg·s⁻¹). For the 250 deg·s⁻¹ condition, a 60-ms period after the onset of stretch was analyzed in order to include any neural effects of the stretch reflex. During this period (60 ms), the range of motion was about 8 deg, and angular velocity reached about 250 deg·s⁻¹. For 100 deg·s⁻¹ condition, a 110-ms period after the onset of stretch was analyzed in order to avoid any neural effects. During this period (110 ms), the range of motion was about 8 deg, and angular velocity reached about 100 deg·s⁻¹.

An additional measurement was performed two times at 0% MVC before the short-range stretch experiment for data correction purposes. The averaged torque during relaxed condition was subtracted from the measured torque of each active stretch trial. Measurement of active muscle stiffness was performed two times per condition at 30% of MVC with visual aid of exerted torque on an oscilloscope. In the present study, the same absolute torque (30% of MVC before static stretching) was adopted before and after static stretching. Measured values were the means of two trials. The exerted muscle force (Fm) was calculated from the torque measured by dynamometer using the following equation:

\[
F_m = k \cdot TQ \cdot MA^{-1}
\]

where \( k \) is the relative contribution of the physiological cross-sectional area of medial gastrocnemius muscle (MG) within plantar flexor muscles, and \( MA \) is the moment arm length of triceps surae muscles with ankle joint at 0 deg, which was estimated from the lower leg length of each subject.

During the measurement of active muscle stiffness, the fascicle length of MG was measured using an ultrasonic apparatus (SSD-6500, Aloka, Japan). At 30% of lower leg length, the scanning probe of the apparatus was fastened with adhesive tape to the skin. Ultrasonic images were stored at 98 Hz in the computer memory of the apparatus. An electric signal was superimposed on the images to synchronize them with the torque, joint angle, and electromyographic activity (see below). The slope of muscle force–fascicle length in the analyzed duration was defined as active muscle stiffness.

In our previous study, the repeatability of the measurements of active muscle stiffness was confirmed.

Electromyograms. Electromyographic activity (EMG) during measurements of active muscle stiffness was recorded using a wireless EMG telemeter system (BioLog DL-5500, S&ME, Japan) at a sampling rate of 1 kHz. Surface electrodes (DL-510, S&ME, Japan) were placed over the bellies along the direction of fascicles of lateral gastrocnemius muscle (LG) and soleus muscle (SOL). The raw data were band-pass filtered between 10 to 500 Hz. EMG was full-wave rectified and averaged over two different phases: a 60-ms period for 250 deg·s⁻¹ condition and a 110-ms period for 100 deg·s⁻¹ condition, just before (mEMGa) and after (mEMGb) stretch. In the present study, the mEMGb/mEMGa ratio was used to evaluate the effects of stretch reflex.

Static stretching. Static stretching was performed by subjects using the right lower leg. The posture of subjects (except for ankle angle) and setup were similar to those for measurements of active muscle stiffness, as described earlier. The platform of the dynamometer, which was attached to the sole of the subject’s foot, was moved to 36 deg dorsiflexion and held at this position for 10 min. Throughout stretching, subjects were requested to relax completely and not offer any voluntary resistance. Measurement of active muscle stiffness was performed before and immediately after 10 min of static stretching.

Statistical analysis. All analyses were performed using SPSS Statistics software version 19.0 (IBM, Armonk, NY, United States). Descriptive data are presented as means ± SD. The significance of difference before and after static stretching was analyzed by Student’s t-test. The level of significance was set at \( p < 0.05 \).
Results

Concerning LG and SOL, the \( \frac{m\text{EMGb}}{m\text{EMGa}} \) ratio for the 100 deg·s\(^{-1} \) condition tended to decrease after 10 min of static stretching (LG: \( p = 0.059 \); SOL: \( p = 0.073 \)), whereas that for 250 deg·s\(^{-1} \) condition did not (LG: \( p = 0.164 \); SOL: \( p = 0.347 \)) (Fig. 1).

After 10 min of static stretching, increases in torque and fascicle length during fast stretching did not change for 250 deg·s\(^{-1} \) (\( p = 0.383 \), \( p = 0.388 \)) or 100 deg·s\(^{-1} \) (\( p = 0.076 \), \( p = 0.288 \)) conditions (Fig. 2). For both conditions, active muscle stiffness did not change after 10 min of static stretching (250 deg·s\(^{-1} \): \( p = 0.905 \); 100 deg·s\(^{-1} \): \( p = 0.247 \)) (Fig. 2).

Discussion

To date, changes in passive muscle stiffness following static stretching have been widely assessed based on the relationship between passive torque and joint angle (or fascicle length)\(^{15,16,25} \). In addition, ultrasound shear wave elastography was used to investigate the effects of static stretching on muscle stiffness\(^{17,18} \). On the other hand, active muscle stiffness for 250 and 100 deg·s\(^{-1} \) conditions did not change after 10 min of static stretching in the present study. Our previous study demonstrated that passive and active muscle stiffness clearly represented respective mechanical properties\(^{19} \). Regarding active muscle stiffness for the 250 deg·s\(^{-1} \) condition, the measured variables were not affected by any potential neural effects, e.g., stretch reflex, since changes in torque and fascicle length during a 60 ms period after the commencement of ankle joint movement was analyzed\(^{19,20} \). Therefore, the present result on active muscle stiffness for the 250 deg·s\(^{-1} \) condition suggested that the mechanical properties of cross-bridges and titin filaments within the sarcomere did not change after 10 min of static stretching.

In the present study, we also found that active muscle stiffness in the 100 deg·s\(^{-1} \) condition did not change after...
10 min of static stretching. Since changes in torque and fascicle length were measured during a 110 ms period after ankle joint commenced, the active muscle stiffness under the 100 deg·s⁻¹ condition included the effect of stretch reflex. At the beginning of this study, we hypothesized that acute static stretching would reduce active muscle stiffness with the stretch reflex, i.e., 100 deg·s⁻¹ condition, since the stretch reflex declined following acute static stretching. However, this hypothesis was rejected in the present study. In our recent study, we suggested that active muscle stiffness was not influenced by the stretch reflex, because there was no significant difference in active muscle stiffness between the 250 deg·s⁻¹ (without stretch reflex) and 100 deg·s⁻¹ (with stretch reflex) conditions. Therefore, the present results further support the notion that active muscle stiffness was not influenced by the stretch reflex.

Previous studies demonstrated that performance during stretch-shortening cycle exercises as well as muscle strength decreased after static stretching. However, the mechanisms responsible for these negative effects on stretch-shortening cycle exercises have not been clarified so far. According to the previous and present findings, passive muscle stiffness was decreased by acute static stretching, whereas tendon and active muscle stiffness weren’t. To our knowledge, no studies have shown that a decline in jump height after static stretching is related to changes in electromechanical activities of lower limb muscles during jumping. Considering these points, decreases in jump performance after static stretching would be associated with changes in passive muscle stiffness, reflecting a change in the property of the parallel elastic components.

In the present study, the mEMGb/mEMGa ratio was used to evaluate the effects of stretch reflex, as described earlier. For the 100 deg·s⁻¹ condition, the values of LG and SOL for 8 out of 12 subjects decreased after static stretching, but did not reach statistical significance. Therefore, we may say that the stretch reflex decreases after 10 min of static stretching. Furthermore, mEMGb/mEMGa ratio values of SOL were significantly higher than those of LG, except for 100 deg·s⁻¹ condition before stretching (data not shown). Several studies showed that the electromyogram amplitude of stretch reflex in endurance trained athletes (who had many slow-twitch fibers) was greater than that in power trained athletes (who had many fast-twitch fibers). Hence, the present results were supported by the previous findings. However, there wasn’t any difference in the amount of decrease in the mEMGb/mEMGa ratio for the 100 deg·s⁻¹ condition between LG and SOL in the present study.

There was a limitation to this study. Static stretching should be performed at the same relative ankle angle to the maximal range of motion for each subject. However, we adopted 36 deg dorsiflexion for all subjects. Therefore, it is not to be denied that the intensity of stretch would differ among the subjects. On the other hand, it is known that the maximal range of motion values is affected by psychological factors (e.g., pain threshold). In the present study, we aimed to investigate the acute effects of static stretching on active muscle stiffness. Therefore, we considered that this point did not affect the main results. In addition, we adopted the same procedure of static stretching in our previous studies which determined the effects of static stretching on the mechanical properties and collagen fiber orientation of tendons.

In conclusion, active muscle stiffness with and without the stretch reflex did not change after 10 min of static stretching, whereas the stretch reflex during contractions tended to decrease. Furthermore, these results imply that the stretch reflex does not influence active muscle stiffness.

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Conflict of Interests

The authors declare that they have no conflict of interests.

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