

Clinical Study

Combined Effects of Stretching and Resistance Training on Ankle Joint Flexibility

E. Kato,¹ T. Kurihara,² H. Kanehisa,³ T. Fukunaga,³ and Y. Kawakami⁴

¹ Department of Sports Sciences, Japan Institute of Sports Science, Tokyo 1560056, Japan

² Faculty of Sport and Health Science, Ritsumeikan University, Shiga 5258577, Japan

³ National Institute of Fitness and Sports in Kanoya, Kagoshima 8912393, Japan

⁴ Faculty of Sport Sciences, Waseda University, Saitama 3591192, Japan

Correspondence should be addressed to E. Kato; emika.kato@jpnssport.go.jp

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The purpose of the present study was to clarify the combined effects of stretching and resistance training on the active and passive dorsiflexion range of motion of ankle joint. Sixteen young adult men were randomly assigned to a training ($n = 8$) or a control ($n = 8$) group. The training group trained one leg for the combined program of static calf stretching and dorsiflexors resistance training program (STR+TR) and the other leg for static stretching program only (STR). The training group executed stretching of both legs every day and resistance training every other day for six weeks. After the training program, in STR+TR side, both active and passive dorsiflexion range of motions significantly ($P < 0.05$) increased and also isometric maximal voluntary dorsiflexion torque increased, while in STR side, only passive dorsiflexion range of motion increased. In passive dorsiflexion range of motion, increased dorsiflexion ROM was accompanied by increased tendon elongation not muscle elongation. In conclusion, the combined program of stretching for calf muscles and resistance training for dorsiflexors increases active as well as passive dorsiflexion range of motion, while static calf stretching program is effective only for the increase in passive dorsiflexion range of motion.

1. Introduction

The range of motion (ROM) is a common index of joint mobility (flexibility). The ROM is generally defined in two conditions: active ROM, joint mobility with voluntarily effort using her/his own muscle strength, and passive ROM, joint mobility by an external force while the muscles crossing the joint remaining relaxed [1–4]. Both active and passive dorsiflexion (DF) ROMs are related to performances in daily activities and sports and a larger DF ROM is associated with higher efficiency of walking and running [5–8]. Also, Tainaka et al. [7] showed that, for elderly women, active DF ROM is one of the predictors of the onset of functional dependence. Clinically, reduced DF ROM is related to several leg and foot disorders, including Achilles tendinitis [9] and plantar fasciitis [10]. Furthermore, Wiesler et al. [8] found a relationship between the history of lower limb injury and the narrowness of DF ROM in dance students with the

history of sprain. These reports indicate that DF ROM, active ROM in particular, plays an important role in improving or maintaining physical performances.

However, many studies have shown that stretching training increases flexibility of the ankle joint [5, 11–13], although one study failed to improve active DF ROM after a 6-week static stretching regimen [4]. From the reports of Alter [14] and Kawakami et al. [15], active DF ROM requires force development of the dorsiflexor muscles as well as the extensibility of the plantar flexor muscles. Hence, it is assumed that the combined training program of both stretching of the plantar flexors and resistance training of the dorsiflexors is required to improve DF ROM in not only passive but also active conditions.

The purpose of the present study was to determine the influence of the combined training program employing both stretching and resistance training on active and passive DF ROM. Based on the previous reports cited above, we

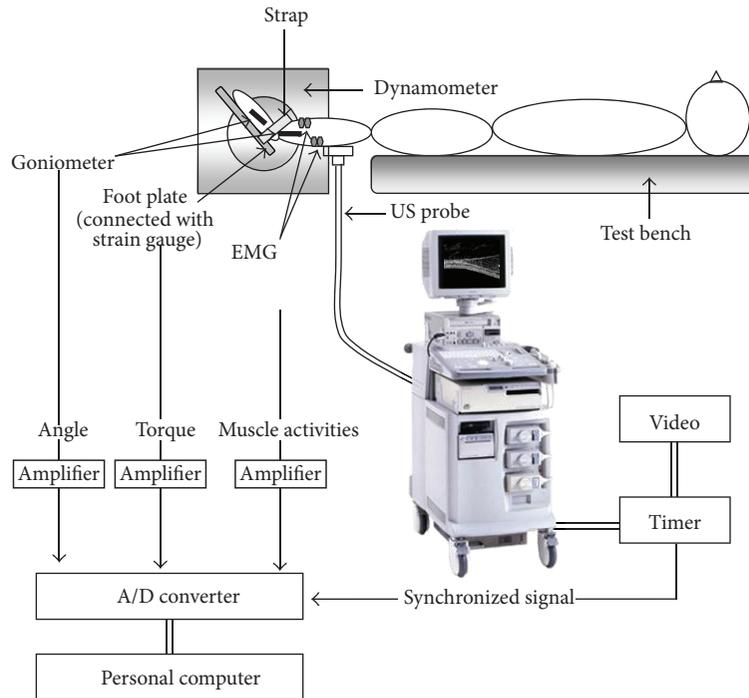


FIGURE 1: Experimental setup.

hypothesized that the combined training increases active and passive DF ROM as well as muscle strength of dorsiflexors, but training with stretching alone increases passive ROM only.

2. Methods

2.1. Participants. Sixteen healthy men (age: 25.6 ± 3.9 years, height: 171.6 ± 6.1 cm, body mass: 65.8 ± 7.5 kg, mean \pm SD) voluntarily participated in this study. None reported any current or ongoing neuromuscular diseases or musculoskeletal injuries specific to ankle, knee, or hip joints. They were all moderately active and recreationally trained but not engaged in systematic stretching and resistance training programs. This study was approved by the ethics committee of the Faculty of Sport Sciences, Waseda University, and was consistent with their requirements for human experimentation in accordance with the Declaration of Helsinki. The participants were fully informed about the procedures to be used as well as the purpose of the study. Written informed consent was obtained from all participants.

2.2. Experimental Outline. The participants were allocated to one, either training or control, group (CON). The training group trained one leg for the combined program of static calf stretching and dorsiflexors resistance training program (STR+TR) and the other leg for static stretching program (STR) only. The participants visited the laboratory for all training and assessments of DF ROM, extensibilities of calf muscle and Achilles tendon, and muscle strength of maximal

voluntary isometric contraction of DF (DF MVC). In the first visit, the participants were asked to familiarize the content of the experiments and training program (passive dorsiflexion of ankle joint and exertion of MVC) and measured plantar flexion (PF) MVC torque to determine stretching intensity. The subsequent visits included the following assessments or training sessions. The participants in CON group were asked to maintain their habitual physical activity for six weeks. Assessments after the training period were performed more than 20 hours after the last training session in order to eliminate the stretching effect [13] and at the same time of day (± 2 h) for each participant to consider the possible influences of the circadian variation in flexibility and muscle strength [4]. The room temperature of the laboratory was kept constant at around 24°C throughout the training period.

Before the assessments, the participants sat quietly for about 10 min and performed no warm-up such as stretching or low intensity exercise (i.e., jogging) in order to eliminate its influence on flexibility and muscle strength [16]. The experimental setup is shown in Figure 1. During the assessment, the participants lay in a supine position with the hip and knee joints fully extended. The foot was secured in a heel cup attached to the footplate of a customized dynamometer (VINE, Japan) with toe and ankle nonelastic straps over the metatarsals and malleoli. A goniometer (SG 110/A, Biometrics, UK) was attached to the shank and foot, crossing the lateral malleolus to measure ankle joint angles. In this study, the negative and positive values of the joint angles are for PF and DF, respectively, with the anatomically neutral position at 0 deg.

2.3. Ultrasound Measurements. The elongation of the gastrocnemius medialis (MG) muscle and Achilles tendon due to stretching training was investigated by ultrasonography. A B-mode ultrasound probe (7.5 MHz wave frequency with 60 mm scanning length; UST-5712, with a system SSD-6500, ALOKA, Japan) mounted with a water bag (MP-2463, ALOKA, Japan) was attached over the distal end of the MG, that is, at the muscle-tendon junction (MTJ), so that longitudinal scanning was made along the lower leg length. The width and depth resolution of the images was 0.16 mm. The MTJ was identified as described in previous studies [15–19]. The displacement of MTJ by rotation of the ankle joint was measured relatively to a reference marker placed between the skin and the probe [15, 19]. The probe was fixed firmly onto the right leg around the MTJ with a water-soluble transmission gel to provide acoustic contact. Once a MTJ was clearly identified, the position of the probe was firmly held in place using a custom-made resin sheath strapped to the skin. The restraint ensured a constant orientation and pressure of the probe and an acoustic marker was placed between the skin and the ultrasound probe to verify that the probe did not move throughout the experiment. The reference marker was placed to correct the probe movement relative to the skin during the experiment. A custom-made fixation device was used to secure the probe onto the subject's calf. Before static stretching and the passive test, the experimenter stained marks on the skin of lower leg of each subject at the corners of fixation device. All subjects were checked stained marks on their skin when they came to the laboratory to do daily training. The ultrasound images were digitally recorded at 30 Hz (HR-DVS3, Victor, Japan) and synchronized with the passive torque, ankle joint angle, and EMG signals via recordings of a clock timer (VTG-55, FOR-A, Japan). The images were brought into a personal computer and analysed by using an open-source software (Image J 1.33, National Institute of Health, USA).

2.4. Calculation of Muscle and Tendon Elongation. The displacements of MTJ in the ultrasound images from 20 deg of plantar flexion to the predetermined dorsiflexed position were manually measured for each frame and defined as muscle elongation [15–17, 19]. The measurements were performed two times for each frame, and the mean values were used for further analyses. The coefficients of variation of the two measurements were 1.8% on average (0.4–3.0%). The intraclass correlation coefficients of the measurements were more than 0.89. The change of MTU length was calculated from ankle joint angle changes based on estimation using a cadaveric regression model [16, 20]. The length change in MTU length (ΔL) was calculated as follows:

$$\begin{aligned} \Delta L = & -22.18468 + 0.30141(90 + \theta A) - 0.00061(90 + \theta A)^2 \\ & + (6.4625125 - 0.07987 \times \theta K + 0.00011 \times (\theta K)^2) \\ & \times (\text{lower leg length}) \times 10, \end{aligned} \quad (1)$$

where θA is the ankle joint angle (deg) measured from the neutral position with the foot at right angles to the tibia, θK is the knee joint angle (deg). The difference between the change of MTU length and muscle elongation was defined as the tendon elongation.

2.5. EMG Recordings. Surface electromyogram (EMG) was recorded using Ag–AgCl disposable electrodes (Blue Sensor, P-00-S, Ambu A/S, Denmark, measuring area 154 mm²) that were pregelled and self-adhesive, placed 20 mm apart (centre to centre) on the middle of the muscle bellies of the MG and lateral gastrocnemius (LG), the soleus (SOL), and the tibialis anterior (TA) muscles. A ground electrode was placed on the medial malleolus of the ankle joint opposite a measurement leg. The skin was shaved, abraded with high-grit sandpaper, and cleaned with alcohol. In order to maintain electrode positions throughout the training period, photographs of all participants' feet and legs were taken to record the positions of the electrodes by using a digital camera (LUMIX DMC-FX30, Panasonic, Japan) and printed sheets of photo papers. EMG signals were amplified and band-pass filtered (5–1000 Hz) with a multitelemeter system (WEB-5000, Nihon KOHDEN, Japan).

2.6. Measurements of DF ROM. DF ROM was assessed in both active and passive conditions. All measurements were taken in the sagittal plane after the assumption of the fundamental anatomical position. To measure the active DF ROM, participants were instructed to perform active dorsiflexion with the maximal voluntary effort for three times. The highest value of these measurements was adopted as a parameter of active DF ROM for each participant. The experimenters paid close attention to the dorsiflexion movement to ensure that there was no supination and/or pronation during the active DF ROM measurements.

Passive DF ROM was measured using the foot dynamometer without muscle activities of plantar flexors and TA (less than 5% MVC, 18) for all participants. The dynamometer passively dorsiflexed the ankle joint at an angular velocity of 5 deg/s until the passive torque reached pre-determined torque value (around 15% PF MVC for each participant in familiarization session), being similar to the procedures of previous studies [5, 11, 16, 21]. The passive DF ROM was calculated as the ROM attained from 0 deg (neutral) to the dorsiflexion angle. However, some participants achieved larger passive torque (more than 15% PF MVC) during measurement of passive DF ROM without muscle activity, and all parameters beyond 15% PF MVC were excluded from analysis to standardize across participants throughout the training period [16].

2.7. Measurements of MVC Torque. Isometric DF MVC torque was determined before and after the training period. All MVC tasks were performed from relaxed to the voluntary maximum in 3–4 s, which was then sustained for 2 s with the ankle joint angle fixed at 20 deg of plantar flexion. Two minutes of rest was allowed between the MVC trials. The participants were instructed to make the maximal effort for

each measurement. Each participant performed at least two MVC measurements, and a subsequent measurement was performed if the difference in the peak torque of two MVCs was more than 10%. The trial with the highest torque value was chosen for assessment.

2.8. Signal Processing. The torque, ankle joint angle, and EMG signals were recorded simultaneously with a data acquisition system (Chart v5.5.6, ADInstrument, Australia) during DF MVC and the measurements of the active and passive DF ROMs. The torque signal from the dynamometer, ankle joint angle signal from the goniometer, and the EMG signal from the MG, LG, SOL, and TA were sampled at 2 kHz. All signals were stored on a personal computer (iBook G4, Apple, USA) and processed offline using a general-purpose software (Chart v5.5.6, ADInstrument, Australia).

2.9. Training Program. The training group executed a training program that involved static stretching both legs every day and resistance training for one leg every other day lasting for 6 weeks. The training program followed safety guidelines of the stretching and strength training. The participants trained one leg for STR+TR and the other for STR. For the STR+TR side, strength training was performed after the completion of stretching training, with a rest interval of a few min between the two programs. All training programs were performed in the laboratory and controlled by the experimenter.

2.10. Static Stretching. The stretching intensity was determined based on the PF MVC value to take into account interparticipant differences in stretched muscle volume of calf muscles [16]. Repeated static stretching of the calf muscles was performed on the ankle joint dynamometer (VINE, Japan) with the same procedure as used for the measurement of passive DF ROM. The dynamometer passively dorsiflexed the participant's ankle joint from 20 deg of plantar flexed position until the pre-determined torque threshold (around 15% PF MVC) was reached and this position was held for 60 s and repeated 5 times per session with 10 s intervals between the stretches [18]. All participants were asked to remain relaxed and not to resist the movement of the ankle during the static stretching.

2.11. Resistance Training. Using a customized ankle dynamometer (VINE, Japan), they completed resistance training, which consisted of unilateral isometric DF MVC for as long as possible until the exerted torque became less than 90% MVC of each participant. The torque signal was displayed in real time on the liquid-crystal display monitor (FR50S, HYUNDAI, Korea). This was repeated 5 times with a 90 s rest between trials [22]. All participants were given oral encouragement during all trials to ensure they exerted with maximal effort. Prior to the resistance training, DF MVC torque was measured for each participant. The training intensity was determined based on the DF MVC torque of each day.

2.12. Statistical Analyses. Data are reported as means \pm standard deviation (SD) throughout the text and figures. A two-way repeated-measures analysis variance (ANOVA) [time (before training period versus after training period) \times condition (STR+TR versus STR versus CON)] was used to test the effects of time and condition on the measured variables. When a significant interaction was found, follow-up analyses were performed using one-way repeated-measures ANOVAs with Bonferroni corrections. To detect training effect of STR+TR and STR, we calculated the relationships between these values as below and examined the statistical significance using Pearson's product moment correlation. The relationships between the initial values and the amount of differences before and after training about DF ROM. Also the amount of differences both DF ROM and DF MVC before and after training for each subject. An alpha level of 0.05 was considered significant. Data were analyzed using statistical software (SPSS 12.0 J for Windows, SPSS Japan Inc., Japan).

3. Results

3.1. DF ROM. Figure 2 illustrates descriptive data of the active and passive DF ROMs before and after training period. Active DF ROM significantly increased in STR+TR only (from 19.3 ± 5.0 deg to 28.1 ± 3.9 deg, $P < 0.05$). Antagonist muscle activities during active DF ROM measures were unchanged before and after training period (5–10% MVC for MG and LG and 10–15% MVC for SOL). Antagonist muscle activity did not affect active dorsiflexion. Passive DF ROM significantly increased in both sides (STR+TR: 16.0 ± 5.9 deg to 20.1 ± 5.2 deg, $P < 0.05$; STR: 14.8 ± 8.8 deg to 18.6 ± 7.1 deg, $P < 0.05$). The EMG activities of the triceps surae and TA muscles were less than 5% MVC during the measurement of passive DF ROM. In CON, neither active nor passive DF ROM changed significantly.

3.2. Elongations of Muscle and Tendon. Figure 3 illustrates the typical example of the relationship between passive torque and tissue elongation before and after stretching training. Although passive torque was constant, tendon elongation increased after stretch training. On the other hand, muscle elongation was increasing in 20 Nm or less, but did not change at final value. All subjects were also similar trend about muscle and tendon elongation. Muscle elongation did not change any side and group (STR+TR: 25.1 ± 3.6 mm to 24.4 ± 2.6 mm, $P > 0.05$, STR: 24.9 ± 4.2 mm to 23.2 ± 3.1 mm, $P > 0.05$, CON: 24.1 ± 3.1 mm to 23.9 ± 5.1 mm, $P > 0.05$), while tendon elongation increased significantly in STR+TR and TR but CON did not change after 6 weeks (STR+TR: 9.6 ± 3.2 mm to 14.4 ± 2.8 mm, $P < 0.05$, STR: 10.3 ± 3.9 mm to 14.5 ± 4.6 mm, $P < 0.05$, CON: 10.2 ± 1.6 mm to 11.2 ± 3.3 mm, $P > 0.05$). There is no change muscle elongation between STR+TR and TR, and tendon elongation neither STR+TR nor TR after stretching training.

3.3. MVC Torque. There were no significant differences among the three groups in DF MVC torque values before training period. DF MVC torque increased significantly only

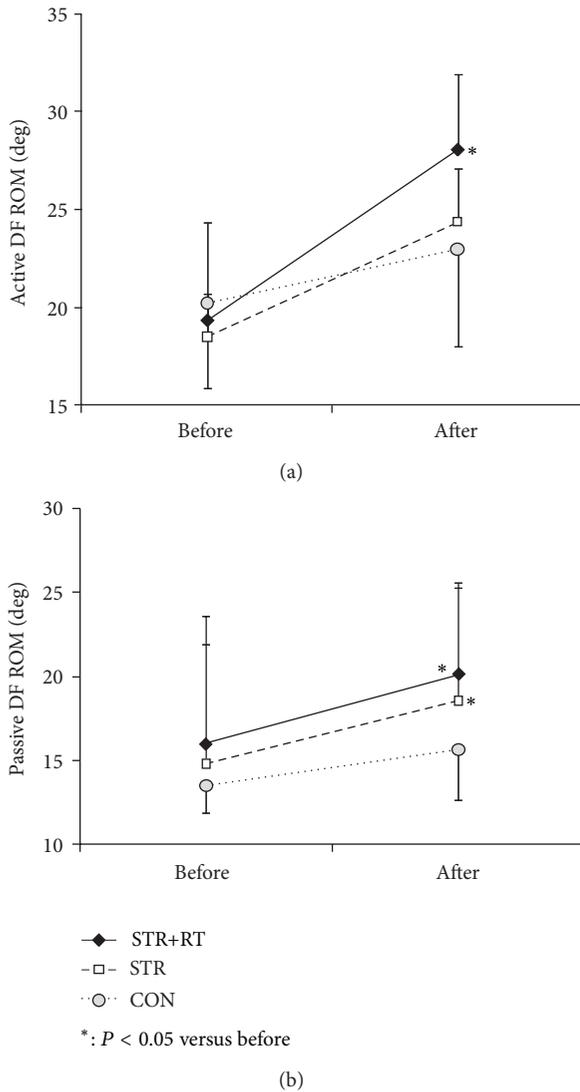


FIGURE 2: Dorsiflexion (DF) range of motion (ROM) in active (a) and passive (b) conditions. Closed rhombus represents STR+TR side, opened square represents STR side and opened circle represents control group, respectively.

in STR+TR (from 52 ± 8 Nm to 56 ± 9 Nm, $P < 0.05$), but in STR, there was no change (from 53 ± 6 Nm to 53 ± 6 Nm). In CON, DF MVC torque values did not change significantly after the training period (from 53 ± 11 Nm to 52 ± 9 Nm).

3.4. Association between Training Effects and Initial Condition (Flexibility and Muscle Strength). We examined the relationships between the initial values of DF ROM and their changes (Δ DF ROM) in STR+TR and STR. Also we calculated the coefficient of correlation for the relationships between Δ DF ROM and Δ DF MVC. The initial value of active DF ROM was significantly correlated with the Δ active DF ROM in STR+TR ($r = -0.73$, $P < 0.05$) but not in STR ($r = 0.56$, $P > 0.05$). The initial value of passive DF ROM was significantly correlated with the Δ passive DF ROM in both sides ($r = -0.67$ for both

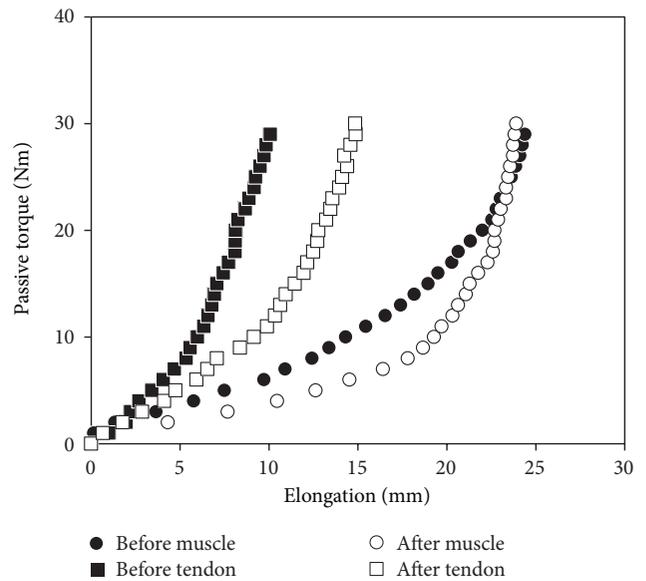


FIGURE 3: The typical example of the function of the muscle and tendon elongation for the passive torque before and after stretching training. Closed and opened circles represent before and after muscle elongation, respectively. Also Closed and opened squares represent before and after tendon elongation, respectively.

sides, $P < 0.05$). There was no significant correlation Δ active DF ROM and Δ DF MVC ($r = 0.29$, $P > 0.05$).

4. Discussion

The main findings obtained here are that STR+TR increased both active and passive DF ROMs, but STR increased passive DF ROM only. This result supports the hypothesis set at the start of the study and indicates that active and passive DF ROMs were affected differently by the two training programs.

Passive DF ROM increased after both STR+TR and STR training. The present study followed procedures described in previous studies [5, 11] to assess passive DF ROM. Gajdosik et al. [5, 11] reported that passive DF ROM increased significantly at the identical passive torque level without the effects of stretch tolerance or psychological effects [13]. The present study adopted this maneuver and kept the final passive torque identical during the measurements of passive DF ROM before and after the training period. These data imply that the mechanical properties of the calf muscles and/or soft tissues around the ankle joint changed after the intervention. Figure 2 shows that stretching training caused a significant increase in ankle dorsiflexion angle, which was accompanied by an increase in tendon elongation but not muscle elongation. Since it was a large dorsiflexion angle and tendon elongation in the identical load, these results imply that the increase in ankle joint angle after stretching training was due to increase in the tendon but not in the muscle. These results are similar to previous studies that examined the acute effect of static stretching [16, 23]. Kato et al. [17] reported that muscle-tendon unit (MTU) elongation was strongly correlated with tendon elongation, but not muscle

elongation. Maganaris [24] reported the possibility of creep deformation of the tendon and other soft tissues comprising the ankle joint due to tissue stretching, which results in an increase in compliance. Stromberg and Wiederhielm [25] showed that collagen fibers follow a wave-like course in unstressed tendons, but they become aligned or parallel with increasing stress. These structural changes in the elements in the tendon might explain the increased tendon elongation after stretching training. Taking these findings into account together with the current results, we can say that MTU elongation reflects that of tendon elongation.

However, it is considered that the muscle elongation was also increased under 20 Nm; both muscle and tendon were affected by stretching training. Kato et al. [17] showed that the passive torque—MTU length curve during passive dorsiflexion has two different slopes (a lower passive torque region and a higher passive torque region). It has been shown that the former phase (lower passive torque region) is mainly due to muscle elongation, and the latter phase (higher passive torque region) is mainly due to tendon elongation [17, 26]. Muscle is easier to elongate than tendon [26], muscle was elongated on a priority at lower passive torque region, and tendon was elongated at higher passive torque region. We cannot describe detailed reason about there is an upper limit to muscle elongation; perhaps muscle has necessity to exert muscle strength; thus muscle is restricted not to stretch further higher torque level.

The active DF ROM increased in STR+TR only (Figure 2(a)). Like the present study, Youdas et al. [4] reported that stretching training did not significantly increase active DF ROM. In their study, after 6-week stretching program more than 95% of the experimental group participatively perceived stretching training was effective for their own active DF ROM but did not show a significant increase in active DF ROM. In STR+TR, DF MVC torque also significantly increased. Alter [14] and Kawakami et al. [15] showed that larger active DF ROM was attained by greater muscle strength to voluntarily rotate the joint. Taking these into account, it is likely that the observed increase in active DF ROM for STR+TR can be attributed to the gain in DF MVC torque. Alternatively, the current result indicates that a training program consisting of stretching only is insufficient to increase the active ROM.

In the present study, both active and passive ROM differed substantially among individuals. Thus we calculated the relationships between the initial values of DF ROM and their changes (Δ DF ROM) in STR+TR and STR sides to examine training effect for DF ROM. The values of the coefficient of correlation were statistically significant in STR+TR for active condition, in both sides for passive condition. The significant values of these were negative; thus the training effect was greater for the subjects who had smaller value of DF ROM before stretching training.

The force-length relationship is an important factor for determining force generation potential. It showed that TA operates along the ascending limb of the force-length relationship [27]. As a pilot experiment before training experiment, we tested the force-length relationships between

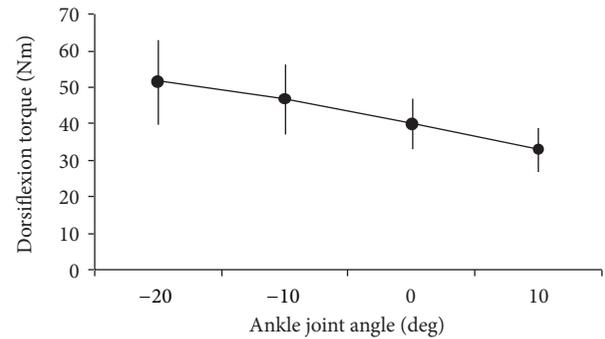


FIGURE 4: The relationship between ankle joint angle and isometric voluntary DF MVC torque in a pilot experiment ($n = 7$). The negative values represented plantar flexed position, the positive values represented dorsiflexed position.

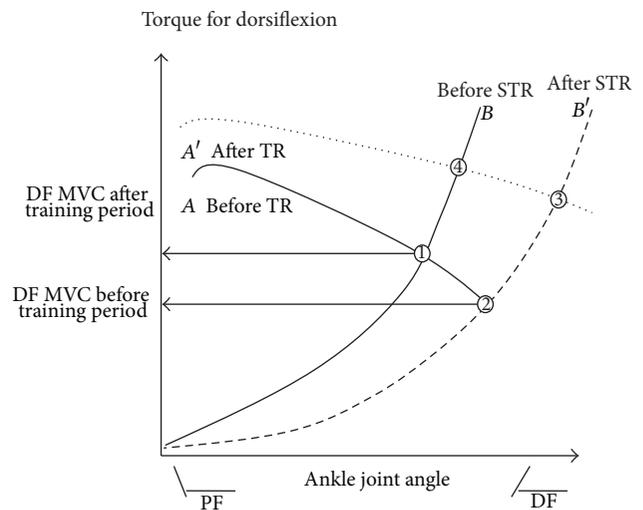


FIGURE 5: A schematic diagram of the relationships between angle joint angle and DF torque in active (A) and passive (B) conditions, respectively. A and A' represent the relationships between voluntary DF MVC torque and ankle joint angle before and after resistance training period. B and B' represent the relationship between passive torque and ankle joint angle before and after stretching training, respectively. TR means strength training of dorsiflexors and STR means stretching training of calf muscles, respectively. #1 means active DF ROM before-test condition and #2 and #3 mean active DF ROM after training in STR and STR+TR, respectively. #4 means theoretical plot after resistance training only.

muscle strength of dorsiflexors and ankle joint angle. Figure 4 showed the relationship between DF MVC and ankle joint angle in seven participants of present study.

DF MVC torques decreased as the ankle joint angle was positioned more into dorsiflexion. Based on this result, the associations between the initial values and either Δ DF ROM or Δ DF MVC torque can be illustrated as in Figure 5. In Figure 5, #1, #2, #3, and #4 represent the values in the active condition. In STR+TR, since DF MVC torque increased significantly after resistance training period, the force-length curve of the dorsiflexors could have shifted upward (from

line A to line A' in Figure 5). In STR, despite the significant increase in passive DF ROM, active DF ROM did not increase significantly after training period. It is possible therefore that the relationship between the ankle joint angle and passive torque shifted rightward after stretching training period (from B to B' in Figure 5). In the ankle joint ROM, therefore, isometric DF torque would be lesser as the ankle is dorsiflexed and TA muscle length becomes shorter (Figure 4). It is likely therefore that only the strength training cannot sufficiently increase active DF ROM. #4 in Figure 5 represents a hypothetical plot if strength training only had been performed. Although the active DF ROM of #4 increased from #1, the amount of increase was less than #3. Lack of correlation between Δ DF MVC and Δ active DF ROM ($r = 0.29$, $P > 0.05$) suggests a need for increasing extensibility of tissues (muscle and/or tendon) as well as muscle strength to increase active DF ROM.

In conclusion, the current results indicate that active DF ROM as well as passive DF ROM can be increased by a combined program of stretching for calf muscles and resistance training for dorsiflexors, while a static calf stretching program is effective only for the increase in passive DF ROM.

Conflict of Interests

The authors declare that there is no conflict of interests reading the publication of this paper.

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