Influences of fascicle length during isometric training on improvement of muscle strength

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Abstract

This study investigated whether low-intensity isometric training would elicit a greater improvement in maximum voluntary contraction (MVC) at the same fascicle length, rather than the joint angle, adopted during training. Sixteen healthy women (21.8 ± 1.5 years) were randomly divided into an intervention group and a control group. Before (Pre-) and after (Post-) training, isometric plantarflexion MVCs were measured every 10 ° through the range of ankle joint position from 20°dorsiflexion to 30°plantarflexion (i.e. 6 ankle angles). Medial gastrocnemius (MG) fascicle length was also measured at each positions, using B-mode ultrasound under 3 conditions of muscle activation: at rest, 30%MVC at respective angles, and MVC. Plantarflexion resistance training at an angle of 20°plantarflexion was performed 3 days a week for 4 weeks at 30%MVC using 3 sets of twenty, 3 seconds (-s) isometric contractions. MVC in the intervention group increased at 0° and 10° plantarflexion (0°; Pre 81.2 ± 26.5 Nm, Post 105.0 ± 21.6 Nm, 10°; Pre 63.0 ± 23.6 Nm, Post 81.3 ± 20.3 Nm), which was not the angle used in training (20°). However, the fascicle length adopted in training at 20° plantarflexion and 30%MVC was similar to the value at 0° or 10° plantarflexion at MVC. Low-intensity isometric training at a shortened muscle length may be effective for improving MVC at a lengthened muscle length because of specificity of the fascicle length than the joint angle.

Keywords: Strength, Isometric training, Low-intensity training, Specificity of fascicle length,

Specificity of joint angle・Ankle plantarflexion

INTRODUCTION

It is well known that greater effects of resistance training on muscle strength, both with concentric or eccentric contractions, are observed under the conditions used during training, such as the same movement speed (9) or the same movement pattern (19). When resistance training is performed under isometric conditions, strength gains are known to be influenced by the specificity of the joint angle used during training (10, 13). Kitai and Sale (10) reported that isometric training of ankle plantarflexion using maximum voluntary contraction (MVC) at an angle of 0° (i.e., 90° angle between the tibia and sole of foot) produced improvement in MVC only around 0° of ankle position (MVC between −5° and 5°). These results demonstrate the 'so called' specificity of joint angle on training effects. However, Weir et al. (20, 21) reported that isometric training of knee extension at an intensity of 80%MVC and at a 45° knee position angle resulted in significant improvement in MVC over a range of 30° around the training angle. Rasch and Pierson (18) similarly reported that isometric training of elbow flexion at an intensity of 100%MVC and at a 90° elbow angle produced significant improvement in MVC over a range of 30° around the training angle. Thus, contrary to the specificity of joint angle in isometric training previously accepted, some reports have now demonstrated that improvement in MVC can be obtained over a wide range of joint angles around the training angle. The reason for this inconsistency, however, has not been clearly elucidated.

Recent studies examining the changes in the muscle fascicle length during isometric contraction, using ultrasound imaging, have shown the fascicle length to be influenced by both the joint angle and the force exerted during an isometric contraction (3, 8). In particular, these two studies (3, 8) demonstrated that the fascicle length is dependent on the contraction levels, even if a constant joint angle is used during isometric contraction. From these facts, we hypothesized that "specificity" in isometric training, which results in the maximum improvement of MVC, may depend not on the joint angle but, rather, on the fascicle length during training. Several previous studies (18, 20, 21) found improvements of MVC over wide range of joint angles including the training angle, which indicates that the training effect did not strictly follow the specificity of joint angle. In these studies, high-intensity and long-duration isometric contraction or a short rest time was adopted. For instance, the training protocol used in Rasch and Pierson (18) was 15 s (long duration) of MVC, and it was 80%MVC with 30 s (short) rest time in Weir et al. (20, 21). Therefore, it could be predicted that fatigue would occur during training, and the contraction may not have been maintained throughout training, which means that actual contraction during training may have been performed at various fascicle length in these studies (18, 20, 21). Taking these previous results into account, there is a possibility that the underlying cause of the wider range of joint angles in strength improvement following isometric training may be that the specificity of strength improvement may owe to the fascicle length during training rather than the joint angle.

Arampatzis et al. (3) indicated that the fascicle length measured during low-intensity contraction at a joint position in which the muscle is in a shortened length was equal to the fascicle length measured during a high-intensity contraction at a joint position in which the muscle is in an extended length. In order to discriminate the difference of specificity in training between the fascicle length and the joint angle, we conducted this study by investigating the effect of low-intensity training at shortened muscle length and examine whether the MVC improvement occurs at the same fascicle length or at the same joint angle.

The purpose of the present study was to examine whether low-intensity isometric training would yield a greater improvement in MVC at the same fascicle length as the training condition. We hypothesized that low-intensity isometric training would have a greater improvement in MVC at the same fascicle length, rather than at the same joint angle, used during training.

METHODS

Experimental Approach to the Problem

The experimental design of this study was a randomized controlled trial. A flowchart of the experimental protocol is shown in Figure 1. Prior to obtaining pre-training measurements, all subjects were familiarized with the MVC procedure for plantarflexion. In the initial week of the experiment, subjects attended 3 familiarization sessions, practicing MVCs at the 6 ankle joint positions used for testing, set at 10° intervals over the range from 20° dorsiflexion to 30° plantarflexion. An ankle joint angle of 0° (neutral position) was defined as a 90°angle between the fibula and fifth metatarsal bone. Following the familiarization sessions, MVC of the ankle plantarflexors and the fascicle length of the medial gastrocnemius (MG) were measured (Pre-measurement). The same measurements were performed after 4 weeks of intervention (Post-measurement), resulting in a total experimental period of 5 weeks. All measurements and analysis were implemented only at Kyoto University.

Subjects

Sixteen healthy women (age 21.8 ± 1.5 years), who were non-athletes and had not been involved in any regular stretching or resistance training, participated in this study. Subjects with a history of neuromuscular disease or musculoskeletal injury involving the lower limbs were excluded. The subjects were randomly assigned to the intervention group (n = 8) or to the control group (n = 8) using a computerized random number function in Microsoft Excel. All subjects were fully informed of the procedures and purpose of the study, which conformed to the Declaration of Helsinki. Written informed consent was obtained from all subjects. This study was approved by the ethics committee of

Kyoto University Graduate School and the Faculty of Medicine (R-0216).

Measurements of MVC, the fascicle length and the muscle thickness

MVC was measured using a Biodex dynamometer (Biodex System 4, Biodex Medical Systems Inc., Shirley, New York, USA.) with 1000Hz sampling rate, at 6 ankle positions, set at 10° intervals over the range from 20° dorsiflexion to 30° plantarflexion, with the order of MVCs randomized across participants. A range of ankle joint angles (from 20° dorsiflexion to 30° plantarflexion) was determined by a range of motion that all subjects can exert force. For measurement, the ankle joint of the dominant leg was securely attached by velcro strap to the footplate of the dynamometer. Soft cloth was inserted between the velcro strap and instep to prevent unwanted movement of the ankle joint. The trunk and distal thigh were securely fixed by the dynamometer belts to keep the hip joint position of 80° flexion and the knee joint in full extension. The subjects grasped horizontal bars attached to the dynamometer. MVC was exerted for 5 seconds (-s) at each of the 6 ankle joint angles, with more than 1 minute (-min) of rest provided between each MVC. The MVC peak torque over each 5-s trial was used for analysis.

The fascicle length of the MG was measured at the proximal 30% of the lower leg length (1), using B-mode ultrasound imaging (LOGIQ e, General Electric, Duluth, GA, USA) with an 8-MHz linear array probe (6 cm). The ultrasound settings used by the measurements were set at 58–70 dB gain. Depth and Dynamic focus of the equipment settings were controlled to achieve a clear image of the muscle thickness and the fascicle length of the MG. The fascicle length was measured at each of the 6 test angles of the ankle and under three levels of activation—rest, 30%MVC at the respective angles, and MVC—for a total of 18 test conditions in randomized order. Three images of the fascicle were recorded for each condition. In measurement of the fascicle length at MVC, the images were preserved when exerted force displayed on the dynamometer monitor reached a plateau. The fascicle length was estimated from these images based on the methods which evaluated the distance along a straight line, between extension lines from the aponeurosis and the origin of the fascicle. (Figure 2). Ando et al. (2) demonstrated that this method is useful technique for estimating the fascicle length of quadriceps muscle. This method has been used to determine the fascicle length of the quadriceps muscle in a number of previous studies (4, 6, 7). However, the reliability of the measurements of the MG has not been shown before. Therefore, the reliability of the measurements of MG was assessed at the 6 test ankle angles in a control group. A intraclass correlation coefficients (ICC 1.1) value higher than 0.75 is considered valid (12). ICC value for the fascicle length of the MG was valid at all ankle angles in both inter session (ICC > 0.9) that were measured by two images at pre-measurement, and inter day (ICC > 0.75) that were measured by images at pre- and post-measurement. The fascicle length was measured for each condition using image processing software (ImageJ, version 1.48, National

Institutes of Health, Bethesda, MD, USA). The mean value of all three images, obtained for each condition, was used in the analysis. The outcome assessors were blinded to measurement conditions (i.e., ankle joint position and level of activation). The fascicle length and the muscle thickness of MG at rest with ankle position of 0° were measured from the ultrasound imaging on the longitudinal plane at baseline and after 4 weeks to examine morphological changes. The muscle thickness was also measured to assess whether the improvement in muscle strength is due to morphologic changes such as muscle hypertrophy. The muscle thickness of MG was measured at the proximal 30% of the lower leg length. The muscle thickness was measured by measuring the line drawn perpendicular from the surface to the deep aponeurosis. To accurately measure the muscle thickness without including non-contractile tissue, the measurement between the inside edges of the aponeurosis was used. Previous studies have shown the reliability of the ultrasound technique for measuring muscle thickness of the MG. (14, 17)

Training protocol

The intervention group performed resistance training at an intensity of 30%MVC, 3 days per week, for 4 weeks, using a Biodex dynamometer. The isometric resistance training protocol consisted of 3 sets of 20 repetitions of plantarflexion contraction, held for 3-s and performed at 20° plantarflexion, with a 1-s rest between contractions, and a 2-min rest between sets. The target intensity of 30%MVC was displayed on the dynamometer monitor during resistance training. The examiner checked whether subjects could exert the target intensity at all training session. The training intensity of 30%MVC was reassessed from MVC values measured after the 2-week intervention. Subjects in the control group did not receive any intervention.

Statistical analysis

Statistical analysis was performed using SPSS (version 22.0, SPSS Japan Inc., Tokyo, Japan). Normality of the data was evaluated using a Shapiro-Wilk test. Group differences for characteristics and MVC of each ankle joint angle at baseline were assessed using an unpaired t-test. Two-way repeated measures analysis of variance (ANOVA) using two factors (the ankle joint angle and the contraction level) was used to determine the differences in the fascicle length at the baseline due to the ankle joint angle and the contraction level. When a significant main effect was observed, Bonferroni's post hoc test was performed. In intervention group, paired t-test was used to determine the differences in the fascicle length between MVCs at each angle in Post-measurement, and at training condition (at 20°plantarflexion with 30%MVC). The fascicle length at training condition was calculated as the mean value of Pre- and Post-measurement to cancel the possible change in the fascicle length due to training. Split-plot ANOVA, using two factors (group × time), was used to analyze interaction effects for muscle strength. When a significant interaction was observed, a paired t-test was used to determine the differences between the value at baseline and after 4 weeks in both groups. The effect size (Cohen's d) of MVC changes in pre- and post-measurement was calculated employing the methods used in the following study (16). Paired t-test was used to determine the differences of the fascicle length and muscle thickness between at baseline and after 4 weeks. Differences were considered to be statistically significant at an alpha level of 0.05.

RESULTS

No subjects dropped out, and all subjects in the intervention group completed the training sessions. Therefore, all data for all subjects in the intervention and control groups were entered in the analysis.

The characteristics of the subjects are shown in Table 1. There were no significant differences in age, height, and body mass between subjects in the intervention and the control groups. Baseline MVC of plantarflexion are shown in Table 2, again reported as the mean ± SD. There were no significant differences in MVC, across all 6 testing positions of the ankle joint angle, between intervention and control groups.

Differences in the fascicle length due to the ankle joint angle and the contraction level at baseline

Figure 3 shows the fascicle length at rest, 30%MVC, and MVC at each of the 6 test angles at baseline (n=16). Two-way repeated measures ANOVA, using two factors—the ankle joint angle and the contraction level—indicated significant main effects for both the factors. The post-hoc analysis showed significant differences in the fascicle length between all 6 test angles at each contraction level, indicating that the fascicle length decreased with ankle plantarflexion. In addition, the post-hoc analysis showed significant differences between all contraction levels, which shows that the fascicle length decreases with increases in the contraction level at each ankle joint angle.

Effects of intervention on MVC

Effects of intervention on MVC, measured at each of the 6 test angles of ankle position, are shown in Table 2. Split-plot ANOVA, using two factors (group × time), showed significant interactions at the discrete ankle positions of 0° and 10° plantarflexion. At 0° and 10° plantarflexion, there were significant differences in MVC between Pre- and Post-measurements for the intervention group, but not for the control group.

Effects of intervention on the muscle thickness and the fascicle length

There were no significant differences in the fascicle length between baseline and after 4 weeks in both groups (intervention group; baseline: 5.53 ± 0.75 cm, after: 5.56 ± 0.78 cm, control group; baseline: 5.99 ± 1.11 cm, after: 5.73 ± 1.36 cm). There were also no significant differences in muscle thickness between baseline and after 4 weeks in both groups (intervention group; baseline: 1.80 ± 0.17 cm, after: 1.76 ± 0.18 cm, control group; baseline: 1.79 ± 0.35 cm, after: 1.74 ± 0.27 cm).

Comparison of the fascicle length during the training condition and MVC contraction

The fascicle lengths measured at 20°, 10° dorsiflexion, 0°, 10°, 20° and 30° plantarflexion with the contraction level of MVC at Post-measurement were 4.39 ± 1.29 cm, 3.54 ± 0.90 cm, 3.30 ± 1.16 cm, 2.77 ± 0.68 cm, 2.48 ± 0.43 cm and 2.33 ± 0.34 cm, respectively. The fascicle length at 20° plantarflexion and 30%MVC used for our training condition was 2.95 ± 0.35 cm. Paired t-test showed that there were no significant differences in the fascicle length between training condition (20°plantarflexion with the contraction level of 30%MVC) and at 0°and 10°plantarflexion with MVC, although there was significant difference between training condition and at 20°, 10° dorsiflexion, 20° and 30° plantarflexion with MVC.

DISCUSSION

This is the first report demonstrating the influences of fascicle length during isometric training on improvement in muscle strength. The hypothesis of this study was that the effects of isometric training on MVC would be influenced by the muscle fascicle length rather than by the joint angle. Our results provided some evidence for this hypothesis, showing that MVC at 0° and 10° ankle plantarflexion increased after isometric training at 20° plantarflexion, whereas no significant increase were observed in MVC at 20° plantarflexion. In this study, the length of the muscle fascicle of the MG was defined as the length of the bundle of muscle fiber, estimated using ultrasound imaging. Our results showed that the fascicle length varied as a function of both the joint angle and the contraction level, which is consistent with previous studies (3, 8). The fascicle length of the MG muscle at 20° plantarflexion and at a contraction level of 30%MVC (i.e. the training condition), was 2.95 ± 0.35 cm. This fascicle length was equivalent to the length measured at 0° and 10° plantarflexion at MVC (0°; 3.30 ± 1.16 cm, 10°; 2.77 ± 0.68 cm). In this study, MVC improved not significantly at 20°plantarflexion but at 0° and 10° plantarflexion. This result indicated that improvements in MVC were obtained at the same fascicle length, rather than at the same joint angle, used during training, which consists with our hypothesis. This finding is inconsistent with previous studies (10, 13), which reported the effects of training on

MVC to be specific to the joint angle used during training. However, the results of these studies stating the specificity of joint angle could also be considered that MVC improved specific to the fascicle length. Since MVC was exerted during training in these studies, the relation of the fascicle length and the joint angle would be equal in training and MVC measurement. Therefore, the improvement found in the same joint angle would indicate improvement in the same fascicle length.

The training intensity used in this study was set at a low-intensity level of 30%MVC. Moreover, the isometric contractions were performed for 3-s, which was shorter than contraction durations used in previous studies (18, 20, 21). The rest period provided between sets was 2-min, which may be sufficient to recover from muscle fatigue. Therefore, we consider that in our study, the targeted training intensity of 30%MVC was maintained and, therefore, that the fascicle length of the MG muscle was consistent during training. Previous studies (18, 20, 21) showed that effects of high-intensity training on MVC were obtained at wider range of joint angles. In these previous studies (18, 20, 21), the high resistance training intensity of 80%MVC or 100%MVC was performed with long isometric contraction or short rest time, such that the target intensity of 80%MVC or 100%MVC may not have been maintained. Under these conditions of isometric training with non-fixed intensities, the fascicle length could have varied, explaining the reported improvements in MVC over a range of joint angles. In addition, it could be hypothesized that the muscle strength may increase over a wide range of joint angles if the magnitude of strength improvements was large.

Improvement in muscle strength after resistance training depends on neural adaptations over the initial period of training (i.e., <4 weeks), followed by morphological adaptations in the muscles after 6–8 weeks, which mainly contributes to the strength gains (11, 15). Our study showed no changes in morphological measurements such as the fascicle length or the muscle thickness after training. Therefore, the improvement in MVC after a 4-week intervention in this study may be influenced by neural adaptations, such as the increases in muscle activity of agonist muscles and decreases in antagonist coactivation (5). Further investigation is necessary to clarify the interaction between neural adaptation mechanisms and the effects of specificity in the fascicle length during training.

This study has some limitations. First, the fascicle length during training was not directly measured. Second, our study considered the fascicle length only for the MG muscle. Therefore, the influence of other plantar flexor muscles and the soleus and lateral gastrocnemius muscles, on measured improvements in MVC is unclear. That is to say, we cannot differentiate if improvements in MVC may also be contributed by specificity in the fascicle length of the soleus or the lateral gastrocnemius muscles during training. Further research is required to clarify the effect of isometric training on MVC, considering the fascicle length of all muscles, which may contribute to strength gain.

PRACTICAL APPLICATIONS

The results of the present study showed that low-intensity isometric training of ankle plantarflexion improved MVC at more dorsiflexed position than at the training angle. Moreover, the fascicle length of the MG at the training position was similar to the fascicle length at the position that improved MVC, which suggests "specificity" of the fascicle length in isometric training. It is possible that low-intensity training at shortened muscle length may be suitable and safer for the elderly who cannot perform high-intensity training or for patients who have restricted range of joint motion.

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Table 1 Characteristics of the participants

	Intervention group(n = 8)	Control group(n = 8)	*p*-value
Age (years)	21.75 ± 0.71	21.88 ± 2.10	0.88
Height (cm)	159.13 ± 5.41	158.13 ± 3.50	0.67
Body mass (kg)	50.63 ± 5.32	49.13 ± 4.05	0.54

Values are expressed as mean ± SD (standard deviation)

Table 2 Effects of intervention on MVC at each ankle joint angle

ankle joint angle	intervention group (n = 8)			control group (n = 8)		
	Pre (Nm)	Post (Nm)	Effect size (95%CI)	Pre (Nm)	Post (Nm)	Effect size (95%CI)
Dorsiflexion 20°	112.55 ± 37.79	131.09 ± 31.92	0.53 (-0.47 - 1.53)	116.08 ± 40.98	118.53 ± 42.26	0.06 (-0.92 - 1.04)
Dorsiflexion 10°	101.88 ± 30.15	119.24 ± 27.26	0.60 (-0.40 - 1.61)	103.28 ± 35.82	104.76 ± 36.09	0.04 (-0.94 - 1.02)
0°**	81.26 ± 26.52	105.08 ± 21.56	0.99 (-0.05 - 2.02)	91.50 ± 24.60	90.78 ± 29.04	-0.03 (-1.01 - 0.95)
Plantarflexion 10°*	62.96 ± 23.55	81.29 ± 20.30	0.83 (-0.19 - 1.86)	71.50 ± 21.06	70.15 ± 21.06	-0.06 (-1.04 - 0.92)
Plantarflexion 20°	50.23 ± 21.14	62.24 ± 20.43	0.58 (-0.42 - 1.58)	51.51 ± 16.30	53.76 ± 17.44	0.13 (-0.85 - 1.11)
Plantarflexion 30°	31.84 ± 14.70	42.74 ± 16.60	0.70 (-0.31 - 1.70)	34.03 ± 15.96	36.38 ± 15.32	0.15 (-0.83 - 1.13)

Values are expressed as mean ± SD (standard deviation)

CI = confidence interval

Effect size is Cohen’s d. d = 0.2, 0.5, 0.8 were considered “small,” “medium,” and “large” effects, respectively.

*; significant interaction between time (Pre and Post) and groups (intervention and control groups)

***P*<0.01,**P*<0.05

Fig. 1 Flowchart of this study

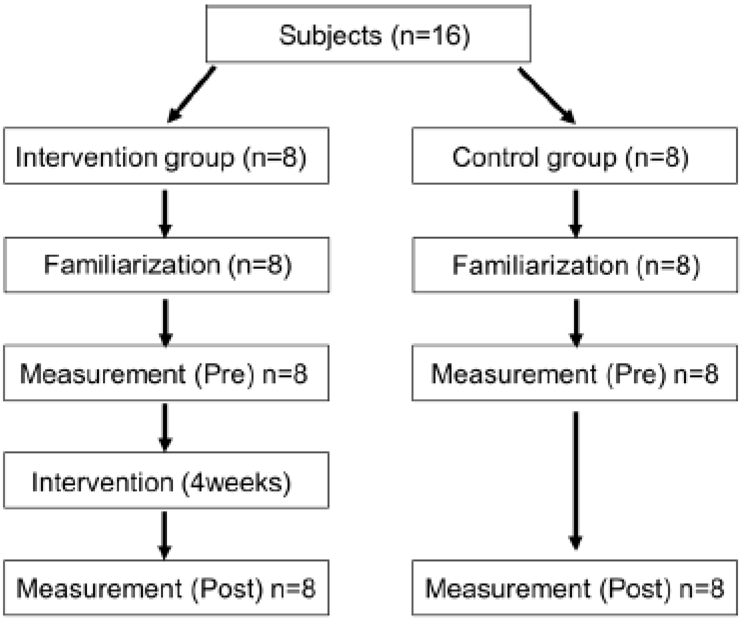
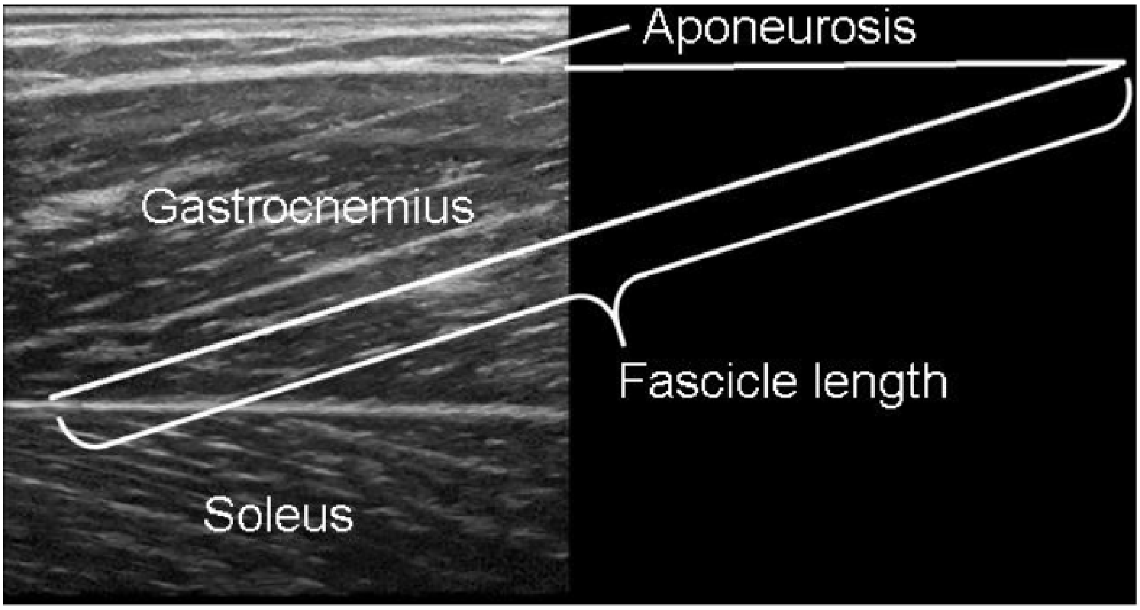
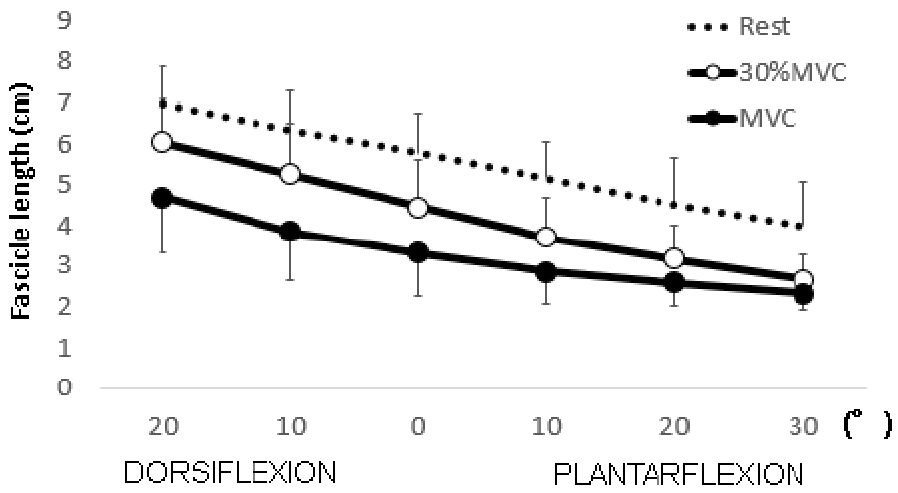


Fig. 2 Estimation of fascicle length



The fascicle length of the MG was defined as a distance in a straight line between extension lines from aponeurosis and fascicle origin.

Fig.3 Fascicle length in both groups at baseline



An open circle indicates 30%MVC, and a filled circle indicates MVC values. At all contraction levels, the fascicle length decreases toward plantarflexion. At the same ankle angle, fascicle length decreases toward MVC.