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Relation between the ankle joint angle and the maximum isometric force of the toe flexor muscles

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ABSTRACT

The purpose of this study was to investigate the relationships between the ankle joint angle and maximum isometric force of the toe flexor muscles. Toe flexor strength and electromyography activity of the foot muscles were measured in 12 healthy men at 6 different ankle joint angles with the knee joint at 90 deg in the sitting position. To measure the maximum isometric force of the toe flexor muscles, subjects exerted maximum force on a toe grip dynamometer while the activity levels of the intrinsic and extrinsic plantar muscles were measured. The relation between ankle joint angle and maximum isometric force of the toe flexor muscles was determined, and the isometric force exhibited a peak when the ankle joint was at 70–90 deg on average. From this optimal neutral position, the isometric force gradually decreased and reached its nadir in the plantar flexion position (i.e., 120 deg). The EMG activity of the abductor hallucis (intrinsic plantar muscle) and peroneus longus (extrinsic plantar muscle) did not differ at any ankle joint angles. The results of this study suggest that the force generation of toe flexor muscles is regulated at the ankle joint and that changes in the length-tension relations of the extrinsic plantar muscle could be a reason for the force-generating capacity at the metatarsophalangeal joint when the ankle joint angle is changed.

1. Introduction

Muscle force produced during isometric contractions is a function of the muscle length (the length-tension relation). Gordon et al. (1966) found that the isometric force in single fibres of frog semitendinosus muscles changes depending on sarcomere length and that maximum force is generated at a sarcomere length of approximately 2.0 µm. This relation supports the sliding filament theory of muscle contraction that had been previously proposed (Huxley and Hanson, 1954; Huxley and Niedergerke, 1954). During movement in vivo, the length-tension relation of muscles is generally interpreted in terms of the joint angle-torque relation (Kulig et al., 1984), which is defined by the lever system or joint configuration in addition to the length-tension relation of the muscle itself. It has been reported that the shape of the length-tension relation in knee extension is determined by the sum of the length-tension relations of the individual muscles (Herzog et al., 1991). However, during voluntary contraction, the neural activation level also changes with muscle length during isometric knee extension (Babault et al., 2003). Moreover, tendon compliance affects the ability to generate muscle force depending on the range of motion, i.e., the length of the muscle-tendon complex (Hawkins and Bey, 1997). Therefore, the in vivo length-tension relation in human movements not only may be related to the contractile mechanism of muscle fibres but also may be influenced by other factors, such as muscle activation level and tendon compliance.

The foot muscles include intrinsic and extrinsic muscles. The extrinsic muscles of the foot function in both plantar flexion and toe flexion since their origin and insertion cross over both the ankle and metatarsophalangeal (MTP) joints. Our recent study showed that the maximum force generation of the toe flexor muscles at the MTP joint was related to the cross-sectional areas of both the intrinsic and the extrinsic muscles of the foot in adults (Kurihara et al., 2014). Additionally, the toe flexor muscles help to support the foot arches (Bojsen-Møller, 1979). Regarding the clinical relevance of toe flexor muscle strength, foot strength and structure often receive attention because they are associated with injuries (Kaufman et al., 1999; Williams et al., 2001). Weakness of the foot muscles may play a role in pain and mobility problems,

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including difficulties with walking or running (Garth and Miller, 1989), and it increases the risk of falls in elderly individuals (Mickle et al., 2009). On the other hand, strong toe flexor muscles help prevent increased mobility when pronation control is required and thus lead to decreased risk of lower limb overuse injuries (Aibast et al., 2017). The abductor hallucis muscle is one of the toe flexor muscles and functions to elevate the arch of the foot when the hallux is fixed on the ground (Wong, 2007). Therefore, given that the muscle strength and structure of the foot are important factors in enhancing physical performance and preventing lower limb injuries, it is necessary to clarify the functional role of the human foot.

From a practical standpoint, some artefactual factors, such as shoes and ankle braces, may affect the function of the foot and impair the force-generating capacity of the foot. Indeed, we showed that the acute responses in ground reaction force, lower limb joint kinematics and muscle activity during a drop jump were different between shoed and barefoot conditions (Koyama and Yamauchi, 2018). Moreover, limiting the movement of the ankle joint and the foot using ankle braces impaired force production by the muscles of the foot and lower leg (Yamauchi and Koyama, 2015) as well as jump performance (Koyama et al., 2014). These results assume that the extrinsic plantar muscles influence the ability to produce maximum force at the MTP joint when the ankle joint angle is changed. Changes in the length-tension relations of the extrinsic plantar muscles could affect the force-generating capacity of the foot to some extent. Therefore, it would be valuable to know how changes in the ankle joint angle affect the maximum isometric force of the toe flexor muscles. To date, there has been no study into how the extrinsic plantar muscles contribute to the force-generating capacity of the foot when the ankle joint angle is changed. The purpose of this study was to investigate the relation between the ankle joint angle and the maximum isometric force of the toe flexor muscles in the sitting position. The study of the ankle joint angle-toe flexor force relation will further help our understanding of the mechanisms underlying the contractile properties of the foot muscles.

2. Methods

2.1. Experimental procedures

The toe flexor strength (TFS) of the study subjects was measured at 6 ankle joint angles (70, 80, 90, 100, 110 and 120 deg) with the knee joint at 90 deg in the sitting position (Fig. 1). Ankle joint angles were changed without changing the knee joint angle using a customised angle gauge. The toe grip dynamometer was fixed to the unit. During TFS measurement, muscle activity levels of the intrinsic and extrinsic plantar muscles were also measured by a telemetric EMG unit (WEB-5000, Nihon Kohden, Tokyo, JAPAN). Subjects wore training shorts, and they were asked to perform warm-up exercises and to stretch their leg and foot muscles before the experiment.

2.2. Subjects

Twelve healthy men (age, 21.4 ± 1.2 years; height, 1.72 ± 0.07 m; body mass, 67.1 ± 10.2 kg; mean ± SD) participated in this study. The methods and all procedures used during this experiment were in accordance with current local guidelines and the Declaration of Helsinki. All subjects were informed about the experimental procedure as well as the purpose of the study prior to the initiation of the study. Written informed consent was obtained from all participants.

2.3. Toe flexor strength (TFS)

TFS was measured in the sitting position using a specifically designed toe grip dynamometer (T.K.K.3361, Takei Scientific Instruments Co., Niigata, JAPAN). Details of the apparatus and methodology and the reproducibility of the measurements have been described elsewhere (Koyama and Yamauchi, 2017; Kurihara et al., 2014; Morita et al., 2015; Otsuka et al., 2015; Yamauchi and Koyama, 2015). The range of force captured by this dynamometer is 1–400 N. The experimental setup is shown in Fig. 1. The dynamometer consists of strain gauge force transducers, and the force was measured when the grip bar was pulled. After subjects had warmed up for several minutes and stretched their leg and foot muscles, the foot was placed on the dynamometer and was fixed with the heel stopper. During the measurements, subjects placed their arms in front of their chests, and they were instructed to perform the task without flexing their knee joint. The opposite foot was positioned beside the dynamometer. Prior to obtaining the maximum measurement, subjects performed 3–5 trials at a submaximum level of isometric force. For measurement of maximum TFS, subjects exerted maximum force on the dynamometer for ~3 s. Three measurements of maximum force in the right foot were averaged and used for further analysis.

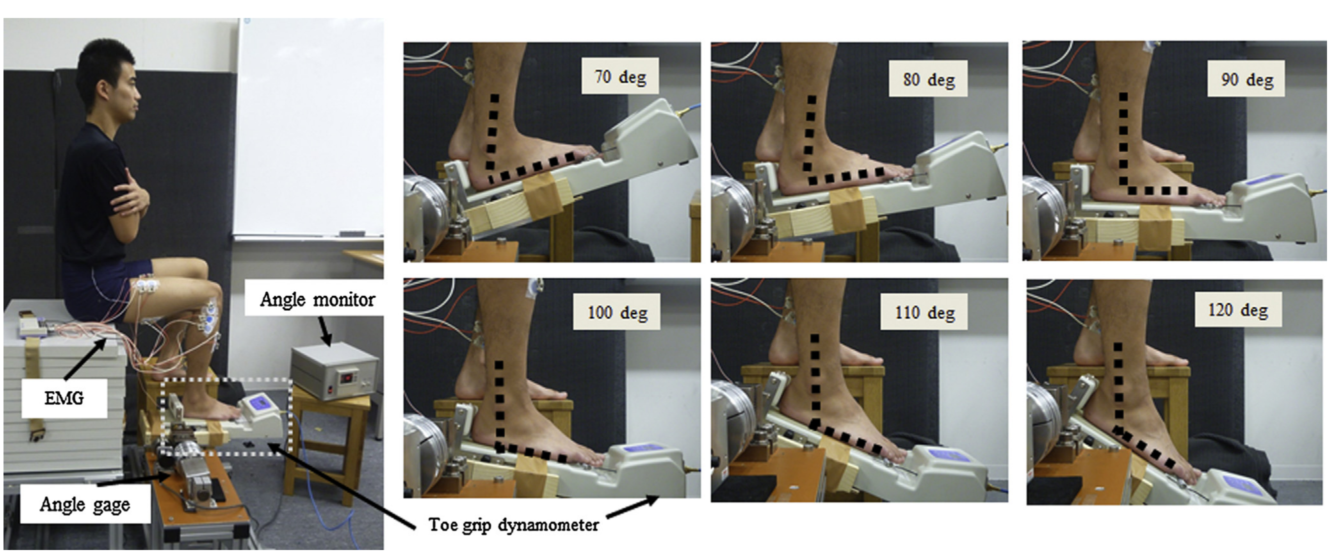

Fig. 1. Experimental set-up.

Because TFS was affected by body mass (Yamauchi and Koyama, in press), the absolute value of the TFS was divided by body mass (BM) and the following equation was used: relative TFS (rTFS) = TFS (N)/BM (kg).

2.4. Electromyography (EMG) analysis

EMG signals were recorded from superficial intrinsic (abductor hallucis; ABH) and extrinsic (peroneus longus; PL) plantar muscles of the right foot using a telemetric EMG unit system at a sampling frequency of 1 kHz. EMG measurements of six other leg muscles (gastrocnemius medialis, MG; soleus, SOL; tibialis anterior, TA; rectus femoris, RF; lateral vastus, VL; biceps femoris, BF) were concomitantly recorded for reference. The signals were passed through a locally grounded preamplifier (AM-511H, Nihon Kohden, Tokyo, JAPAN) to a receiving unit (ZR-550H, Nihon Kohden, Tokyo, JAPAN). The analogue signals were telemetrically sent to a recording computer (a 12-bit analogue-to-digital converter). EMG signals were detected by bipolar electrodes (Blue Sensor M-00-S/50, Ambu, Ballerup, Denmark) with a diameter of 10 mm and a centre-to-centre distance of 20 mm. To detect ABH and PL under the skin surface, B-mode ultrasound (FC1-X, Fujifilm, Tokyo, JAPAN) with an electronic linear array probe at 6–13 MHz wave frequency (HFL38xp/13-6, Fujifilm, Tokyo, JAPAN) was used. The ultrasound probe was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface and it was placed perpendicular to the skin. After the skin was shaved and cleaned with isopropyl alcohol, the electrodes were placed at the midpoint of each muscle, parallel to the directions of the underlying muscle fibres. The reference electrode was attached over the flat portion of the anteromedial aspect of the tibia. Pulling artefacts were avoided by carefully fixing the electrode cables to the skin with tape. Band-pass filtering (15–200 Hz) was used to remove movement artefacts and signal noise. EMG data were full-wave rectified and averaged with respect to time; rectified mean values are denoted as mEMG. The means value of the three trials were used for farther analysis. Absolute values of mEMG were further normalized in each muscle with respect to the maximum value during maximum voluntary contractions (MVC); these normalized values are denoted as %mEMG. MVC in each muscle was measured in the sitting position and during the abduction of the toe for ABH, abduction of the ankle for PL, plantar flexion for MG and SOL, dorsiflexion for TA, hip flexion for RF, knee extension for VL, and knee flexion for BF. To measure the MVC of each muscle, subjects exerted maximum force for 3 s and performed at least three trials with a 30-second rest period between trials. The maximum value for each muscle were used for farther analysis.

2.5. Data analysis

All data are presented as the mean ± SD. To quantify the differences in rTFS and mEMG at different ankle joint angles, a one-way repeated-measures analysis of variance with Bonferroni-corrected pairwise post-hoc comparisons was used. The level of statistical significance was set at $p < 0.05$.

3. Results

Figure 2 shows typical examples of force- and EMG-time records during maximum toe flexion in one subject. The relation between ankle joint angle and toe flexor strength is shown in Fig. 3. The isometric force exhibited a peak when the ankle joint angle was at 70–90 deg. The optimum isometric force was achieved from the neutral position (i.e., 90 deg) to the most dorsiflexed angle (i.e., 70 deg) of the ankle joint; it gradually declined to its nadir in the plantar flexed position (i.e., 120 deg). Table 1 shows the %mEMG data for all muscles. The %mEMG activity of all muscles did not differ at any ankle joint angles, except that those values for TA were significantly lower in the plantarflexed position.

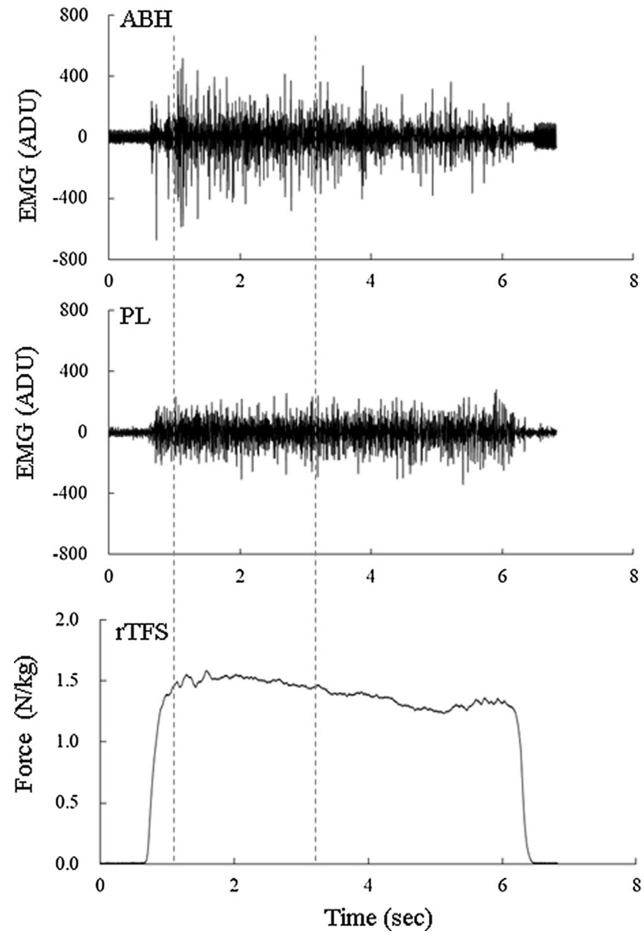

Fig. 2. Force- and EMG-time records during maximum toe flexion in one subject, at a 90-degree angle of the ankle joint. The two vertical lines indicate the selected area of the steady state values for the analysis. ABH, abductor hallucis; PL, peroneus longus; rTFS, relative toe flexor strength = TFS (N)/BM (kg).

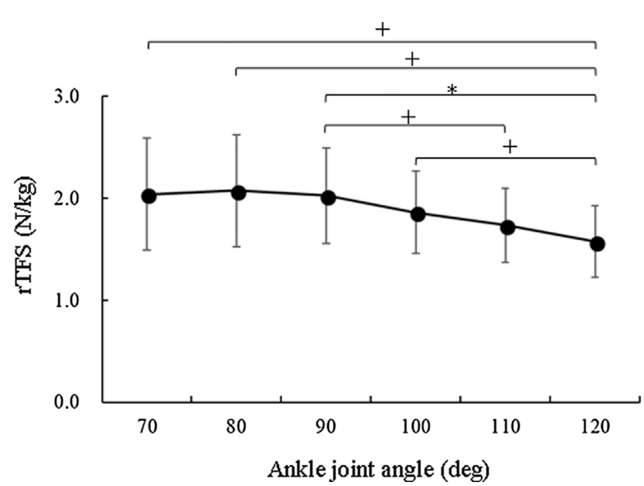

Fig. 3. Relation between ankle joint angle and relative toe flexor strength (rTFS) +, $p < 0.05$; *, $p < 0.01$.

Table 1
Relative %mEMG during maximum toe flexion at different ankle joint angles.

Ankle joint angle (deg)						
mEMG (%)	70	80	90	100	110	120
ABH	27.0 ± 31.5	28.1 ± 26.9	35.9 ± 31.4	35.0 ± 32.5	35.3 ± 32.4	41.1 ± 34.8
PL	41.8 ± 17.9	42.5 ± 17.8	44.3 ± 23.7	52.4 ± 33.0	60.2 ± 44.2	83.9 ± 66.4
MG	22.9 ± 18.2	34.0 ± 28.6	46.1 ± 41.7	54.2 ± 54.0	56.6 ± 49.5	56.5 ± 44.2
SOL	35.7 ± 23.0	37.6 ± 22.9	38.9 ± 24.5	45.8 ± 28.6	48.6 ± 30.9	62.6 ± 42.3
TA	45.7 ± 10.4a,b	39.6 ± 12.1c,d	32.3 ± 12.7e	30.4 ± 14.0	26.9 ± 12.2	24.2 ± 14.8
RF	11.7 ± 15.3	11.5 ± 15.9	12.0 ± 17.1	11.7 ± 15.7	10.8 ± 15.0	11.0 ± 13.3
VL	14.8 ± 16.3	12.1 ± 15.5	13.0 ± 16.4	11.7 ± 13.5	11.2 ± 10.8	11.4 ± 9.4
BF	19.9 ± 20.0	20.1 ± 16.6	23.2 ± 13.9	25.1 ± 14.9	29.1 ± 13.5	33.5 ± 17.1

ABH; abductor hallucis, PL; peroneus longus, MG; gastrocnemius medialis, SOL; soleus, TA; tibialis anterior, RF; rectus femoris, VL; lateral vastus, BF; biceps femoris. Values are presented as the means ± SDs. a, b, c, d and e denote significant differences between 70 deg and 120 deg ($p = 0.011$), 70 deg and 110 deg ($p = 0.010$), 80 deg and 120 deg ($p = 0.030$), 80 deg and 110 deg ($p = 0.018$) and 90 deg and 110 deg ($p = 0.031$), respectively.

4. Discussion

The present study describes for the first time the maximum force generation and muscle activity of toe flexor muscles at different ankle joint angles without changing the knee joint angle. The relation between ankle joint angle and maximum isometric force of the toe flexor muscles was determined, and the isometric force exhibited a peak when the ankle joint was at 70–90 deg on average. From this optimal neutral position, the isometric force gradually decreased and reached its nadir in the maximum plantar flexion position (i.e., 120 deg). The muscle activity of the intrinsic and extrinsic plantar muscles was quantified by using EMG. The EMG activity of the abductor hallucis (intrinsic plantar muscle) and peroneus longus (extrinsic plantar muscle) did not differ at any of the ankle joint angles. The results of this study suggest that the force generation of toe flexor muscles is regulated at the ankle joint and that changes in the length-tension relations of the extrinsic plantar muscles could be a reason for the force-generating capacity at the MTP joint when the ankle joint angle was changed.

The force-generating mechanism of the foot is key to understanding the unique function of human bipedal locomotion. Foot muscles are classified as the intrinsic and extrinsic plantar muscles. These intrinsic and extrinsic muscles and tendon complexes of the foot help to support the foot arch and generate the muscle force of the foot at the MTP joint during human bipedal movement (Bojsen-Møller, 1979; Fiolkowski et al., 2003; Kura et al., 1997; McKeon et al., 2015). The intrinsic toe flexor muscles originate at the calcaneus and insert on the proximal phalanges, whereas the extrinsic toe flexor muscles originate in the lower leg, cross over the ankle and MTP joints, and insert into the distal phalanges, thus functioning in plantar flexion of both the foot and the toes. This study showed that TFS was optimally generated at an ankle joint angle of 70–90 deg, and it decreased when the ankle joint was plantarflexed. It has been suggested that changes in the joint angle are proportional to changes in muscle length and the length of muscle fibres (Perrine and Edgerton, 1978; Wickiewicz et al., 1984). Since the force generated at various joint angles reflects the length-tension relation of muscle fibres, changes in ankle joint angle affect the maximum force level of extrinsic plantar muscles. Goldmann and Brüggemann (2012) reported that flexion moments at the MTP are influenced by the ankle joint angle. In fact, the fascicle length of extrinsic toe flexor muscles changes with a small amount of ankle rotation (Refshauge et al., 1995). This suggests that extrinsic toe flexor muscles could be shortened by increasing the ankle joint angle, thus causing a decrease in the force-generating capacity. To optimize the force output of the foot muscles in running or jumping, the ankle joint angle is to be kept at approximately 90 deg during ground contact.

Anatomically, the intrinsic toe flexor muscles are mono-articular muscles of the MTP joint, whereas the extrinsic toe flexor muscles are bi-articular muscles of both the ankle and MTP joints, so they play different roles in the motion. As bi-articular muscles, the extrinsic toe flexor muscles may not lengthen or shorten to a large extent; rather, they mostly contract isometrically during multi-joint movements such as walking. As a result, their contraction speed is slow, but their force generation is high (Gregoire et al., 1984). During walking, the winding of the plantar fascia around the metatarsal heads occurs after the mid-stance, when the foot is ready to lift off the ground; the foot muscles activate and generate forces in the push-off phase (Hicks, 1954). This windlass function serves to increase the muscle force at the MTP joint with an increase in plantar fascia tension of the foot arch (Caravaggi et al., 2009). A windlass function at the MTP joint can compensate for a change in muscle length at the ankle joint by being able to transmitting a high force. In addition to the large triceps surae, the extrinsic toe flexor muscles generate an internal plantar flexion moment around the ankle and lift the heel from the ground. The extrinsic toe flexor muscles generate large forces during the push-off phase of walking (Jacob, 2001). The dynamic energy produced by one side of the joint in the bi-articular muscles is transmitted to the other side of the joint, which may help the action of the other side of the joint during motion. Therefore, changes in the length of bi-articular extrinsic toe flexor muscles are crucial to controlling force generation during the push-off phase of locomotion because these muscles are responsible for force transmission from the lower limb to intrinsic toe flexor muscles and the ground. Since the ankle joint also functions as the force modulator of the foot muscle at the MTP joints, the artefactual effects of implements such as high-ankle shoes and ankle braces may impair the force generating capacity of the foot.

Muscle activity during maximum toe flexion did not differ at various ankle joint angles. In general, as force increases, both motor unit recruitment and the firing rate increase. This can be demonstrated by the surface EMG recordings, which show increases in intramuscular spike amplitude (recruitment) and frequency (firing rate modulation) with increasing force (Stephens and Taylor, 1972). The amplitude and duration of the surface EMG recordings is related to the number, size, type and firing rates of active motor units as well as the size of the individual fibre potentials and the degree of synchrony between them (Bigland-Ritchie et al., 1983; Sandercock et al., 1985). However, the EMG activity of the extrinsic plantar (peroneus longus) muscle tended to increase when the ankle joint was plantarflexed. Additionally, EMG activity tended to increase in the triceps surae (soleus and gastrocnemius) muscles but decrease in TA when the ankle joint was plantarflexed. This phenomenon suggests that the extrinsic plantar (peroneus longus) muscle might be activated during plantar flexion in the plantarflexed position of the ankle because of the dual function of PL (i.e., toe flexion and ankle plantar flexion), although we did not measure the plantar flexion torque. In general, the force is initially developed by recruitment of motor units. At some force levels, the contribution of recruitment is decreased or ceased when all the motor units in a muscle are activated by nearly maximum voluntary effort. However, when further generation of force is required, there might be an increase in firing rate or frequency with which the already active motor units are driven. Further study is needed to identify the functional changes in the bi-articular extrinsic toe flexor muscles and neuromuscular properties during locomotion.

5. Conclusion

This study showed that the force generation of toe flexion was regulated at the ankle joint and that maximum isometric force was optimally produced in the neutral position of the ankle joint. These results indicate that maximum isometric force of the toe flexor muscles at different ankle joint angles is affected by muscle length changes in the extrinsic toe flexor muscles.

Conflicts of interest

None.

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