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Original Article

Kinematic analysis during toe-gripping strength exertion: angular changes in the ankle joint and leg muscle activities

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Abstract. [Purposes] To investigate angular changes in the ankle joint and leg muscle activities during toe-gripping, and to examine the relationship between these changes and toe-gripping strength. [Subjects] Eleven healthy young women were selected. [Methods] We measured the toe-gripping strength, angular changes in the ankle joint, and leg muscle activities of all patients during toe-gripping. [Results] The mean change in the ankle angle in dorsiflexion from a neutral position was 3°, and a positive correlation was observed between this angle and toe-gripping strength ($r = 0.61$). Thus, toe-gripping strength increased with the angle of dorsiflexion. Regarding the leg muscle activities, activities of the tibialis anterior muscle and medial head of the gastrocnemius muscle demonstrated positive correlations with toe-gripping strength ($r = 0.75$ and $r = 0.72$, respectively). [Conclusion] These findings suggest that the ankle dorsiflexes in order to exert great toe-gripping strength, and the crural muscles contract simultaneously because of ankle fixation.
Key words: Toe-gripping strength, Angle of the ankle joint, Kinematic analyses

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INTRODUCTION

Similar to hand gripping, toe gripping is a complex motion that involves several muscles. The muscles involved in the foot include the flexor pollicis brevis, flexor pollicis longus, lumbrical, flexor brevis, and flexor longus muscles[1)]. Many studies have reported that a low toe-gripping strength is a risk factor for falls in the elderly[1–5)]. However, there are few reports on the mechanism of foot-gripping strength[6–8)], and kinematics of the ankle joint remain unclear.

Some reports have stated that the mechanism of foot-gripping strength is related to the activities of the crural muscles, and that the ankle position contributes to producing maximum toe-gripping strength[6–8)]. Souma et al.[6, 7)] studied the percentage of integrated electromyogram (%IEMG) of the crural muscles (i.e., the soleus, medial head of the gastrocnemius, and tibialis anterior muscles) and femoral muscles (i.e.,the rectus femoris and biceps femoris muscles) during toe gripping. They reported that the crural muscles help the ankle joint by co-contracting during toe gripping, and the %IEMG of the biceps femoris muscle was significantly higher than that of the rectus femoris muscle. Another study reported that a significant positive correlation exists between toe-gripping strength and the %IEMG of the tibial anterior muscle and that the activity of the tibial anterior muscle plays a specific and important role. Moreover, the ankle should be in a neutral position, and dorsal flexion is a better angle than plantar flexion for producing maximum foot-gripping strength[8)].

Toe-gripping strength is measured by placing the fulcrum in the calcaneal region, grasping a bar with the toe, and bending the toe. The foot is composed of a complex connection among many bones and is characterized by its structural arch. When toe-gripping strength is exerted, the foot changes its arched structure, and the forefoot ankle joint, and toe joint are linked and activate. Thus, as the angle of flexion in the toe joint is increased by bending the toe while the heel makes contact with the ground, the angle of dorsiflexion in the ankle joint is also increased. Murata et al.[9)] demonstrated that toe-gripping strength is affected by factors such as foot flexibility. These findings indicate that in order to elucidate the mechanism at work during the exertion of toe-gripping strength, changes in the foot that are associated with this exertion must be understood. However, no previous report has

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kinetically analyzed the movements of the foot that occur during the exertion of toe-gripping strength.

The purposes of this study were to evaluate the angular changes in the ankle joint and leg muscle activities during toe-gripping action, and to examine the relationship between toe-gripping strength and these changes.

SUBJECTS AND METHODS

The subjects were 11 healthy women with no known orthopedic impairments. Their age, height, and body weight (mean ± standard deviation) were 20.2 ± 0.4 years, 159.3 ± 4.1 cm, and 51.6 ± 5.0 kg, respectively. The present study was approved by the Ethics Committee for Human Research of Tohoku Fukushi University (RS14071105), and subjects provided informed consent to participate.

Toe-gripping strength of the dominant toe, the angle of the ankle as measured by an electrogoniometer, and the electromograhic (EMG) activity of the ipsilateral thigh were synchronously recorded to assess the activity of the rectus femoris, biceps femoris, medial head of the gastrocnemius, and tibialis anterior muscles.

Toe-gripping strength was measured using a toe-gripping dynamometer (T.K.K.3360; Takei Co., Ltd., Niigata, Japan). Regarding the reproducibility of this instrument, the intraclass correlation coefficient (1,1) was as high as 0.823. As described by Uritani[9], the subjects were instructed to sit with their trunk in a vertical position, place their hip and knee joints at 90°, and keep their ankle joints in a neutral position. To eliminate the effect of artifacts on EMG data, the measurements were performed with the subjects in an upright sitting position in which the midpoint between the head of the fibula (the electrode attachment site at the long head of the biceps femoris muscle) and the ischial tuberosity did not touch the seating surface. In a normal upright sitting position, weight is mainly supported by the ischial tuberosity, posterior surface of the thigh, and sole of the foot. However, in the present study, weight was mainly supported by the ischial tuberosity and sole of the foot. The handle of the force meter was set on the first metatarsophalangeal joint. After a sufficient number of training trials and adequate rest, the toe-gripping strength was measured twice. The maximum force was used in the analysis. In all subjects, the right toe was dominant; the dominant toe was defined as the toe used to kick a ball.

To measure the angle of the ankle, an electrogoniometer (EM-551; Noraxon Inc., Scottsdale, AZ, USA) attached to crural of inside over the center line and the toe-plantar surface was used. When achieving the maximum voluntary isometric contraction of the rectus femoris, biceps femoris muscle, tibialis anterior muscle, and medial head of the gastrocnemius muscle, the level of exertion of muscular activity may vary depending on each joint angle. Therefore, the maximum muscular strength at a specific angle was measured according to each joint angle at the time that the foot-gripping strength was measured. Thus, to measure the maximum voluntary contraction (MVC) activities of the tibialis anterior and medial head of the gastrocnemius muscle, each subject was instructed to sit in a chair with the ankle joint in a neutral position, and to exert maximal force of plantar flexion and dorsiflexion in isometric contraction to resist the force applied by the examiner in the direction of dorsiflexion and plantar flexion. To measure the MVC activity of the rectus femoris and biceps femoris muscles, each subject was instructed to sit in a chair with the hip and knee joints at 90°, and to exert maximal isometric force of knee extension and flexion in isometric contraction to resist the force applied by the examiner in the direction of flexion and extension. The EMG was recorded for 3 s while each subject exerted maximal force.

Muscular activity was measured using a surface EMG apparatus (TeleMyoG2; Noraxon Inc., Scottsdale, AZ, USA). After confirming adequate skin preparation (skin resistance of <5 kΩ), electrodes (Blue sensor; Ambu Inc. Ballerup, Denmark) were attached to the tibialis anterior, medial head of the gastrocnemius, rectus femoris, and biceps femoris muscles, as described by Peroto[10].

In the tibialis anterior muscle, electrodes were attached four finger breadths from the tibial tuberosity and one finger breadth outside the tibial crest. In the medial head of the gastrocnemius muscle, electrodes were attached five finger breadths from the popliteal fossa crease and in the medial belly. To measure the rectus femoris muscle, an electrode was attached to the midpoint between the superior edge of the patella and the anterior superior iliac spine. To measure the long head of the biceps femoris, an electrode was attached to the midpoint between the head of the fibula and ischial tuberosity.

The EMG signals were collected using analysis software (MyoResearch XP; Noraxon Inc., Scottsdale, AZ, USA), which was transferred to a personal computer. The bandwidth was 20–500 Hz. The EMG signal segment selected and integrated (IEMG) for analysis was the middle 1 s of the entire 3-s duration of the continuous maximal toe-gripping exertion. The IEMG was normalized to the IEMG of the MVC of each muscle. The muscular activity used for analysis was based on the data of the maximum toe-gripping strength.

SPSS software (version 12.0 for Windows; SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The relationship between the toe-gripping strength and angular changes in the ankle joint, and the %IEMG of each muscle was statistically analyzed using Spearman correlation coefficients. The level of significance was set at 5%.

RESULTS

Table 1 shows the average and standard deviations of the measured values in the 11 subjects. According to Spearman correlation coefficient analysis, a significant positive correlation was found between the toe-gripping strength and angular changes in the ankle joint ($r = 0.61$, $p < 0.05$; Table 2).

Additionally, according to Spearman correlation coefficient analysis, a significant positive correlation was found between the toe-gripping strength and %IEMG of the tibialis anterior ($r = 0.75$, $p < 0.05$), and between the toe-gripping strength and %IEMG of the gastrocnemius ($r = 0.72$, $p < 0.05$). However, this correlation was not seen in the rectus femoris and biceps femoris muscles (Table 3).

Table 1. Average and standard deviations of the measured values (n = 11)

	Average	Standard deviation
Toe-gripping strength (kg)	15.9	4.3
Angular changes in the ankle joint (°)	3.1	2.1
Rectus femoris muscle (%IEMG)	3.2	1.7
Long head of the biceps femoris muscle (%IEMG)	34.3	20.0
Tibialis anterior muscle (%IEMG)	35.4	20.2
Medial head of the gastrocnemius muscle (%IEMG)	51.5	20.0

%EMG: percentage of integrated electromyography

Table 2. Correlation between the toe-gripping strength and angular changes in the ankle joint

		Correlation (r)
Toe-gripping strength	Angular changes in the ankle joint	0.61*

*p < 0.05

Table 3. Correlation between the toe-gripping strength and percentage of integrated electromyography (%EMG) in several muscles during toe-gripping strength exertion

		Correlation (r)
Toe-gripping strength	Rectus femoris muscle (%IEMG)	0.12
	Long head of the biceps femoris muscle (%IEMG)	−0.27
	Tibialis anterior muscle (%IEMG)	0.75*
	Medial head of the gastrocnemius muscle (%IEMG)	0.72*

%EMG: percentage of integrated electromyography; *p < 0.05.

DISCUSSION

The present study determined changes in the ankle angle and leg muscle activity during the exertion of toe-gripping strength, and the relationship between the changes in the ankle and leg muscle activity during toe-gripping. In our analysis, the mean change in the ankle angle in dorsiflexion from a neutral position was a mere 3°; however, a positive correlation was observed between that angle and the toe-gripping strength. Thus, it was demonstrated that toe-gripping strength increases as the angle of dorsiflexion increases. Regarding the leg muscle activity, activities of the tibialis anterior muscle and medial head of the gastrocnemius muscle demonstrated positive correlations with toe-gripping strength. These findings suggested that the ankle dorsiflexes in order to exert great toe-gripping strength, and that the crural muscles must contract simultaneously because of ankle fixation.

The angle of the ankle changed by 3° in dorsiflexion from a neutral position during the exertion of toe-gripping strength. Furthermore, a significant positive correlation was observed between the ankle angle, which resulted from the movement and toe-gripping strength exertion. This suggests that greater toe-gripping strength can be exerted by increasing the ankle angle. The crural joint surface has a concave shape; as a result, in dorsiflexion in a neutral position, the ankle is wedged and stability is acheived[11]. Therefore, the more the ankle is in a dorsiflexed position, the more effective it is in exerting the maximum toe-gripping strength. In addition, it is surmised that the ankle dorsiflexion angle associated with toe bending increases as the flexibility for large bending of the forefoot (including the toes) increases. Murata et al.[9] demonstrated that greater toe-gripping strength can be exerted by more flexible feet; thus, the finding in the present study (i.e., that the more dorsiflexed the ankle is, the greater the toe-gripping strength it can exert) is consistent with the result demonstrated by Murata et al. Therefore, change in the ankle to dorsiflexion during the exertion of toe-gripping strength, which occurs as a result of bending the toes with the heel as the fulcrum, is also considered to be useful for the stabilization of the talocrural joint.

The %IEMG of the tibialis anterior muscle and the medial head of the gastrocnemius muscle during exertion of toe-gripping strength demonstrated significant positive correlations with toe-gripping strength. Previous studies also demonstrated a significant positive correlation between the %IEMG of the tibialis anterior muscle during exertion of toe-gripping strength and the toe-gripping strength; thus, the present study reconfirms this correlation. However, the findings of the present study also demonstrated a significant positive correlation between the %IEMG of the medial head of the gastrocnemius and the toe-gripping strength, which has not been demonstrated in previous studies. The toe flexor muscles, which output toe-gripping strength, also act as accessory muscles in plantar flexion of the ankle[12]. Thus, as toe-gripping strength is exerted, the plantar flexion of the ankle, i.e., the %IEMG of the medial head of the gastrocnemius, increases. Therefore, the ankle is thought to be stabilized by contraction of the antagonist tibialis receptor muscle and simultaneous contraction of the crural muscles. Although we cannot demonstrate the reason for the observed correlation between the %IEMG of the medial head of the gastrocnemius and the toe-gripping strength from the present study, we inferred the following observations. The difference between previous studies and the present study is the position in which the toe-gripping strength was measured. In the present study, to eliminate artifacts during EMG measurement, the measurements were performed with the subjects in an upright sitting position by which the midpoint connecting the head of the fibula (the electrode attachment site in the long head of the biceps femoris muscle) and the ischial tuberosity did not touch the seating surface. In a normal upright sitting position, weight is mainly supported by the ischial tuberosity, posterior surface of the thigh, and sole of the foot. In the present study, however, weight was mainly supported by the ischial tuberosity and sole of the foot. Therefore, the load on the heel was inferred to be greater in this study than in previous studies. In addition, the fixation of the heel by its own weight was considered to result in easier activity of the medial head of the gastrocnemius.

Our study has some limitations. First, we were unable to avoid various common problems that negatively affect surface EMG, such as resistance of the skin, artifacts, and the effects of proximal muscles. Second, we were unable to clearly differentiate the activities of the crural muscles between this study and previous studies. Third, only healthy young women participated; thus, it is difficult to extrapolate our findings to the general population. Future studies should include healthy young men and other age groups.

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