

Force Generation of the Hallux is More Sensitive to the Ankle and Metatarsophalangeal Joint Angle Than the Lesser Toes

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Abstract

Background: Because the structure of the hallux is independent of that of the lesser toes and it uses different muscles to move, the force generation characteristics of the hallux could be independent of those of the lesser toes. The purpose of this study is to clarify the torque–angle relationships in the first and second–fifth metatarsophalangeal joints (MTPJs).

Methods: Ten healthy young men served as volunteers in this study. The maximal voluntary contraction (MVC) of the plantar-flexion torques of the first and second–fifth MTPJs were measured at 0°, 15°, 30°, and 45° dorsiflexed positions of the MTPJs and 20° plantar-flexed, neutral, and 20° dorsiflexed positions of the ankle. The Friedman test and the Wilcoxon signed-rank test with a Holm correction was used for the ankle and MTPJ angles.

Results: When the first MTPJ was 0° to DF30°, the MVC torque of the first MTPJ at DF20° of the ankle was higher than at PF20° of the ankle. On the other hand, no significant difference existed between the MVC torques of the second–fifth MTPJs at any ankle position. When the ankle was in a neutral position, the MVC of the first MTPJ torque increased as the MTPJ was dorsiflexed. However, the MVC torques of the second through fifth MTPJs did not significantly differ for the 15°, 30°, and 45° dorsiflexed positions of the MTPJ.

Conclusion: The MVC torque of the first MTPJ is more sensitive to the MTPJ and ankle positions than the second–fifth MTPJs.

Background

The toe flexor muscles are activated during walking and holding a single-leg stance [1, 2]. It has been reported that toe grip strength is associated with functional mobility in the older people [3]. Consequently, the weakness of the toe grip is a risk factor for falls in the older people [4]. In addition, in healthy young people, the cross-sectional area of the intrinsic foot muscles affects their performance during the single-leg stance [5]. Thus, the toe flexor muscle function affects the balance ability for all ages, and the assessment of the toe flexor muscle strength is important for the improvement of the balancing ability in humans.

The joint angle alters the maximum force generated by the muscle [6]. Additionally, it affects the muscle length and internal moment arm [7, 8], which further affect the force generation capacity. The length of the extrinsic toe flexor muscles is altered by the metatarsophalangeal joint (MTPJ) as well as the ankle joint angle [7]. The plantar flexion torque of the MTPJ is influenced by the force–length relationship of the intrinsic and extrinsic muscles of the foot when the MTPJ angle is changed, and it is influenced by the relationship with the extrinsic muscles when the ankle joint angle is changed. During the plantar-flexion of the ankle, the soleus muscle is activated selectively at the knee flexion position [9]. Measuring muscle strength at various joint angles helps us determine the measurement positions of the maximal voluntary contraction (MVC) torque according to the muscle that needs to be assessed.

A previous study reported the relationship between the MVC torque and joint angle (torque–angle relationship) of an MTPJ for all toes [10]. However, the structure of the first toe (hallux) is independent of that of the other toes and it is moved using different muscles in most primates, including humans [11]. Our previous study reported that runners with a history of medial tibial stress syndrome exhibit higher plantar-flexion strength in their first MTPJ [12]. Regarding adaptation in sports, this study suggests that it is important to consider the strengths of the hallux and lesser toes separately. Moreover, the composition ratio of the intrinsic and extrinsic muscles is different between the plantar-flexion muscle of the first and second–fifth MTPJs [13]. Consequently, there is a possibility that the sensitivity of the plantar-flexion muscle to the joint angle is different in case of first and second-fifth MTPJs.

Recently, we developed a device that could measure the plantar-flexion torque of the first MTPJ and a unit of the second–fifth MTPJs [14]. It is possible to measure the plantar-flexion torque of the first MTPJ and second–fifth MTPJs at various MTPJ and ankle positions. The purpose of this study was to determine the relationship between the MVC of the plantar-flexion torque and joint angle in the first and second–fifth MTPJs using this device. We hypothesized that the plantar-flexion of the first MTPJ is sensitive to the joint positions due to the large composition ratio of the extrinsic muscles.

Methods

Participants

Ten healthy young men voluntarily participated in this study. The mean \pm standard deviations of their age, height, and mass were 23.2 ± 1.9 years, 169.2 ± 3.7 cm, and 58.4 ± 8.1 kg, respectively. The individual values are detailed in Table 1. The required sample size for a repeated analysis of variance [effect size = 0.25, α error = 0.05, power = 0.80, correlation among repeated measures = 0.6] was calculated using a statistical power analysis software (G*power 3.1, Heinrich Heine University, Germany), and the value obtained was 10. This study was approved by institutional human research ethics committee and was carried out in accordance with the declaration of Helsinki.

Procedures

Measurement of MVC torque

The MVC torque was measured using a custom-made torque-measuring device. This device recorded the tensile force data from the strain gauge (TU-BR, TEAC, Japan), and converted it from analog to digital using an A/D converter (Power Lab, AD instruments, Australia) via an amplifier (DPM-711B, Kyowa Electronics, Japan). The torque values were calculated as the corresponding tensile forces multiplied by the 0.10 m lever arm of the force plate.

Each subject was sat back in a dedicated chair and their trunk was secured to the chair using non-elastic straps. Their right foot (dominant side) was secured to the torque-measuring device (Fig. 1). Additionally,

it was confirmed that the bottom of the toes and foot of the subject did not float from the device in all measurements. After a warming-up session with subjective 60% contractions, each subject performed the MVC torques of the first and the second–fifth MTPJs at each position for approximately 3 s. The results thus obtained were used to determine the highest torque. The subjects were verbally instructed to avoid counter movement. The MVC torque was calculated as the highest torque minus the lowest torque obtained during contraction (Fig. 2). To avoid the effects of muscle fatigue, the resting period was set as at least 2 min. For analysis, the average torque between the two measurements conducted at each position was chosen. The reliability of the measurements was previously reported [14].

The MVC torques of the first and second–fifth MTPJs were measured at four MTPJ positions and three ankle positions for a total of 12 positions. The MTPJs were measured at 0°, 15°, 30°, and 45° dorsiflexed positions (0°, DF15°, DF30°, and DF45°, respectively), and the ankle was measured at 20° plantar-flexed position (PF20°), neutral position (0°), and 20° dorsiflexed position (DF20°). These positions are determined to cover the typical joint angle at push off, and the range of motion during running and sprinting [15, 16]. The neutral position of the MTPJ was defined as the parallel position between the sole of the foot and toes. The neutral position of the ankle was defined as the perpendicular position between the sole of the foot and longitudinal axis of the fibula. The ankle position was measured using a goniometer prior to each measurement. The MVC torque was measured twice in each position. For both types of MTPJs, the MVC torque values were measured at four MTPJ positions and at a single ankle position per day. This series of measurements was spread over three days for three different ankle positions. The order of the measured MTPJ and ankle was randomly chosen.

Statistical Analysis

The descriptive data are presented as means \pm SDs. Shapiro–Wilk tests were used to verify a normal distribution, and the results showed that some components did not follow a normal distribution. Therefore, the Friedman test was used for the ankle and MTPJ angles. When significant differences were found in the Friedman test, the Wilcoxon signed-rank test with a Holm correction was used for multiple comparisons. The same method was used to examine the differences in the torque–angle relationships of the first and second–fifth MTPJs. For all the MTPJ and the ankle positions, the MVC torque values were compared between the first and second–fifth MTPJs using the Mann–Whitney U test. Statistical analyses were performed using a statistical software (SPSS Statistics 26, IBM, USA). For all the tests, the statistical significance was set as $p < 0.05$.

Results

There were significant variations in the ankle positions at 0°, DF15°, and DF30° of the first MTPJ in the Friedman test ($p < 0.01$, < 0.01 , and 0.01 , respectively). In contrast, there was no significant difference in the ankle positions at DF45° of the first MTPJ ($p = 0.15$). When the first MTPJ was at 0° to DF30°, the MVC torques at PF20° of the ankle were smaller than those at DF20° of the ankle. There were significant variations in the first MTPJ positions at PF20°, 0°, and DF20° of the ankle in the Friedman test, t ($p < 0.01$, < 0.01 , and 0.01 , respectively). When the ankle was at PF20°, the MVC torques were significantly different

from all other torques and increased as the MTPJ dorsiflexed (Fig. 3). When the ankle was at 0°, the MVC torques increased significantly as the MTPJ dorsiflexed in four comparisons (0° and DF30°, 0° and DF45°, DF15° and DF45° as well as DF30° and DF45°). When the ankle was at DF20°, the MVC torque at 0° of the MTPJ was significantly lower than that at DF15° and DF45°. In contrast, there was no significant difference in the MVC torques at DF15°, DF30°, and DF45°.

There was no significant variation in the ankle positions at all second–fifth MTPJ positions in the Friedman test ($p = 0.12, 0.06, 0.06, \text{ and } 0.20$, respectively). There were significant differences in the second–fifth MTPJ angles at PF20°, 0°, and DF20° of the ankle in the Friedman test ($p < 0.01, < 0.01, \text{ and } 0.03$, respectively). When the ankle was at PF20°, the MVC torques increased significantly as the MTPJ dorsiflexed in four comparisons (0° and DF15°, 0° and DF45°, DF15° and DF45° as well as DF30° and DF45°) (Fig. 4). When the ankle was at 0° and DF20°, the MVC torques at 0° of each MTPJ were significantly lower than those at the other MTPJ angles.

The highest torque values obtained for the first and second–fifth MTPJs, were $11.4 \pm 2.3 \text{ N m}$ and $7.8 \pm 1.7 \text{ N m}$, respectively. The position at which the highest values of torque were obtained was DF45° of the MTPJ at 0° of the ankle. According to the Mann–Whitney U test results, the MVC torque of the first MTPJ was found to be larger compared to that of the second–fifth MTPJs at all positions ($p < 0.01$ for all positions).

Discussion

This study demonstrated the torque–angle relationships for the first and second–fifth MTPJs. The main findings of the present study were 1) the force generation of the first MTPJ was sensitive to the ankle position and 2) the force generation of the first MTPJ was sensitive to the MTPJ angle when the ankle was at DF0°. To the best of our knowledge, this is the first study to show each force generation characteristic of the first MTPJ and second–fifth MTPJs. To the best of our knowledge, this is the first study to show each force generation characteristic of the first MTPJ and second–fifth MTPJs.

When the first MTPJ was 0°, DF15°, and DF30°, the MVC torque of the first MTPJ at DF20° of the ankle was higher than at PF20° of the ankle. However, there was no significant variation in the ankle positions at all second–fifth MTPJ positions. These results supported our hypothesis. The plantar-flexion moment arm of the ankle is larger in the flexor hallucis longus muscle compared to the flexor digitorum longus muscle [8]. As a result, the flexor hallucis longus muscle varies more in length compared to the flexor digitorum longus muscle during the plantar-flexion/dorsiflexion of the ankle. Therefore, we considered that the extrinsic muscles make a large contribution to the plantar-flexion torque of the MTPJ in the dorsiflexion position of the ankle, and the muscle activity of the first MTPJ becomes relatively large at the dorsiflexed position of the ankle.

The MVC torques of the first MTPJ increased as the MTPJ was dorsiflexed when the ankle was at PF20° and 0°. However, we observed no significant difference between the MVC torques measured at DF15° to DF45° of the first MTPJ when the ankle was at DF20°. The force capacity generated by a muscle fiber is

altered by the muscle fiber length (force–length relationships) [17]. These results suggested that the ranges of MTPJ and ankle correspond to the ascending arm of the torque–angle relationship at 0° to DF45° of the first MTPJ, when the ankle was at PF20° and 0°, and the plateau region (i.e., optimum angle zone) at DF15° to DF45° of the first MTPJ, when the ankle was at DF20°. The maximal torque is generated at DF20° of first MTPJ during sprinting [16]. In addition, the ankle lies in the neutral to plantar-flexed position when maximal torque is generated at the first MTPJ during sprinting [15, 18]. The obtained results indicate that plantar-flexion torque of the MTPJs was generated in ascending limb of the torque–angle relationship during sprinting. Therefore, to generate the higher torque, it could be advantageous not to limit the dorsiflexion of the MTPJ during running and sprinting.

The MVC torques of the second–fifth MTPJs increased as the MTPJ was dorsiflexed when the ankle was at PF20°. However, no significant difference could be observed between the MVC torques at DF15° to DF45° of the second–fifth MTPJs when the ankle was at 0° and DF20°. The force generation characteristics are different between the first and the second–fifth MTPJs. The torque–angle relationship of the extrinsic and intrinsic muscles was found to be in the optimum angle zone between DF15° to DF45° when the ankle was at 0° in the second–fifth MTPJs. In contrast, the torque–angle relationship was in the ascending arm at 0° in the first MTPJ. A previous study reported that the fifth MTPJ was less dorsiflexed than the first MTPJ in human walking [19]. We considered that the optimum muscle lengths of the second–fifth MTPJs could be shorter than that of the first MTPJ. Therefore, the muscle activity of the first MTPJ becomes relatively large at the dorsiflexed position of the MTPJ.

The highest torques were 11.4 ± 2.3 and 7.8 ± 1.7 N m on the first and second–fifth MTPJs, respectively. The MVC torque of the first MTPJ was larger than second–fifth MTPJ at all positions. The torques measured in the present study were higher than those estimated in a previous study [13], wherein, the productivity of the torque was calculated from the anatomical cross-sectional area and estimated muscle tensions reported in a study of cadavers. However, physiological cross-sectional area has been reported to be more suitable for predicting functional properties than anatomical cross-sectional area [20]. In addition, the force that a muscle can generate per unit area is altered by the number and firing rate of a motor unit [21], and varies from muscle to muscle [22]. Thus, an estimated value may be different from the measured value. Consequently, the in vivo measured torques of this study were higher than the estimated values reported in the previous study. In the present study, the MVC torque was particularly greater in the first MTPJ. During walking, humans push off from an axis between the first and second MTPJ [23]. In such cases, the first MTPJ was greatly dorsiflexed [19]. These walking characteristics possibly contribute to the development of the motor unit of the hallux.

The MVC torque in the present study was lower than the plantar-flexion torque of the MTPJ during running [24]. A previous study reported that the intrinsic foot muscle lengthens and recoils rapidly during the later stance in accordance with the recoil of the foot arch during running [25]. It is considered that this recoil action causes the stretch shortening cycle [26], which results in an increased torque production.

Some limitations should be noted. The sample size was small, and the subjects were limited to young men and normal structure of their foot in this study. Hence, the applicable range of the results may be limited. Previous studies have shown that arch height is not correlated to toe grip strength [27]. Additionally, the optimal angle for force production is independent of age or gender [28]. However, there is room to investigate the behavior of the torque–angle relationship among the wide population to understand the toe function.

Conclusions

This study demonstrated the torque–angle relationships for the first and second–fifth MTPJs. When ankle was at 0°, the MVC torque of the first MTPJ increased with the MTPJ dorsiflexion, but the MVC torques of the second–fifth MTPJ were not significantly different at DF15° to DF45° of the MTPJ when the ankle was at 0°. Furthermore, when the first MTPJ was 0° to DF30°, the MVC torque of the first MTPJ at DF20° of the ankle was higher than at PF20° of the ankle. On the other hand, no significant difference existed between the MVC torques of the second–fifth MTPJs at any ankle position. Thus, the present study suggested that the force generation characteristic of the first MTPJ is more sensitive to the MTPJ and ankle position than the second–fifth MTPJs.

Abbreviations

MTPJ

metatarsophalangeal joint, MVC: maximal voluntary contraction

Declarations

Ethics approval and consent to participate

Informed consent was obtained from all participants. This study was approved by the Ethics Committee on Human Research of Waseda University (approval number: 2013 – 195).

Consent for publication

Not applicable.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

JS, SI and ST designed the experiments. JS performed the experiments, data analysis, and drafted the manuscript. SI and ST contributed to discussion and review of the manuscript. All authors read and approved the final manuscript prior to the submission.

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Figures

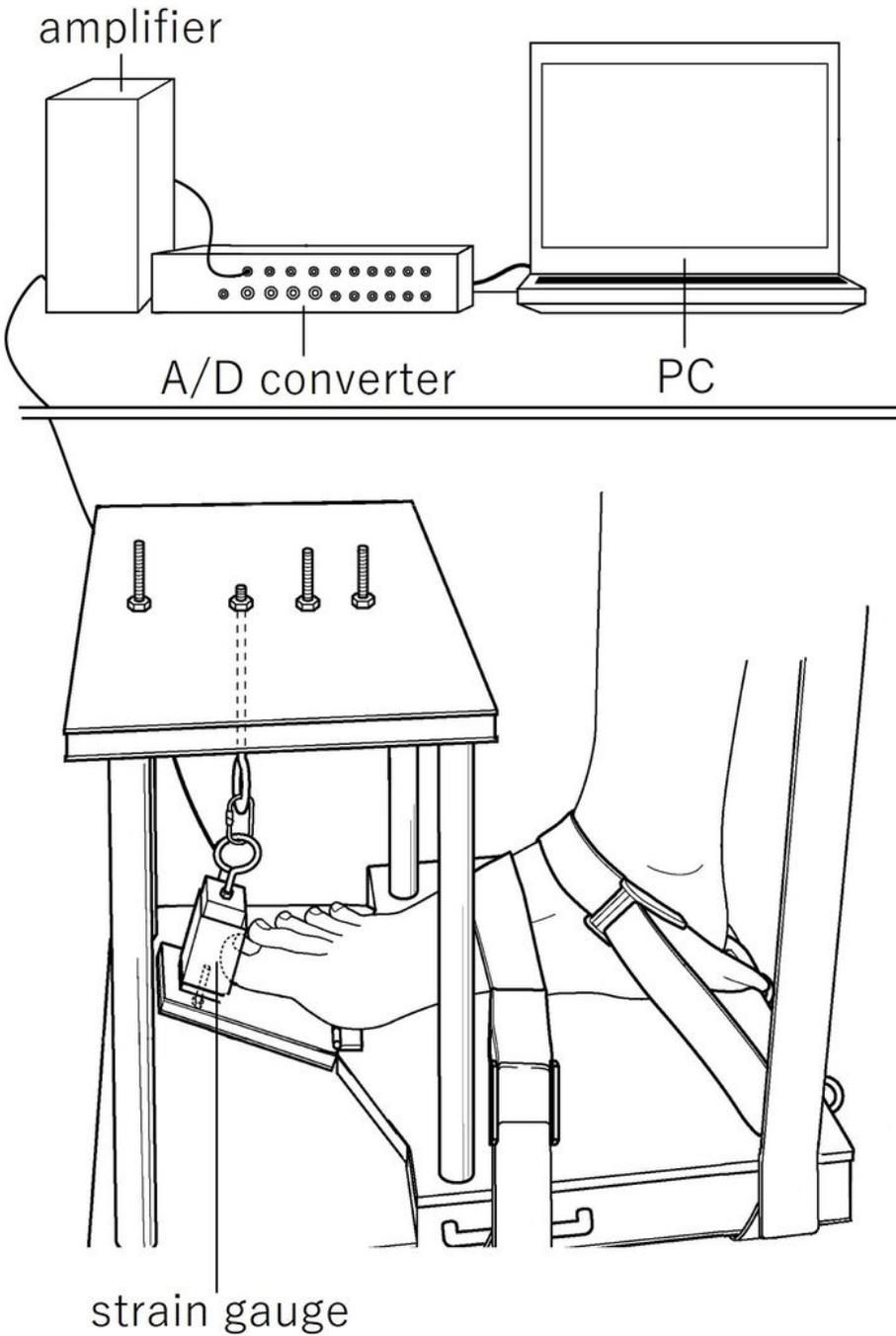


Figure 1

Structure of the metatarsophalangeal joint (MTPJ) plantar-flexion torque-meater for measuring the isometric torque. The plantar-flexion torque was calculated from the tensile force (ϵ) and lever arm of the foot plate (0.10 m).

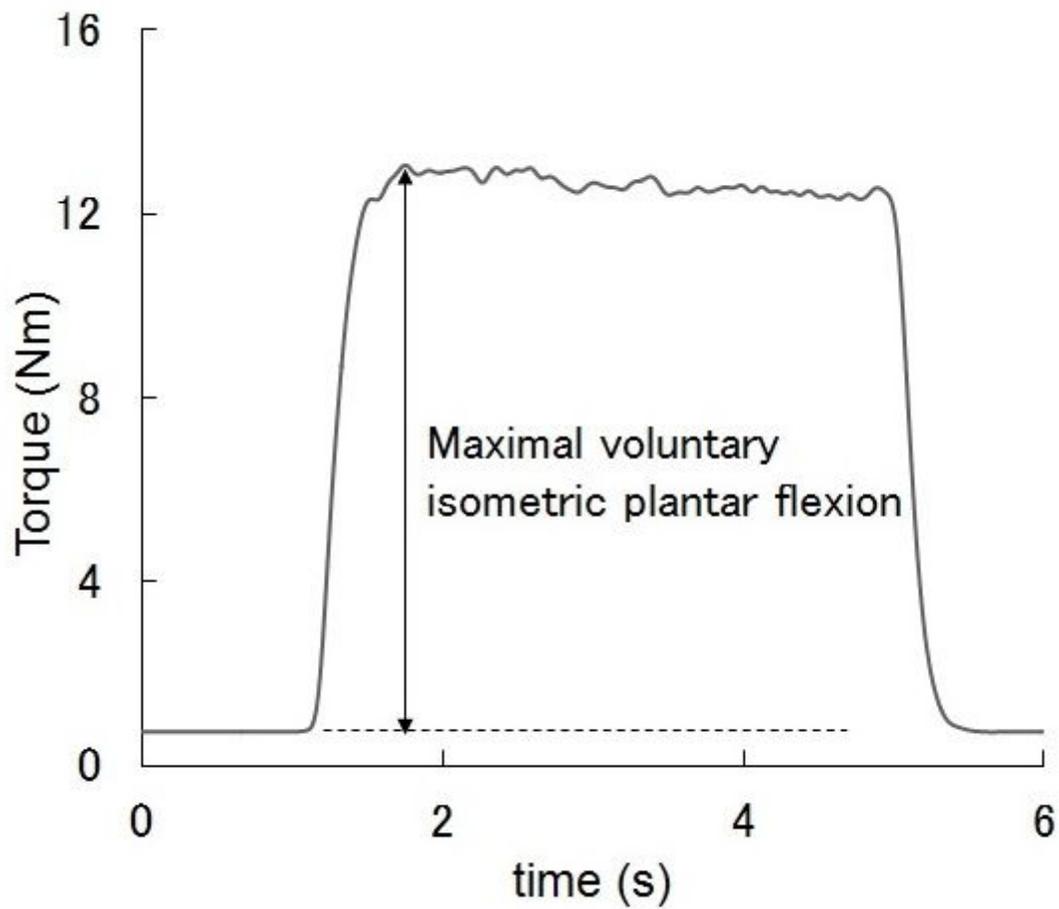


Figure 2

Typical data of the measured maximal voluntary isometric plantar-flexion torque of each metatarsophalangeal joint (MTPJ). Maximal voluntary isometric plantar-flexion torque was defined as the difference between the maximal torque during maximal voluntary isometric contraction (MVC) and passive torque at rest.

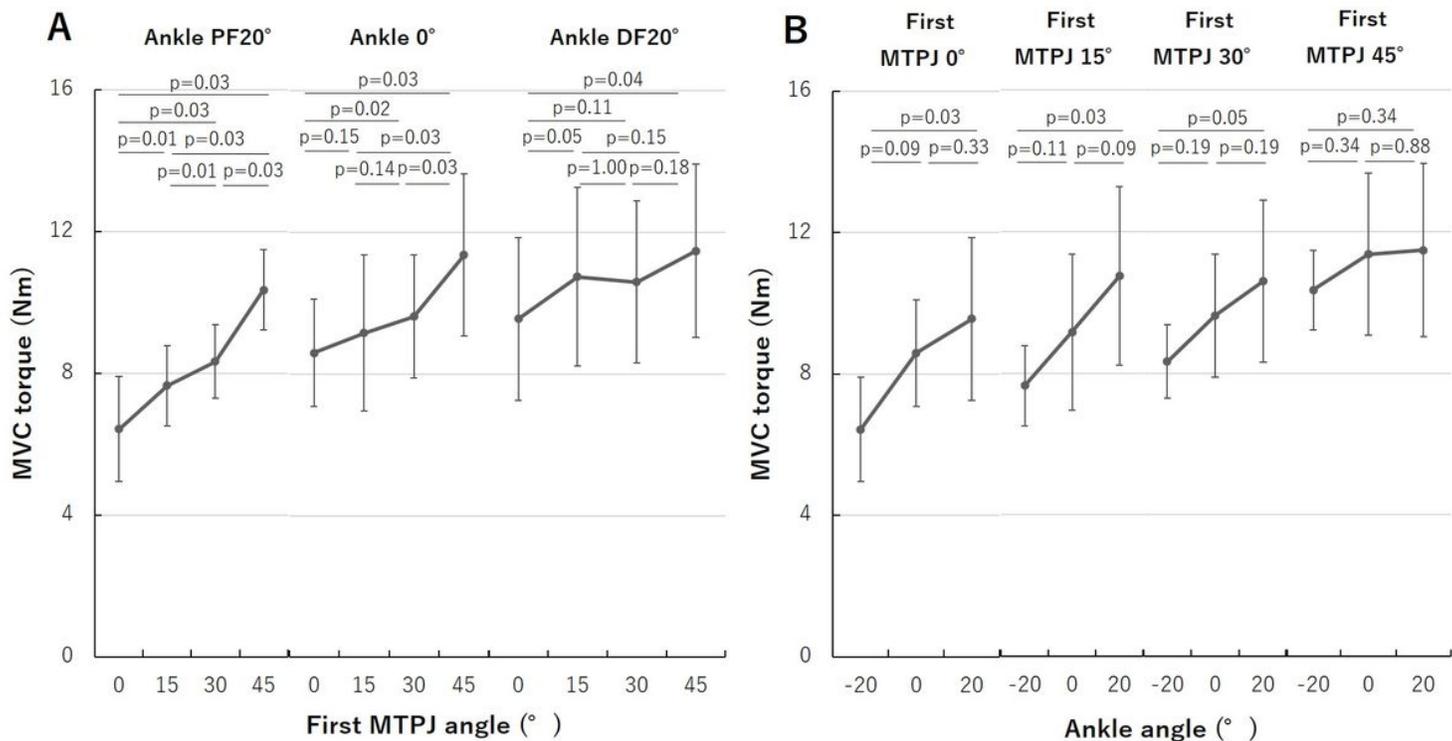


Figure 3

Maximal voluntary isometric contraction (MVC) torque of the first metatarsophalangeal joint (MTPJ) at each ankle position. PF20°: 20° plantar-flexed position, 0°: neutral position, DF20°: 20° dorsiflexed position. Numbers indicate the p-value in the multiple comparison test.

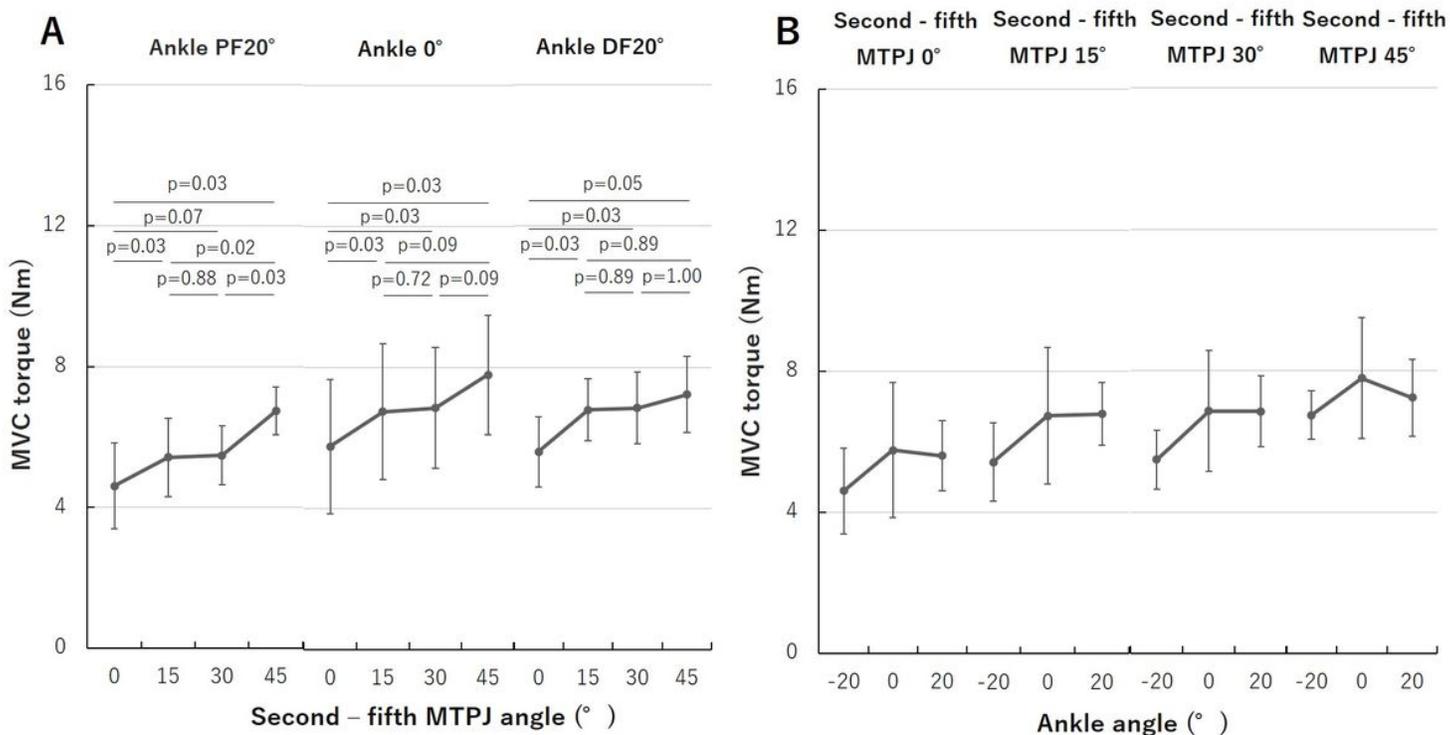


Figure 4

Maximal voluntary isometric contraction (MVC) torque of the second–fifth metatarsophalangeal joints (MTPJs) at each ankle joint angle. PF20°: 20° plantar-flexed position, 0°: neutral position, DF20°: 20° dorsiflexed position. Numbers indicate the p-value in the multiple comparison test.