

Force fluctuations during steady plantar flexion and dorsiflexion in young adults

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Abstract (237/250)

The aim of the study was to evaluate the difference on force fluctuations during isometric plantar flexion (PF) and dorsiflexion (DF) and the potential influence of changes in ankle joint angle. Twelve young adults performed 2 maximal voluntary contractions (MVC) and 3 steady submaximal isometric contractions at three ankle angles (70°, 90° and 110°) and five target forces (5, 10, 20, 40 and 60% MVC) with both the plantar flexors and dorsiflexors. The electromyographic (EMG) activity of Medial Gastrocnemius (MGAS), Soleus (SOL) and Tibialis Anterior (TA) was recorded. MVC force was greater during PF compared to DF for all ankle angles ($p > 0.05$). The normalized amplitude (coefficient of variation, CoV) of the force fluctuations was similar between PF and DF. However, the absolute amplitude (standard deviation) was higher during PF compared to DF, regardless of ankle angle and target force ($p < 0.05$). The CoV for force exhibited a gradual decrease from 5% to 20% MVC, and then it plateaued at 40% and 60% MVC force. During plantar flexion, the normalized EMG amplitude (root mean square) of the agonists MGAS and SOL increased progressively from 5% to 60% MVC force ($p > 0.05$), as the same happened with the TA during DF. These findings indicate that muscle groups with large differences in maximal force production are likely to have the same force steadiness during submaximal contractions, apparently because the neural activation of agonist and antagonist muscles has common features.

Keywords: Force steadiness, plantar flexion, dorsiflexion, joint angle, EMG

Introduction

The forces applied by muscle during voluntary contractions are not constant, but rather fluctuate around an average value. The functional consequences of these fluctuations is that they contribute to movement variability within and across trials. The absolute amplitude (standard deviation) of force fluctuations increases with the target force, but the normalized amplitude (coefficient of variation, CoV) declines from an initial high value at low forces to a relative constant value at moderate forces (Enoka & Farina, 2021; Jones et al., 2002; Trypidakis et al., 2022).

The quantification of CoV for force during submaximal isometric contractions could be used as an index of force variability (the greater the value, the greater the force variability) and represents the oscillations in the neural drive to muscle. Additionally, previous investigations have observed that the CoV for force was a significant factor to explain the variability in performance across various assessments, such as tests of walking ability (Davis et al., 2020), pegboard tests of manual dexterity (Almuklass et al., 2016) and postural sway during upright standing (Kouzaki & Shinohara, 2010). Finally, it has been indicated that force steadiness could discriminate fallers from non-fallers (Carville et al., 2007).

Changes in muscle length influence the mechanical properties of a muscle (Gordon et al., 1966), twitch time course (Bigland-Ritchie, 1992), and motor unit discharge rates during submaximal contractions (Shinohara et al., 2006). However, recently in our lab, we did not identify any differences between muscle lengths on force steadiness during submaximal isometric contractions with the dorsiflexors (Tsatsaki et al., 2022). Moreover, the absence of a difference in force steadiness, across the muscle lengths, was accompanied by no differences in the variability of neural drive (estimated with the filtered cumulative spike train) and the discharge times of motor units in tibialis anterior, which is consistent with the notion that the fluctuations in force are correlated with population estimates of the modulation in motor unit activity. Nonetheless, the CoV for force of the plantar

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flexors was smaller (better force steadiness) at long (75°) than at short (105°) lengths and there were changes in the discharge characteristics of motor units in the soleus muscle (Trypidakis et al., 2022). The observed adjustments in discharge times were interpreted as indicating changes in the proportion of independent and shared synaptic inputs received by the motor neurons that innervate soleus.

Despite the relevance of force steadiness as a metric for the neural control of muscle, few studies have compared this attribute in antagonistic muscles that differ in architecture, muscle activation, and function (de Hamilton et al., 2004; Salonikidis et al., 2011).

One such study, found that the CoV for force during isometric contractions at the ankle angle of 90° was greater (less steady) over a broad range (2.5% - 80% MVC force) for the dorsiflexors compared with the plantar flexors of both young and old adults (Tracy, 2007).

The purpose of our study was to investigate the influence of muscle length on the difference in force steadiness during submaximal isometric contractions with the plantar flexor (PF) and dorsiflexor (DF) muscles. We hypothesized that maximal force and force steadiness during isometric contractions would be greater for the PF than the DF muscles.

Materials & Methods

Participants

Twelve young adults (5 women, age: 25.1 ± 6.57 yrs, height: 177.1 ± 10.3 cm, weight: 71.8 ± 13.2 kg) volunteered to take part in the present study following the acquisition of written informed consent. This sample size was justified with an a priori power analysis (G*Power, v3.1.9.2) that showed repeated-measures ANOVA analyses required a minimum of 11 participants to detect significant interactions with a medium effect size ($f = 0.25$; assuming $1-\beta = 95\%$, $\alpha = 0.05$; $r = 0.5$). Participants reported no neurological disorders or musculoskeletal injury to the legs. In accordance with the principles outlined in the Declaration of Helsinki, approval (ERC-006/2023) was obtained from the Ethics Committee on Human Research at Aristotle University.

Experimental setup

The evaluation of applied force was conducted using an isometric dynamometer (TF022-NEG1, OT Bioelettronica, IT), following a recently described methodology (Petrović et al., 2022; Trypidakis et al., 2022). In summary, the force applied by the participant was presented on a 50-inch monitor (110.7 x 62.2 cm) positioned at eye level ~1.5 m in front of the participant. To quantify the angles of the knee and ankle, two digital goniometers (MLTS700, AD Instruments) were employed. The knee joint was set at 180° (full knee extension). The influence of muscle length on force fluctuations and EMG activity was compared at three ankle angles: 70°, 90°, and 110°.

Electromyographic recordings

High-density electromyographic (HD-EMG) signals from the TA, SOL and MGAS muscles were obtained from the left leg using 64-channel surface electrodes arrays (5 × 13, 8 mm inter-electrode distance), following appropriate skin preparation procedures such as shaving, skin abrasion and cleaning (Trypidakis et al., 2022; Tsatsaki et al., 2022).

The electrode grids were positioned over the main part of the muscle, aligning the electrode columns with the direction of the muscle fascicles (Rainoldi et al., 2004). Reference straps were securely attached to the participant's wrist and lower limb. The acquired EMG signals underwent amplification and were subjected to band-pass filtering (-3dB bandwidth, 10-500 Hz). Subsequently, they were digitized using a 16-bit analog-to-digital converter Quattrocento (OT Bioelettronica, IT) at a sampling rate of 2048 Hz

Maximal Voluntary Contractions

At each ankle angle, participants performed two maximum voluntary contractions (MVCs) lasting 5 sec, for both the dorsiflexors and plantar flexors. They were instructed to gradually increase the force from zero to the maximum and maintain it for ~3 seconds, while receiving verbal encouragement. In cases where the difference in peak force between the two MVCs exceeded 5%, additional trials were conducted until the criterion was met, with ~60 seconds of rest between each trial. The highest MVC force was considered as the reference for the subsequent submaximal isometric contractions.

Sustained Isometric Contractions

Force steadiness was measured during submaximal isometric contractions with the dorsiflexors and plantar flexors at five target forces: 5%, 10%, 20%, 40%, and 60% of MVC at each muscle length (short, intermediate, and long) (Figure 1).

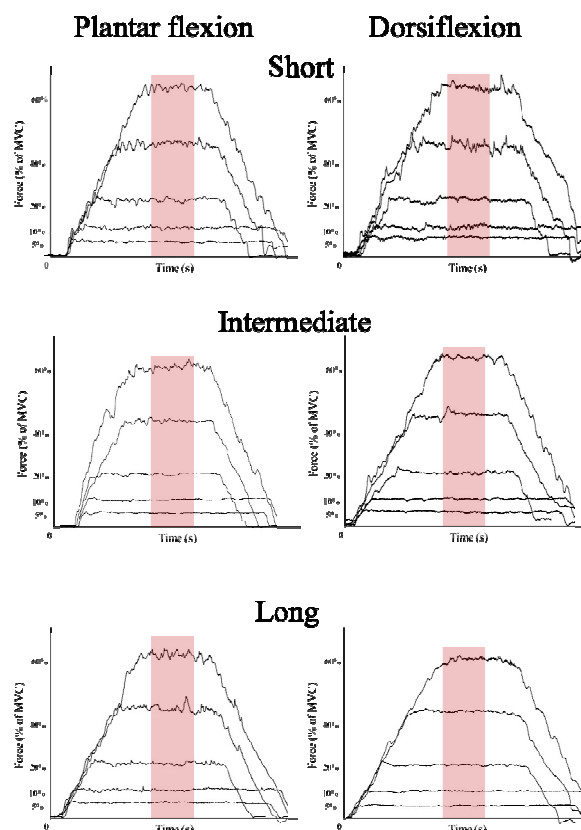


Figure 1. Representative data depicting the plantar flexion and dorsiflexion forces during submaximal isometric contractions at 5%, 10%, 20%, 40% and 60% of MVC force, across three ankle angles, 70°, 90° and 110° (180°: full plantar flexion). Force fluctuations were measured during the steadiest 6 s in the plateau (shaded area).

The required trapezoidal trajectory was visually represented as a light blue line, while the permissible error margins were highlighted using red lines. The force change rate during both the ramp-up and ramp-down phases was specified as $5\% \text{ MVC} \cdot \text{s}^{-1}$, and the acceptable range of error for each target force was set at 5% MVC. The duration of the isometric plateau varied from 30 s at 5% MVC to 10 s at 60% MVC (Petrović et al., 2023; Tsatsaki et al., 2022). Three trials were performed in each target force and the steadiest one was selected for analysis. The rest between trials was ~1 min and the contraction levels and ankle angles performed at a randomized order to counteract potential biases or learning effects between the tasks.

Data analysis

The recording of HD-EMG signals was conducted utilizing the Bio Lab+ software (version 1.0.3, OT-Bioelettronica, IT). After removing the data from missing and noisy channels, the root mean square (RMS) amplitude was calculated by summing the band-pass filtered (20-500 Hz) average values from the single-differential signals for each viable channel. A customized MATLAB code was utilized to extract the most stable 6-second interval during the isometric contraction for each target force and muscle length. The absolute amplitude (Standard Deviation, SD), the normalized amplitude (Coefficient of Variation, CoV) for the force fluctuations, and the EMG amplitude (RMS) of each muscle were calculated. The RMS during the submaximal isometric contractions was normalized (nRMS) with the EMG obtained during the MVCs performed at each muscle length.

Statistical analysis

The statistical analysis was conducted utilizing SPSS software (version 28, IBM, Chicago). To examine the differences in MVC force between the two muscle groups (DF and PF) at three ankle angles (70°, 90° and 110°) a two-way analysis of variance (ANOVA) was employed. Subsequently, a three-way ANOVA for repeated measures was applied to examine force steadiness, quantified as absolute (SD) and normalized amplitudes (CoV), between the two functions (DF and PF), the three muscle lengths (short, intermediate, and long), and the five target forces (5%, 10%, 20%, 40% and 60% of MVC). Differences in normalized RMS across the different muscle lengths and target forces between SOL and MGAS were examined with three-way ANOVA. Additionally, the differences in normalized RMS for TA were investigated with two-way ANOVA. Tukey tests were employed to identify significant differences between pairs of means. To explore the associations between MVC vs. CoV for force; MVC and SD of force; CoV for DF force vs. CoV for PF force; SD of DF force vs. SD of PF force, Pearson's correlation coefficient was computed. The significance level was established at $p < 0.05$.

Results

Maximal force

The two-way ANOVA revealed a significant muscle group $\times$ muscle length interaction for MVC force ($F_{(2,22)} = 12.672$, $p < 0.001$, $\eta^2 = 0.535$). Post-hoc tests indicated that the PF force (short: 412 ± 38 N, intermediate: 488 ± 53 N, long: 538 ± 66 N) was greater ($p < 0.001$) than DF force (short: 100 ± 11 N, intermediate: 122 ± 18 N, long: 130 ± 12 N) independent of muscle length (Figure 2). Additionally, MVC force for the PF ($p = 0.017$) and DF ($p = 0.008$) were greater at the long than the short length.

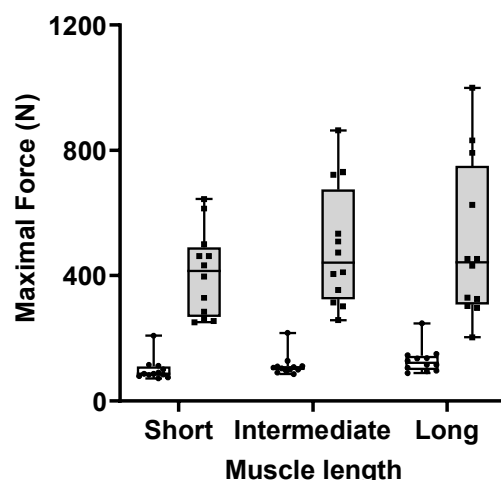


Figure 2. Peak MVC force during plantar flexion (grey) and dorsiflexion (white) at short, intermediate and long length (definition as Figure 1). Data are shown as box graphs with “whiskers” displaying the maximal limit (upper whisker), the 3rd quartile (75th percentile), the median value (line inside the box), the first quartile (25th percentile) and the minimal limit (lower whisker). Each data point represents one participant. * $p < 0.05$.

Force fluctuations

Coefficient of Variance (CoV) for force

The three-way ANOVA revealed a significant muscle group $\times$ muscle length $\times$ target force interaction ($F_{(8,88)} = 3.950$, $p < 0.001$, $\eta^2 = 0.264$) for the CoV for force. Tukey post-hoc tests showed that the PF were steadier compared to DF at 5% and 10% of MVC force for the short length as well as at 5% of MVC force for the intermediate length (Figure 3), while no differences were observed for the long length. Moreover, the CoV for force during DF exhibited higher values at the short than the long length ($p < 0.05$) at 5%, 10% and 20% of MVC force. Similarly, it was also greater compared to the intermediate length ($p < 0.05$) at 10% and 20% of MVC force. Conversely, the CoV for force of the PF exhibited higher values at the long length than at the intermediate length ($p < 0.05$) at the 60% of MVC force. The CoV for force exhibited a gradual decrease from 5% to 20% of MVC force ($p < 0.05$), and then it was remained similar from 20% to 60% of MVC force ($p > 0.05$) for both muscle groups and all three muscle lengths.

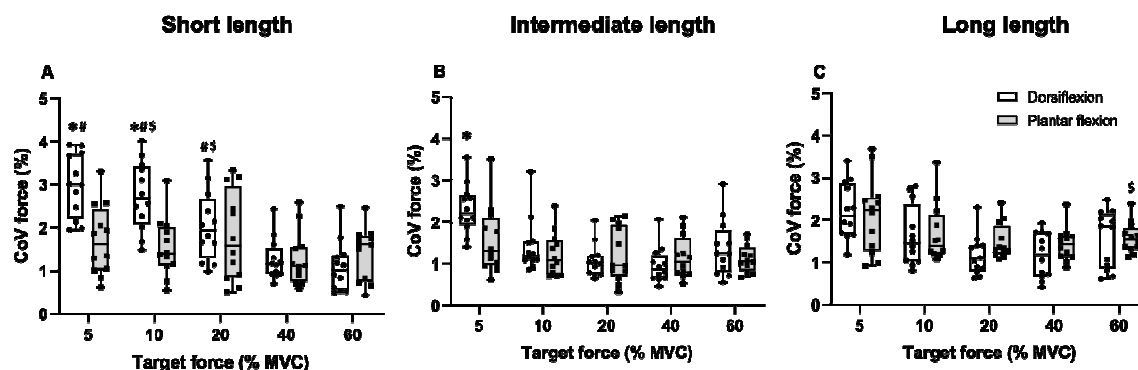


Figure 3. Force steadiness expressed as normalized force fluctuations (Coefficient of variation for force, CoV force) during steady submaximal contractions with the plantar flexors (grey) and the dorsi-flexors (white) at five target forces (5%, 10%, 20%, 40% and 60% MVC) at short, intermediate and long length (definition as Figure 1). Data are shown as box-and-whisker plots. *Greater compared to plantar flexors ($p < 0.05$); # Greater compared to long length ($p < 0.05$); \$ Greater compared to intermediate length ($p < 0.05$)

Standard Deviation of force

The three-way ANOVA indicated a significant muscle group $\times$ muscle length $\times$ target force interaction ($F_{(8,88)} = 2.550$, $p = 0.015$, $\eta^2 = 0.188$) on SD for force (Figure 4). Post-hoc analysis reveals that, regardless of muscle length and target force, the SD of force for PF was significantly greater than that for DF ($p < 0.05$). Moreover, the SD of force during DF was greater at the short length compared to long length ($p < 0.05$) at 5%, 10% and 60% of MVC force. However, no significant differences between the muscle lengths were found for the PF ($p > 0.05$). In addition, the SD for force during DF was remained constant between 5% to 10% of MVC ($p > 0.05$) and then exhibited a gradual increase from 10% to 60% of MVC force. In contrast, the SD for force during PF showed a gradual increase from 5% to 60% of MVC force.

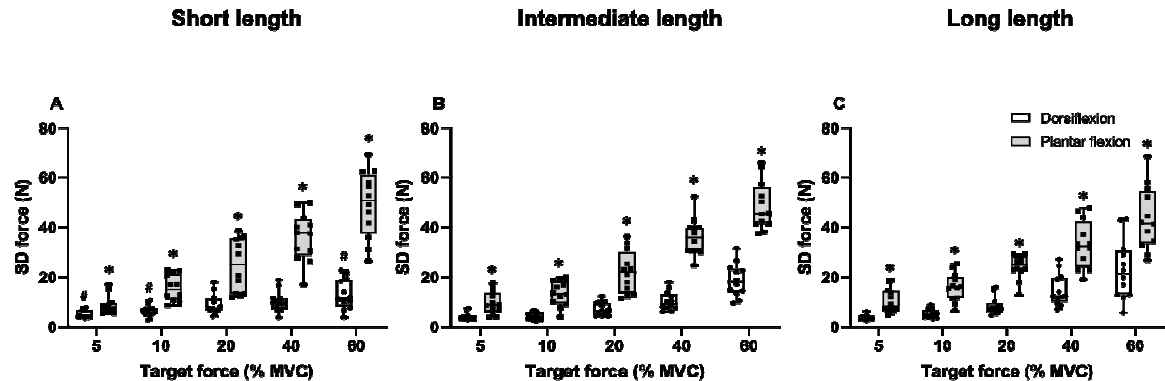


Figure 4. Force steadiness expressed as absolute force fluctuations (standard deviation of force, SD force), during steady submaximal contractions with the plantar flexors (grey) and the dorsiflexors (white) at five target forces (5%, 10%, 20%, 40% and 60% MVC) and three muscle lengths, short, intermediate and long (definition as Figure 1). Data are shown as box- and-whisker plots. *Greater compared to dorsiflexion ($p < 0.01$); # Greater compared to long length ($p < 0.05$)

Electromyography (Root Mean Square, RMS)

As expected, there was a main effect for target force for both the PF ($F_{(4,44)} = 381.351$, $p < 0.001$, $\eta^2 = 0.972$) and the DF ($F_{(4,44)} = 554.478$, $p < 0.001$, $\eta^2 = 0.981$), with a progressive increase in nRMS from 5% to 60% MVC force. Also, a significant main effect of muscle ($F_{(1,11)} = 6.415$, $p = 0.028$, $\eta^2 = 0.368$) on nRMS during submaximal contraction with plantar flexors was observed. The nRMS values for MGAS were greater compared to those for SOL ($p < 0.05$) across the submaximal contractions and muscle lengths (Figure 5).

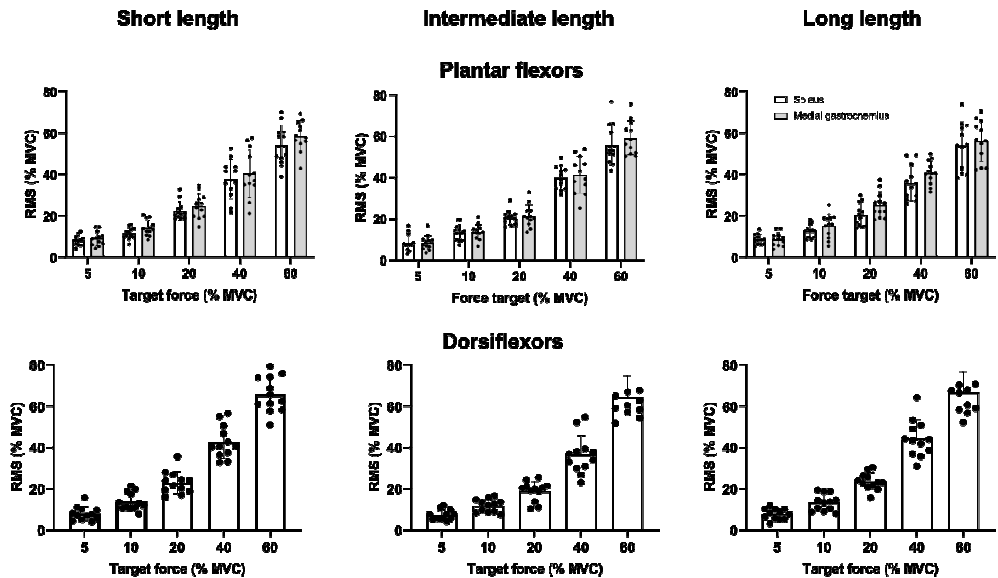


Figure 5. EMG amplitude (RMS) during the submaximal isometric contractions at short, intermediate and long length (definition as Figure 1). Top row: RMS values for Soleus (SOL) and Medial Gas-trocnemius (MGAS) during plantar flexion. Bottom row: RMS values for Tibialis Anterior (TA) during dorsiflexion. Each data point represents a value for one participant. Data reported at mean $\pm$ SD.

Association between force fluctuations for the two muscle groups

There was no statistically significant correlation between MVC force and CoV for force ($p > 0.05$) for plantar flexors, whereas a significant correlation ($r = -0.35$) between MVC force and SD for force ($p = 0.037$) was identified. In contrast, there were no statistically significant association of dorsiflexors between MVC force and both CoV for force ($p > 0.05$) and SD for force ($p > 0.05$).

As shown in Figure 6, the CoV for force averaged across muscle lengths for the five target forces was not significant correlated ($r = 0.24$, $p = 0.064$) between the two muscle groups, whereas there was a strong positive ($r = 0.84$, $p < 0.001$) between the SD for force values.

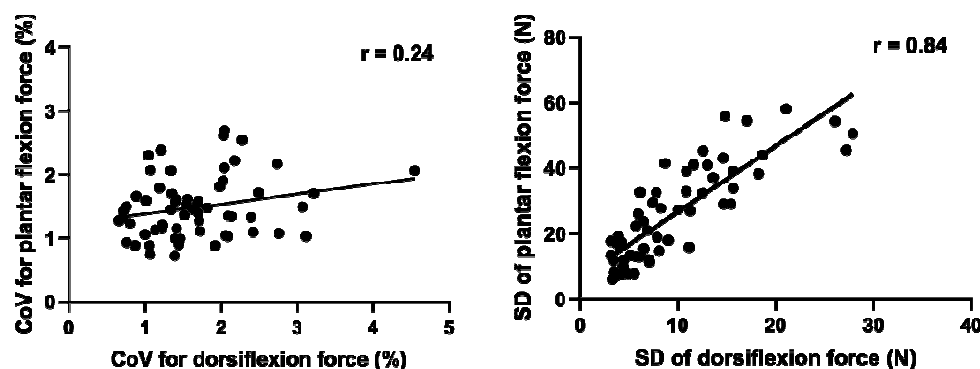


Figure 6. Correlation analysis between the coefficient of variation for force (CoV) during plantar flexion and dorsiflexion at the five target forces. The data were collapsed across muscle lengths.

Discussion

The main finding of our study was that the normalized force fluctuations during steady submaximal contractions were similar during dorsiflexion and plantar flexion, despite a substantial difference in the strength of the two muscle groups. Muscle length did not influence force steadiness during PF, but it was worse at the short length during DF. The normalized EMG amplitude (% MVC) of SOL, MGAS and TA were also identical across muscle lengths when acting as agonists.

Plantar flexors are stronger than dorsiflexors

Peak force during maximal contractions with the plantar flexors was approximately 4 times greater than dorsiflexors in our young participants (Figure 2). This is consistent with previous studies that have reported greater force capacity for the plantar flexors compared with the dorsiflexors (Danneskiold-Samsøe et al., 2009; Simoneau et al., 2007), as the plantar flexors have 4.6 times greater muscle volume and 12 times greater physiological cross-sectional area compared to the dorsiflexors (Fukunaga et al., 1996). However, the torque developed during DF could be underestimated due to the opposing antagonist action of the triceps surae muscle. The mechanical effect of this opposing torque is approximately 42% during maximal contractions of dorsiflexors, thereby reducing the observed force capacity (Billot et al., 2010).

Moreover, muscle length significantly influences the maximal force capacity of both muscle groups. Consistent with previous investigations (Petrović et al., 2022; Tsatsaki et al., 2022), we found that the MVC force during DF at short length (70°) was less than at a long length (110°). Similarly, the maximal force during PF was greater at the longest length (70°) than at the shorter length (110°), as reported previously (Trypidakis et al., 2022; Winegard et al., 1996). The lower MVC force at the shortest length is typically attributed to sarcomere shortening (Pasquet et al., 2005) beyond the optimal overlap of the contractile proteins (Gordon et al., 1966) and associated changes in the orientation and stiffness of the muscle fascicles (Herbert et al., 2002).

Plantar flexors are not steadier than dorsiflexors

Our results were not consistent with the hypothesis that force steadiness expressed as the CoV for force would be greater during PF compared with DF during submaximal contractions. There was some discrepancy between our results and previous reports (Davis et al., 2020; Tracy, 2007) in that the CoV for force was significantly greater during DF than during PF at 3 of 15 target forces: at 5% and 10% MVC for the short length, and at 10% MVC for the intermediate length. These differences could be related to the age of the participants and the influence of length of the muscle-tendon unit. Our participants averaged 21 years of age, whereas those in the study of Davis et al. (2020) were middle-aged (52 years) and those in of Tracy (2007) were 10 young (23 years) and 10 older adults (73 years). Moreover, Tracy (2007) tested the force steadiness at the ankle angle of 95° for both dorsiflexors and plantar flexors, whereas the knee angle was at 150° during the dorsiflexion task and at 180° during the plantar flexion task. We used the same knee angle for both muscular

groups (180°), and 3 different ankle angles (70°, 90° and 110°). Also, the contribution of the toe extensors to the dorsiflexion force at low target forces (>10% MVC) can be significant when the toes are not strapped (Siddiqi et al., 2016) and likely differed across the three studies.

The amplitude of force fluctuations is influenced by the presence and integration of visual feedback (Christou, 2005), task specificity (Enoka et al., 2003), the type and intensity of muscle contractions (Trypidakis et al., 2022), the physical status of the individual (Salonikidis et al., 2009), the number of MUs involved (Castronovo et al., 2018), the upper limit of MU recruitment (Dideriksen et al., 2012), and the contractile properties of the MUs (Watanabe et al., 2013). When several muscles contribute to the applied force, the amplitude of the force fluctuations depends on the collective properties of these muscles, including the proportion of shared synaptic inputs received by the pools of motor neurons (Enoka & Farina, 2021). Thus, the neural mechanism that underlie the fluctuations around an average value, may involve a non-uniform activation of several different muscles around a joint. For example, tibialis anterior contributes only 42% of the total force during dorsiflexion, suggesting large contributions by the other three dorsiflexors, the extensor digitorum longus, the extensor digitorum brevis and peroneus tertius (Marsh et al., 1981). Nevertheless, the dorsiflexors are smaller, have fewer motor units (Feinstein et al., 1955; McNeil et al., 2005), and receive more direct corticospinal input (Bawa et al., 2002; Nielsen & Petersen, 1995) than the plantar flexors. Furthermore, the variability of isometric force can be different between large and small muscles that receive different corticospinal inputs (de Hamilton et al., 2004; Tracy, 2007). Our results underscore the importance of reporting both normalized and absolute amplitudes of the force fluctuations. Thus, it seems the muscle activation of the two antagonistic groups has relatively similar features.

A novel feature of our results was that force steadiness expressed as the absolute amplitude of fluctuations (SD) during DF was highly correlated ($r = 0.84$, Figure 6B) with PF. The CoV for force values for the two muscle groups were not correlated ($r = 0.24$, $p = 0.064$). Similarly, Tracy (2007) reported that the normalized amplitude of the submaximal force fluctuations were not correlated during dorsiflexion and plantar flexion. He attributed the absence of correlated fluctuations to the differing neuromuscular properties of the antagonist muscular groups, whereas similar characteristics between muscles (e.g., muscle size and strength, motor unit number, recurrent inhibition, corticospinal input) tend to result in correlated force variability within the same individuals (de Hamilton et al., 2004; Tracy, 2007). However, based on our RMS results during submaximal isometric contractions, it seems that the normalized level of muscle activation varied similarly across the target forces. Nonetheless, this interpretation needs to be verified at the motor unit level.

Length does not influence steadiness

The normalized amplitude of the force fluctuations during DF was greater at the short length than at the long length at 10% and 20% of MVC force, whereas the absolute amplitude of the force fluctuations was greater at the short length than at the long length at 5%, 10% and 60% MVC force. No differences between either measure of force fluctuations were observed during PF across all ankle angles and target forces. We previously reported no differences in force steadiness across ankle-joint angles during dorsiflexion, which was accompanied by the absence of differences in the variability in the neural drive and the discharge times of motor units in tibialis anterior (Tsatsaki et al. 2022). However, Petrovic et al. (2022) found that force steadiness was less (greater CoV for force) at short than at intermediate and long lengths for the non-dominant leg and at short and intermediate lengths than at a long length for the dominant leg. The primary explanation for the differences between ankle angles is probably the changes in the modulation of motor unit discharge times, underscoring the role of synaptic inputs to the motor neurons in producing the force fluctuations (Petrović et al., 2022). However, this interpretation needs to be examined at the motor unit level.

Conclusion

Force steadiness, when expressed as normalized amplitude (CoV) of force fluctuations, was similar between submaximal isometric contractions with the DF and the PF in young participants. When expressed as the absolute (standard deviation) amplitude of force fluctuations, it was greater during PF than DF at all three muscle lengths, likely due to the greater (3-4 times more) force capacity of the PF muscles. The length of muscle-tendon unit did not influence the force fluctuations during PF, whereas force variability was greater at the short length than at the other two muscle lengths during DF. Nonetheless, muscle length did not influence the normalized EMG amplitude in tibialis anterior, medial gastrocnemius, and soleus muscles when they were acting as agonists.

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Conflicts of Interest

The authors state that they do not have any known competing financial interests or personal relationships that could have influenced the work presented in this article.

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