

Research article

## Alternating or Bilateral Exercise Training does not Influence Force Control during Single-Leg Submaximal Contractions with the Dorsiflexors

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### Abstract

The aim of the study was to assess the influence of habitual training history on force steadiness and the discharge characteristics of motor units in tibialis anterior during submaximal isometric contractions. Fifteen athletes whose training emphasized alternating actions (11 runners and 4 cyclists) and fifteen athletes who relied on bilateral actions with leg muscles (7 volleyball players, 8 weight-lifters) performed 2 maximal voluntary contractions (MVC) with the dorsiflexors, and 3 steady contractions at 8 target forces (2.5%, 5%, 10%, 20%, 30%, 40%, 50% and 60% MVC). The discharge characteristics of motor units in tibialis anterior were recorded using high-density electromyography grids. The MVC force and the absolute (standard deviation) and normalized (coefficient of variation) amplitudes of the force fluctuations at all target forces were similar between groups. The coefficient of variation for force decreased progressively from 2.5% to 20% MVC force, then it plateaued until 60% MVC force. Mean discharge rate of the motor units in tibialis anterior was similar at all target forces between groups. The variability in discharge times (coefficient of variation for interspike interval) and the variability in neural drive (coefficient of variation of filtered cumulative spike train) was also similar for the two groups. These results indicate that athletes who have trained with either alternating or bilateral actions with leg muscles has similar effects on maximal force, force control, and variability in the independent and common synaptic input during a single-limb isometric task with the dorsiflexors.

**Key words:** Training pattern, alternating contractions, bilateral contractions, force variability, motor unit, tibialis anterior.

### Introduction

The relative force capacity of muscles during single- and double-limb actions depends on the training pattern of an individual. As reported by Howard and Enoka (1991), the peak force that can be achieved by the knee extensor muscles of one leg during a single-leg contraction can be greater or less than that produced when the knee extensors of both legs are activated at the same time. In untrained individuals, the sum of the peak forces produced during one-legged contractions is greater than that during contractions of both legs at the same time; this is known as a bilateral deficit. Conversely, athletes who habitually train muscles with bilateral actions (e.g., weightlifters) exhibit a bilateral facilitation and produce greater peak forces in each leg during two-legged actions, whereas, the peak

force produced by each leg for those whose training involves alternating movements (e.g., cyclists) does not differ during one- and two-legged actions. The difference in force capacity of leg muscles during these conditions is attributable to an adjustment in the intensity of the activation signals transmitted to the involved muscles by the nervous system. Moreover, a bilateral deficit can be inferred by greater values for the perception of effort during submaximal bilateral trials being greater (9.6%) than during corresponding unilateral trials (5.5%) (McLean et al., 2006).

Exercises with alternating contractions are considered more specific for runners and cyclists, whereas exercises with bilateral contractions are performed from volleyball players and weight-lifters (Luk et al., 2014). Although the results from several studies are consistent with the specificity of the adaptations (Häkkinen et al., 1996; Parkin et al., 2001; Rahnama et al., 2005), others suggest that the transfer of training adaptations between limbs provides an adequate rationale for the use of training with alternating movements when training with bilateral movements is not possible (Appleby et al., 2019). In all these studies, however, the primary outcome variable was the peak force achieved during maximal voluntary contractions (MVCs) with little attention paid to submaximal contractions.

Some insight on the neural control of voluntary actions can be derived from the measurement of force fluctuations during steady submaximal contractions. As reviewed in Enoka and Farina (2020), the amplitude of the fluctuations in force (force steadiness) provides an index of the variability in the neural drive to muscle that is significantly correlated with performance on tests of motor function. For example, the level of force steadiness is superior for trained athletes relative to untrained individuals (Salonikidis et al., 2009). In dynamic conditions, tasks that involve sequences of alternating contractions are performed with higher spatial consistency, greater between-limb synchronization, and a more convergent speed profile than those that involve bilateral contractions (Shih et al., 2019). In static conditions, however, we recently found that neither force capacity (MVC force) nor measures of force control differed between homologous lower limb muscles in 20 active young adults (Petrović et al., 2022).

Compelling evidence indicates that the amplitude of the force fluctuations during steady contractions is largely attributable to the low-frequency oscillations in the

discharge rates of the activated motor units (Enoka and Farina, 2020). For example, 60% of the variance in the plantar flexion force applied by the calf muscles during a contraction at 10% MVC was explained by the fluctuations in the discharge rates of motor units in lateral gastrocnemius, medial gastrocnemius, and soleus (Mazzo et al., 2022). These findings suggest that force steadiness provides an index of the neural drive to muscle that is associated with performance capabilities on tests of motor function.

The purpose of our study was to assess the influence of habitual training pattern on force steadiness and the discharge characteristics of motor units in tibialis anterior during submaximal isometric contractions. We hypothesized that athletes who train with an emphasis on alternating movements (runners and cyclists) would exhibit superior force steadiness than those who focus on training bilateral leg movements (volleyball players and weight lifters), and the difference in force steadiness would be accompanied by differences in the variability in the discharge times of motor units in tibialis anterior. The choice of volleyballers and weightlifters was based on the number of bilateral actions performed with the lower limbs. The most frequent and important technical movements in volleyball involve bilateral limb actions (serving, jumping near the net to perform a spike or to block). For example, setters perform 18 - 22 jumps per set (Esper, 2013), outside hitters execute 12 - 18 jumps per set (Sheppard et al., 2009; Esper, 2013), and middle blockers complete 18 - 23 jumps per set (Sheppard et al., 2009), all with bilateral activation of muscles in both legs. Similarly, most bilateral exercises in weightlifting (back squats, front squats, overhead squats, deadlifts, and the Olympic lifts) involve bilateral actions in both limbs for the development of technique, strength, and performance in that sport.

## Methods

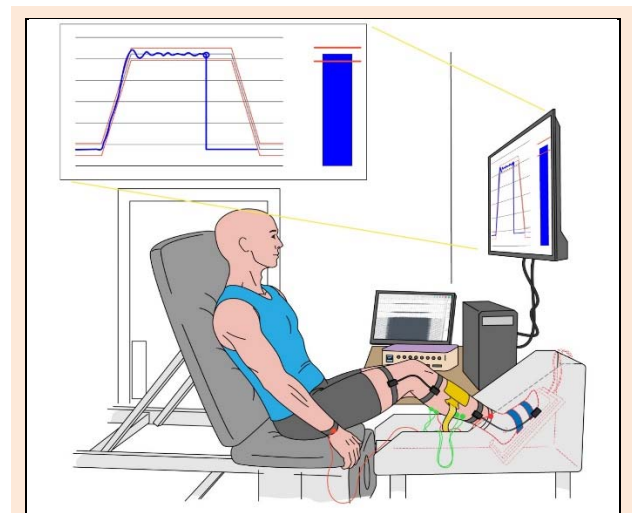
### Participants

Thirty men with at least five years of training (> 4 sessions/week, > 90 min/session) were categorized based on practice history. One group comprised athletes ( $29.4 \pm 9.2$  years,  $177.8 \pm 7.8$  cm,  $73.0 \pm 7.1$  kg) using mainly alternating contractions and included 11 runners (400-meter and 800-meter in track and field) and 4 cyclists (road cycling). The other group included athletes ( $22.5 \pm 5.8$  years,  $180.9 \pm 8.6$  cm,  $85.0 \pm 9.1$  kg) who emphasize bilateral leg actions in their training and comprised 7 volleyball players (National II-regional level) and 8 weight-lifters (regional/national level, class 73 kg, 81 kg and 96 kg). Prior to participation in the study, each candidate completed an extensive phone interview to assess the inclusion criteria of regular training for the last 3 years (3 - 5 times/week). In the first visit, the experimental protocol was explained to each volunteer and written informed consent was obtained. The required measurements were performed in the second visit. To minimize the influence of circadian rhythms, all tests were performed at the same time of the day (Racinais et al., 2005). Leg dominance was verified by the laterality quotient after completing the self-reported Waterloo Footedness Questionnaire-Revised for leg dominance during mobility and stabilizing tasks (van Melick et al., 2017).

Seven participants (3 in the group who trained alternating leg actions) were left-leg dominant. Approval (ERC-003/2021) for the experimental procedures was obtained from Aristotle University Ethics Committee on Human Research in accordance with the Declaration of Helsinki.

### Experimental setup

The ankle of the participants was fixed on an isometric dynamometer (TF022-NEG1, OTBioelettronica, IT) to measure the applied force, which was displayed on a 50-inch monitor (111x62 cm) located at eye level  $\sim 1.5$  m in front (Figure 1). Two goniometers, each with a single degree of freedom (MLTS700, ADInstruments), were used to measure the knee ( $120^\circ$ ) and ankle ( $90^\circ$ ) joint angles. Participants were required to sustain a steady force while performing a submaximal contraction with the dorsiflexors of the dominant leg. The force fluctuations and discharge characteristics of motor units were measured at eight target forces: 2.5%, 5%, 10%, 20%, 30%, 40%, 50%, and 60% MVC.



**Figure 1. Experimental setup.** The force exerted by the dorsiflexor muscle of the dominant leg was measured with a force transducer attached under the foot. Participants were asked to minimize coactivation of thigh and trunk muscles. High-density electromyography (HD-EMG) signals were recorded from the tibialis anterior muscle of the dominant leg with a semi-resistant adhesive grid (yellow pad). Surface EMG recordings were also obtained from a pair of surface electrodes placed over soleus and gastrocnemius medialis (green wires). The reference electrodes were placed at the wrist for the bipolar recordings and at the ankle for the grid (red wires). Two goniometers were placed over the knee and the ankle joints to measure joint angle. Visual feedback was provided on a monitor of the target force (red lines) and the applied force (blue lines) during the ramp-up, plateau, and ramp-down phases (middle screen) and on a moment-to-moment basis (right side of screen). The display covered approximately 80% of the screen.

### Electromyographic recordings

Prior to attaching the surface EMG electrodes, the skin was shaved to remove any hair, scrubbed with an abrasive gel, and cleaned with alcohol. High-density EMG signals were recorded from the tibialis anterior muscle of the dominant leg (5x13, 8 mm inter-electrode distance). The cavities were filled with conductive cream and the electrodes were attached to the main portion of the muscle with the electrode columns oriented along the direction of the fascicles (Rainoldi et al., 2004). Bipolar EMG recordings were also

taken from the soleus and medial gastrocnemius muscles (Thought Technology Ltd, CA) with an inter-electrode distance of 1 cm, according to SENIAM recommendations (Hermens et al., 2000). The signals were acquired, amplified, band-pass filtered (3 dB bandwidth, 10 - 500 Hz), and digitized using a 16-bit analog-to-digital converter (Quattrocento, OTBioelettronica, IT) at 2048 Hz.

### Maximal Voluntary Contractions (MVC)

Two 5-s MVCs were performed with the dorsiflexors of the dominant leg. The instruction was to pull up on the straps of the dynamometer gradually from zero to maximum over 3s and to maintain the maximal contraction for ~2s before relaxing. If the difference between the two MVCs was >10%, additional trials were performed until this criterion was met. Participants rested for ~60 s between each trial and received verbal encouragement during all MVC tasks.

### Submaximal Isometric Contractions

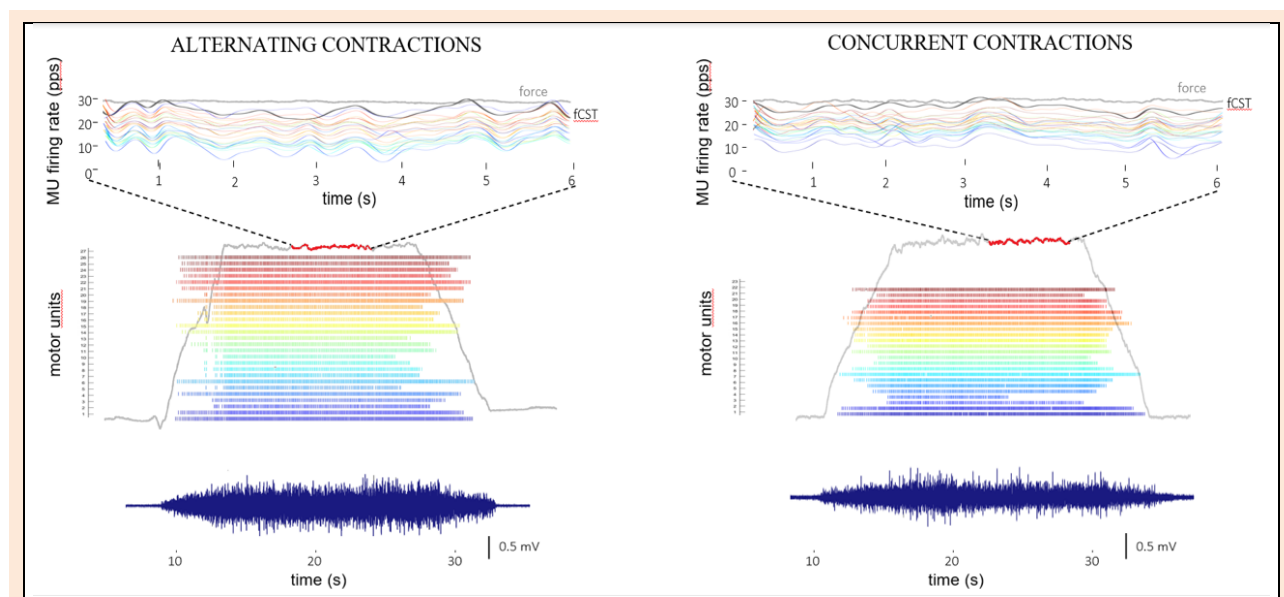
The experimental protocol comprised 3 isometric contractions at 8 target forces: 2.5%, 5%, 10%, 20%, 30%, 40%, 50% & 60% of MVC force. The participant matched a target force displayed on the monitor with the applied force being visualized as a blue line, while the required path depicted as a light blue line and the permissible error margins (5% of the target force) were presented with red lines. On the right side of the screen, a bar diagram indicated the applied force and the target force (Figure 1). The task comprised a trapezoidal trajectory with a ramp-up phase (5 s), an isometric plateau (15 s), and a ramp-down phase (5 s). The steadiest 6-s interval during the plateau phase of the isometric contraction was extracted by a customized written MATLAB code. Participants rested for ~2 min between trials and the order of target forces was randomized. The reported discomfort values were  $\leq 3$  for all angles and target forces (0 = no discomfort and 10 = extreme discomfort).

### Data analysis

The high-density surface EMG signals were recorded using the Bio Lab+ software (OTBioelettronica, IT). Motor unit discrimination was performed offline with a customized MATLAB code that included a semi-automated Convolution Kernel Compensation algorithm (Holobar and Zazula, 2004), previously validated (Marateb et al., 2011; Holobar et al., 2012; Holobar and Farina, 2014), and based on a blind source separation technique. Pulse-to-noise ratio (PNR), introduced by Holobar and Farina (2014), was used to assess the quality of motor unit identification and only motor units with  $\text{PNR} > 30$  dB, which corresponds to an estimated accuracy of > 90%, were included in the analysis. The results of the decomposition process were manually inspected and edited by an experienced operator to improve the automatic DEMUSE tool spike segmentation. Motor units with short interspike intervals (ISI) or with irregular firing patterns were discarded (Pascoe et al., 2013). The motor units showing unstable recruitment events (i.e., more than one recruitment and derecruitment per contraction) were discarded and removed from further analysis (Figure 2).

The bipolar surface EMG signals were conditioned with an 8<sup>th</sup>-order analogue Butterworth bandpass filter (20 - 500 Hz). The coactivation of each antagonist muscle (soleus and medial gastrocnemius) was quantified as the absolute root mean square (RMS) amplitude and normalized (nRMS) as a percentage of its activity during the plantar flexion MVC.

Force variability was quantified as the absolute (standard deviation, SD) and the normalized (coefficient of variation, CoV) amplitudes of the force fluctuations (Tsatsaki et al., 2021). The mean discharge rate (MDR – average rate at which motor units discharged action potentials) and CoV for ISI were calculated for each identified motor unit.



**Figure 2.** Representative data depicting the dorsiflexion force during an isometric contraction at 40% MVC force from an athlete trained with alternating leg actions (left) and an athlete trained with bilateral leg actions (right). Each panel shows (bottom to top traces) the EMG signal for tibialis anterior, the discharge times of multiple MUs (colored tick marks), the force applied by the participant (grey line), and the filtered cumulative spike train (fCST) for each MU and the average trace shown in black.



The variability in the neural drive to muscle was estimated by low-pass filtering the discharge train of each individual motor unit with a 400-ms Hanning window and extracting a cumulative spike train (CST; summed discharge times of all motor units) as the average of smoothed motor unit profiles. The filtered CST (fCST) is correlated with the force oscillations and represents the common neural drive (Thompson et al., 2018). Thus, the absolute/relative variability in motor unit discharge times was quantified with two measures: the SD and CoV for both ISI and fCST.

### Statistical analysis

The statistical analysis was performed with SPSS software (version 25, IBM). A one-way analysis of variance (ANOVA) was used to examine the differences between MVC force for the two groups (alternating vs bilateral leg actions). Subsequently, a two-way, repeated-measures ANOVA was used to compare the force fluctuations (SD and CoV for force) between two groups at eight force targets (2.5%, 5%, 10%, 20%, 30%, 40%, 50% and 60% MVC). Differences in the total number of motor units between the two groups (alternating vs bilateral leg actions) were examined with one-way ANOVA. Differences in motor unit variables (MDR, CoV for ISI, SD for ISI, CoV for fCST, and SD for fCST) were examined with separate two-way ANOVAs. Statistically significant interactions were examined with simple-effect designs and Tukey tests were used to detect significant differences between pairs of means. The level of significance was set at  $p < 0.05$ . Statistically significant differences were identified with Bonfer-

roni corrections. The association between fluctuations in force (SD and CoV for force) and the two measures of the variability in discharge times (SD and CoVs for ISI and fCST) were examined by correlation analysis.

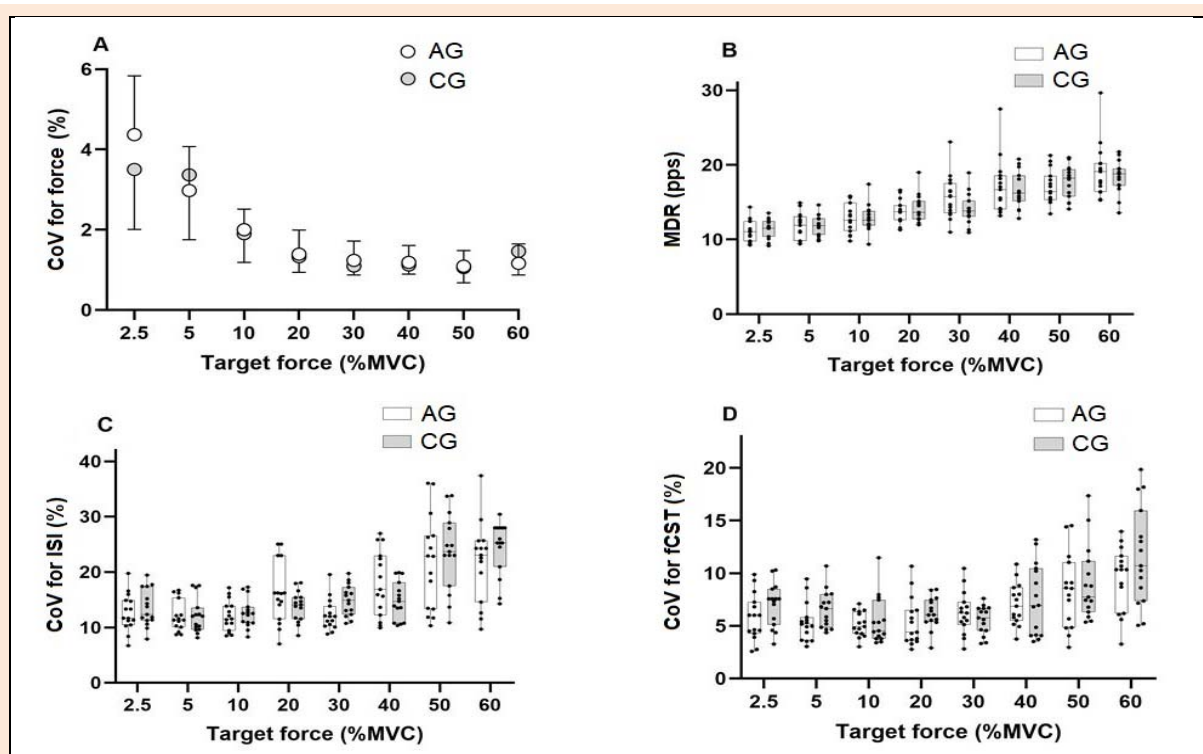
## Results

### Maximal dorsiflexion force

One-way ANOVA revealed no difference in MVC force for the dorsiflexors between the two groups ( $p > 0.05$ ). The MVC force for the group who trained with alternating leg actions ( $152 \pm 31$  N) was similar to that for the group who trained with bilateral leg actions ( $156 \pm 33$  N).

### Force fluctuations

As indicated in Figure 3A, the analysis revealed no main effect of group for the CoV for force ( $F(1,14) = 0.109$ ,  $p = 0.746$ ,  $\eta^2 = 0.008$ ). In contrast, there was a main effect of target force on the CoV for force ( $F(7,98) = 92.256$ ,  $p < 0.0005$ ,  $\eta^2 = 0.868$ ), but the group  $\times$  target force interaction was not significant ( $F(7,98) = 1.932$ ,  $p = 0.157$ ,  $\eta^2 = 0.121$ ). In the group who trained with alternating leg actions, the CoV for force decreased gradually from 2.5% to 20% MVC force ( $p < 0.05$ ), and was similar from 20% to 60% MVC force. In the group who trained with bilateral leg actions, the CoV for force was similar between 2.5% and 5% MVC force before decreasing from 5% to 30% MVC force ( $p < 0.05$ ) and then remaining unaltered at 40% and 50% MVC force and finally decreasing significantly ( $p < 0.05$ ) to 60% MVC force.



**Figure 3.** Force variability during the steady submaximal contractions with the dorsiflexors of the dominant leg at eight target forces by the athletes who trained with either alternating or bilateral leg actions. A. Coefficient of variation (CoV) for force (mean  $\pm$  SD); B. Mean discharge rate (MDR). C. Coefficient of variation (CoV) for interspike interval (ISI); D. Coefficient of variation (CoV) for filtered cumulative spike train (fCST). In B, C, and D, data are shown as box graphs with “whiskers” displaying the 5-number summary of the data: the maximum limit (upper whisker), the 3<sup>rd</sup> quartile (75<sup>th</sup> percentile), the median value (line inside the box), the first quartile (25<sup>th</sup> percentile) and the minimum limit (lower whisker). AG = group trained with alternating leg actions; CG = group trained with bilateral leg actions.

Similarly, there was no main effect of group on the SD of force, but there was a main effect of target force on the SD of force. The group × target force interaction was not significant. In both groups, the SD of force at each target force was greater ( $p < 0.05$ ) than the value at the preceding target force. Moreover, the level of coactivation (nRMS) for the antagonist muscles (soleus and medial gastrocnemius) was similar for both groups across target forces.

**Total number of motor units**

After visual inspection and manual correction of 720 repetitions (30 participants x 8 target forces x 3 repetitions at each target), the total number of identified MUs was 4,838 for the group who trained with alternating leg actions (average  $14.9 \pm 6.7$  per contraction) and 2,880 for the group who trained with bilateral leg actions (average  $8.5 \pm 4.9$  per contraction) (Table 1). Due to large variation of the shapes of MU action potentials, we were not able to match the same MU at each target force. The total number of identified MUs was greater ( $p < 0.05$ ) for the group who trained with alternating leg actions compared to the other group, presumably due to differences in the anatomy of the muscle and its associated tissues between the two groups (Del Vecchio et al., 2020).

**Mean Discharge Rates (MDR)**

Group mean discharge rates of tibialis anterior motor units for each condition are presented in Figure 3B. The ANOVA found no main effect of group, a main effect of target force ( $F(7,98) = 70.490, p < 0.0005, \eta^2 = 0.834$ ), and a non-significant group × target interaction. The MDR for both groups increased gradually from  $11.3 \pm 1.4$  pps at 2.5% MVC to  $18.8 \pm 3.0$  pps at 60% MVC.

**Variation for Interspike Interval (ISI)**

Group mean CoV for ISI values are presented in the Figure

3C. The ANOVA showed no main effect of group, a main effect of target force ( $F(7,98) = 35.322, p < 0.0005, \eta^2 = 0.716$ ), but no interaction. The CoV for ISI for both groups increased from  $13.1 \pm 3.3\%$  at 2.5% MVC to  $23.1 \pm 6.3\%$  at 60% MVC.

Similarly, for the SD for ISI, the ANOVA showed no main effect of group, a main effect of target force ( $F(7,98) = 4.516, p = 0.007, \eta^2 = 0.244$ ), but no interaction. The SD of ISI for both groups varied between  $22.6 \pm 6.2$  ms at 2.5% MVC and  $25.0 \pm 7.2$  ms at 60% MVC.

**Variation of the filtered Cumulative Spike Train (fCST)**

Group means for the CoV for fCST values are presented in Figure 3D. The ANOVA showed that the CoV for fCST was not different between groups, but there was a main effect of target force ( $F(7,98) = 17.437, p < 0.0005, \eta^2 = 0.555$ ). There was not a group × target force interaction. The CoV for fCST for both groups varied from  $6.4 \pm 2.1\%$  at 2.5% MVC to  $10.6 \pm 4.7\%$  at 60% MVC force.

Similarly, the ANOVA showed that the SD of fCST was not different between groups, but there was a main effect of target force on SD of fCST ( $F(7,98) = 28.611, p < 0.0005, \eta^2 = 0.671$ ). There was no group × target force interaction. The SD of fCST for both groups increased gradually from  $3.2 \pm 1.3$  ms at 2.5% to  $9.7 \pm 3.8$  ms at 60% MVC.

**Correlations between fluctuations in force and discharge variability**

Correlations between CoV for force and the two measures of variability in the discharge times of motor units (CoV for ISI and CoV for fCST) during the steady contractions for the two groups are presented in Table 2. The data indicate that the correlation between CoV for force and CoV for ISI ranged from weak to strong: group trained

**Table 1.** Average number (mean ± SD) and range of the tibialis anterior motor units identified for the group who trained with alternating leg actions (AG) and the group who trained with bilateral leg actions (CG) in the dominant leg at 8 target forces during isometric contractions with the dorsiflexors.

Group	Target force							
	2.5%	5%	10%	20%	30%	40%	50%	60%
AG	15 ± 6* (3 - 27)	16 ± 7* (4 - 37)	18 ± 7* (6 - 36)	16 ± 7* (3 - 34)	17 ± 7* (5 - 38)	14 ± 7 (4 - 32)	12 ± 5* (4 - 26)	11 ± 5 (3 - 30)
CG	7 ± 4 (3 - 22)	10 ± 6 (3 - 24)	10 ± 6 (3 - 26)	9 ± 5 (3 - 23)	9 ± 5 (4 - 26)	9 ± 6 (3 - 28)	7 ± 4 (3 - 17)	7 ± 4 (3 - 21)

Abbreviation: AG = participants who trained with alternating leg actions; CG = participants who trained with bilateral leg actions. \* $p < 0.05$

**Table 2.** Correlations between the coefficient of variation (CoV) for force with the CoV for interspike interval (CoV for ISI) and CoV for filtered cumulative spike train (CoV for fCST) at 8 target forces during isometric contractions with the dorsiflexors.

	Group	CoV for force							
		2.5%	5%	10%	20%	30%	40%	50%	60%
CoV for ISI	AG	0.358 n.s.	0.847** p = 0.000	0.348 n.s.	0.701** p = 0.004	0.309 n.s.	0.688** p = 0.005	0.520* p = 0.047	0.575* p = 0.025
	CG	0.821** p = 0.000	0.560* p = 0.030	0.267 n.s.	0.675** p = 0.006	0.610* p = 0.016	0.551* p = 0.033	0.726** p = 0.002	0.524* p = 0.045
CoV for fCST	AG	0.448 n.s.	0.262 n.s.	0.585* p = 0.022	0.536* p = 0.039	0.559* p = 0.030	0.482 n.s.	0.578* p = 0.024	0.692** p = 0.004
	CG	0.425 n.s.	0.578* p = 0.024	0.207 n.s.	0.531* p = 0.042	0.572* p = 0.026	0.580* p = 0.023	0.725** p = 0.002	0.606* p = 0.017

Abbreviation: AG = group trained with alternating leg actions; CG = group trained with bilateral leg actions; n.s. = non-significant. \* $p < 0.05$ , \*\* $p < 0.01$

with alternating leg actions: 0.309 to 0.847; group trained with bilateral leg actions: 0.267 to 0.821. A similar range was found for the correlation between the CoV for force and CoV for fCST: group trained with alternating leg actions: 0.262 to 0.692; group trained with bilateral leg actions: 0.207 to 0.725. The strongest correlations for the CoVs for force and ISI were at the lowest target force for both groups, whereas the strongest correlations for the CoVs for force and fCST were at highest forces for both groups.

## Discussion

The main finding of this study was that different training modalities (alternating vs bilateral leg actions) did not influence either maximal force or force fluctuations and the modulation of discharge times for motor units in tibialis anterior during submaximal isometric contractions. Thus, athletes trained with bilateral leg actions were able to perform steady submaximal contractions with a single leg at the same level of force steadiness as athletes trained with alternating leg actions. Indeed, the standard deviation and the coefficient of variation for force and the modulation of motor unit discharge times were similar between groups. Moreover, coactivation of the antagonist muscles (soleus and medial gastrocnemius) during maximal and submaximal contractions did not differ between groups.

### Force steadiness

The amplitude of the force fluctuations during the low-to-moderate dorsiflexion tasks was similar for the two groups of athletes. At least three explanations are possible for the similar levels of steadiness for the groups: test task, test muscle, and training pattern. First, the participants of both groups were not familiar with relatively long isometric contractions at low target forces, as they typically train with dynamic contractions of a greater magnitude and shorter duration. The dissociation between dynamic movements and isometric steadiness in our experimental setup is well-established and could be related to the nature of feedback provided during the two tasks. The control strategy used during rapid contractions (dynamic task - open loop control) is quite different from that used during steady, submaximal contractions (isometric task - closed loop control) (Christou, 2005). Moreover, there is strong evidence for a contractile-mode specificity when contrasting dynamic and isometric training, each of them producing specific neurophysiological adaptations (Duchateau and Hainaut, 1984). Thus, the dissimilar level and duration of loading likely makes the test task a poor predictor of athletic performance. Second, tibialis anterior may not be the most appropriate test muscle to distinguish between athletes with different habitual training patterns. Even if this muscle contributes up to 60% of the maximal force during dorsiflexion about the ankle joint (Marsh et al., 1981; Andreassen and Arendt-Nielsen, 1987), however, it is not of a primary importance during running, cycling, jumping, and weight-lifting activities. Moreover, the choice of an ankle muscle instead of a knee or hip muscle was likely problematic. For example, the bilateral force deficit appears to be more pronounced for proximal than distal muscles of

the upper limbs (Aune et al., 2013). Third, our study compared athletes who train with an emphasis on either alternating or bilateral leg movements. As found by Howard and Enoka (1991), athletes who trained with bilateral leg actions exhibit a bilateral facilitation for the knee extensor muscles, whereas the peak force produced by the athletes who trained with alternating leg actions did not differ during one- and two-legged contractions. Nonetheless, the habitual training patterns of our participants may not have been distinct enough to elicit unique activation strategies during the unfamiliar isometric contractions.

### Target force

The low-frequency fluctuations in force during steady submaximal contractions are caused by varying combinations of independent and shared synaptic inputs to the motor neuron pool and the ensuing modulation of motor unit discharge times (Farina et al., 2016). The variability in motor unit discharge times is quantified with two measures: the coefficient of variation for interspike interval (CoV for ISI) and the variability in the smoothed discharge times (CoV for fCST). The two measures are influenced by independent and shared synaptic, but the independent inputs likely dominate the interspike-interval measurement whereas the shared inputs establish the variability in the smoothed discharge times. Dideriksen et al. (2012) found that the strength of the correlations for both the CoV for ISI (independent synaptic inputs) and the CoV for fCST (shared synaptic inputs) with the fluctuations in the applied force varied with contraction strength for the abductor digiti minimi muscle. The relative influence of the two sources of modulation on the force fluctuations was quantified as the peak value in the cross-correlation function. The correlation was greater for the CoV for ISI at a very low target force (2.5% MVC), whereas the correlation for the CoV for fCST was stronger at a low target force (10% MVC). The greater role for the CoV for ISI (independent inputs) in the force oscillations at low forces likely explains why the precise control of force is most difficult at low target forces.

In line with our previous studies, we found that the observed values for the CoV for ISI and the CoV for fCST gradually doubled between 2.5% and 60% MVC force. Tsatsaki et al. (2021) reported a greater CoV for ISI values at 40% and 60% MVC than at 20% MVC, whereas Petrović et al. (2022) showed that the CoV for ISI increased on average by 84% and the CoV for fCST increased on average by 36% from low (5% MVC) to high (60% MVC) target forces. The relative influence of the two sources of modulation is attributed to the temporal (twitch) and spatial (summation) filtering effects of muscle properties and the proportion of common synaptic input increases with target force during sustained isometric contractions (Castronovo et al., 2015). In our study, the variability of both inputs increased similarly with the increase of the target force, whereas the variability of force remained constant. Therefore, it seems that force steadiness is influenced not only by the shared synaptic input but also by other factors, such as the number of motor units in the pool, the upper limit of motor unit recruitment, and the contractile properties of motor units (Dideriksen et al., 2012; Watanabe et al., 2013; Castronovo et al., 2018). Moreover, our dorsiflexion task

may have involved several synergistic muscles (extensor hallucis longus, extensor digitorum longus and peroneus tertius), and thus, force steadiness is not only associated with the variability in motor unit discharge times of the primary agonist muscle.

Although the amplitude of the force fluctuations and the variability of neural drive were not statistically different between our two groups of participants, the correlations between the CoV for force and CoV for ISI and CoV for fCST were quite variable (Table 2). The greater correlation coefficients were observed at the lowest target force for the ISI (at 5% MVC for the group trained with alternating leg actions and at 2.5% MVC for the group trained with bilateral leg actions) and at the highest target force for the fCST (at 60% MVC for the group trained with alternating leg actions and at 50% MVC for the group trained with bilateral leg actions). However, this finding was not consistent across target forces. Rather, the values of correlation coefficients between CoV for force and CoV for ISI were typically similar with those between CoV for force and CoV for fCST (Table 2). Nevertheless, the level of training, the familiarity with the task, and the type of contraction (Howard and Enoka, 1991; Jakobi and Cafarelli, 1998; Owings and Grabiner, 1998; Taniguchi, 1998) may have influenced the results; the neurophysiological explanations of force deficit/facilitation during two-legged actions needs to be compared explicitly during both one- and two-legged tasks. As the experimental setup only permitted a one-legged task, the theory of neural inhibition/facilitation was only indirectly assessed. Despite our expectation that athletes who train with bilateral leg actions would have a reduced capacity to provide maximal muscle activation (Howard and Enoka 1991) and force control during one-legged contractions, the findings were not consistent with this hypothesis. Perhaps there was an insufficient difference in training patterns of the participants. To circumvent this limitation, future studies should characterize all participants based on the magnitude of the bilateral facilitation instead of their training history.

## Conclusion

In conclusion, we found no differences in dorsiflexion force control (force steadiness) between athletes with different training patterns across several target forces. This result was accompanied by a lack of differences in the variability in the neural drive and the discharge times of motor units in tibialis anterior. These findings indicate a similar capacity of athletes trained with either bilateral or alternating leg actions to apply steady force during single-limb isometric tasks, despite the utility of this metric as an explanatory variable for performance on tests of motor function.

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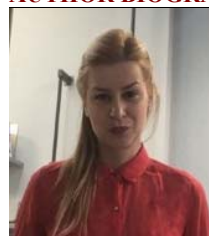
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### Key points

- Training that involves either alternating or bilateral leg actions did not influence force control during single-leg contractions with the dorsiflexors.
- The discharge characteristics of motor units in tibialis anterior during submaximal isometric contractions was similar between the two groups of athletes with different training histories.
- The variability of the independent and the common synaptic inputs, as estimated from measures of variability in the discharge times of motor unit action potentials, increased with target force for both groups of participants.

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