Integrating Motor Learning Principles into Muscle Force and Balance Control

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Word count: 4099 words

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Abstract

The principles of specificity and similarity play a crucial role in supporting the transfer and retention of motor performance in general sports training. Nevertheless, the extent to which force control ability translates into dynamic performance remains uncertain. We aimed to investigate the effect of force control training on the transfer and retention of balance control in 18 young individuals. The force control training utilized a visual-guided force tracking task with either a uniform or non-uniform sinusoidal wave in ankle plantar flexors (PF). Postural stability was assessed by measuring the center of pressure (COP) in a single-leg standing posture. Despite consistent repetitions, no significant differences in COP parameters were observed between the pre- and post-training assessments. However, significant differences were noted between the pre-training assessments and the post-training assessments conducted one week later, utilizing a randomized order. Shifting from a regimen of constant repetition to a randomized order has a positive impact on the transfer and retention of acquired motor skills. This approach, based on the motor learning theory, holds promise for enhancing the motor performance of athletes and patients undergoing rehabilitation.

Keywords*:* Motor skills; Postural Balance; Training; Ankle joint

Introduction

The ankle is a crucial joint in the lower extremity for maintaining standing balance (Kasahara et al., 2021). Coincidentally, it also ranks as the most frequent site for sports injuries (Kawahara et al., 2022). Researchers in recent studies reported that ankle injuries are often recurrent and reduce patients' health-related quality of life (Kawahara et al., 2022; Hernández-Guillén et al., 2022; Wright et al., 2017). These findings emphasize the critical significance of consistently maintaining ankle strength and function. Additionally, declining ankle function is associated with disability, frailty, and an increased risk of falls in older adults (Hernández-Guillén et al., 2022). Therefore, strength training has been proposed as a primary strategy for improving motor performance. However, the parameters of strength training differ between coaches and therapists, and the outcomes of such training interventions are not uniform (Christensen et al., 2020; Wright et al., 2017).

Traditional strength training programs are primarily aimed at increasing absolute muscle strength (Ferri et al., 2003; Krist et al., 2013). However, most daily activities are performed at submaximal strength (~17% in the quadriceps and hamstrings) (Kern et al., 2001). Thus, the ability to properly output the muscle force (i.e., force control) in response to varying tasks and situations is essential in everyday life. While coaches and therapists regulate training variables, such as activity, rest, frequency, intensity, and duration, according to general sports training principles (Kasper, 2019), improving force control requires ingenuity beyond traditional methods. Variable or random training has been proposed as a promising approach (Shi et al., 2022). In previous studies on variable resistance training, Walker et al. (2014) documented that variable resistance training increased maximum muscle strength to the same extent as constant resistance training and also improved fatigue-resistance properties. Additionally, Arazi et al.

(2020) reported that muscle strength increased with variable resistance training. However, since equal exercise numbers and terms were applied for both constant and variable exercises in these studies, the strength gains may be due to a dose-response effect. On the other hand, two systematic reviews concluded that there were no significant differences between the variable and conventional training protocols in muscle mass gain (Fuentes-García et al., 2024) and that variable training was more effective in enhancing velocity and power, optimizing neuromuscular adaptation (Shi et al., 2022). These findings suggest that although variable or randomized training contributes based on the motor learning theory (Schmidt et al., 2011), training focused on force control has not been widely recognized as a motor skill or task and has been minimally targeted in strength training until now.

Enhancement of force control is anticipated to improve motor performance in scenarios involving submaximal strength (Ebisu et al., 2022; Oranchuk et al., 2019; Saeterbakken et al., 2016) and is essential for responding to opponents and varying situations in sports matchups. The transfer effect, as outlined in the motor learning theory, is pertinent to this issue. This effect depends on the specificity and similarity between tasks, and its effectiveness is more pronounced when the required muscle strength and movement are already anticipated or fixed (Kasper, 2019; Stone et al., 2002; Saeterbakken et al., 2016). Thus, consistent rhythm or monotonous training is effective for the initial acquisition of motor skills (Ivusza et al., 2022; Nachmani et al., 2021). In contrast, practicing in a variable or randomized order may result in slower motor skill acquisition but facilitates the transfer of motor skills and contributes to the sustained maintenance of acquired performance (Cimadoro et al., 2013; Kern et al., 2001). Nevertheless, most traditional muscle strength training procedures are performed with constant or progressive loads during the training task (Ferri et al., 2003; Krist et al., 2013). Applying a randomized load in general training is rare, and there is currently a lack of evidence supporting the efficacy of a randomized order in facilitating transfer and retention in force control training. Therefore, the extent to which traditional training methods contribute to variable and multiple force control remains uncertain, prompting coaches and therapists to explore innovative approaches in clinical settings (Ebisu et al., 2022; Oranchuk et al., 2019).

There is no doubt that training to increase muscle strength is important for stabilizing posture, improving motor performance, and avoiding falls or severe injuries. Researchers in previous studies have sporadically investigated the association between force control training and balance (Barbosa et al., 2020; Ebisu et al., 2022; Oshita & Yano, 2011). Oshita & Yano (2011) reported the efficacy of force stability training (i.e., force matching task) in decreasing postural sway, while Barbosa et al. (2020) found that force stability training did not reduce postural sway. Although the disagreement may be due to methodological differences, the contribution of force stability to postural control remains unclear. Recently, we revealed that the ability of variable force tracking in the ankle joint was related to the standing balance stability in both young and older adults (Ebisu et al., 2022), suggesting that fine-tuning muscle strength output is crucial for maintaining postural control in response to various external and internal perturbations.

The deficit of motor control in patients with stroke (Patel, et al., 2020), Parkinson disease (Kurillo, et al., 2004), and autism spectrum disorder (Lidstone, et al., 2020) is characterized by using the force control task. Moreover, the possibility of the force control training for improving the neuromuscular behaviour in patients with anterior cruciate ligament injury and ACL reconstruction is discussed (Sherman, et al., 2023). However, researchers did not consider the acute or chronic order effect on the force control task in previous studies. Although general strength training often uses constant and progressive loading, this stereotyped training may not encourage coordinated performances in variable environments. To our knowledge, no researchers previously investigated whether muscle training focused on variable force control positively affects postural control during the standing posture. Specifically, muscle training dedicated to balance has not been consistently performed in clinical and sports settings until now, and the effect of muscle training with a randomized load on balance is not clear. Therefore, from the viewpoint of the motor learning theory, we aimed to clarify the effect of a randomized order on facilitating transfer and retention in force control training. We hypothesized that training the ankle muscle across multiple force levels would yield a more pronounced impact on the transfer and retention of standing balance stability than repetitive training at a single force level. We propose integrating motor learning theory with general sports training principles to enhance specificity in our approach.

Methods

Participants

Twenty healthy college students (10 females and 10 males) volunteered to participate in this study. According to sample size calculations using G*Power version 3.1.9.7 (Faul et al., 2007), and based on sample size calculations and data from previous related study (Faul et al., 2007; Ialongo, 2016; Bujang, 2021; Ebisu et al., 2022), a minimum of 16 participants was required for the planned experiment, based on test family of F-test, statistical test of ANOVA: Repeated measured, within-between interaction, an effect size of $d = 0.40$, an alpha level of $\alpha = 0.05$, power of $1 - \beta = 0.90$, number of groups of n = 2, number of measurements of n = 3, and correlation among repeated measures (r = 0.50). The students were randomly divided into two groups, with 10 participants per group: a randomly trained group and a constantly trained group. Due to scheduling conflicts, two participants from the constantly trained group were unable to complete the retest after one week. Consequently, the constantly trained group comprised eight individuals who successfully completed all experiments (Table 1). None of the participants had neurological diseases, balance disorders, or a history of ankle sprains within six months prior to participating in the study.

This study was conducted in accordance with the principles of the Declaration of Helsinki. All participants provided written informed consent to participate, and the ethics committee of Hokkaido University School of Medicine approved the procedures (ethics approval number 21-61).

Experimental Procedures

All participants warmed up for 2 minutes on a bicycle ergometer before training. They then performed the force tracking task and single-leg standing balance test before and after training. Retests were performed after one week to evaluate the retention effect of muscle training (Wanner et al., 2020). The force tracking task and single-leg standing balance test were performed on the participant's dominant foot.

The visual-guided force tracking test was performed using a Biodex System 3 dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) (Ebisu et al., 2022). The force was produced by isometric contractions of the ankle plantar flexors (PF) (Fig. 1A). Participants sat in a neutral position with knee extension and an ankle PF angle of 0°. The maximal force during maximal voluntary isometric contraction (MVIC) was recorded using a personal computer (Ebisu et al., 2022). The force tracking test was performed using a customized LabVIEW program (LabVIEW, 2009; National

Instruments, Austin, TX, USA) (Ebisu et al., 2022). Participants were instructed to adjust the force of their ankle PF and to control a bar representing the actual force, aiming to track a sinusoidal target bar displayed on the computer monitor (Fig. 1B). The force tracking test featured three continuous sinusoidal patterns with frequencies of 0.2, 0.5, and 1.0 Hz, each lasting 8 seconds (Fig. 2A). Throughout the experiment, the amplitude of these sinusoidal force patterns remained constant at 10% of the maximum force amplitude. Balance ability was assessed using the single-leg standing test for 20 seconds with the eyes open. Participants stood barefoot on a force plate (Kistler type 9286BA, Switzerland) with their hip and knee joints positioned at neutral (i.e., 0°). They kept their upper limbs positioned in front of their chest. Participants were instructed to maintain an upright posture and stabilize themselves as much as possible. All force signals were recorded using a customized LabVIEW program on a connected personal computer.

Muscle Force Training with Different Training Types

Two types of training were conducted with specifications similar to those of the force tracking test, differing only in frequency and repetition number. Participants were asked to match their actual force to the target force as accurately as possible through visual feedback from the personal computer monitor. The required force control consisted of sinusoidal and smooth force outputs, with an amplitude of ± 10% of MVIC and around 20% of MVIC at baseline (Fig. 2B and C). In the constant training condition, the target force sinusoidally changed at a frequency of 0.5 Hz and repeated nine cycles within one block (Fig. 2B). In contrast, the random training condition involved three frequencies (0.2, 0.5, and 1.0 Hz) arranged pseudo-randomly within one block (Fig. 2C). Each frequency was cycled three times, totaling nine cycles per block.

Both training groups completed nine blocks. Despite differing total training times between groups, all participants completed the same number of cycles, totaling 81 cycles (9 cycles × 9 blocks). To mitigate fatigue and maintain concentration, participants rested for one minute between blocks.

Data Processing and Analysis

The actual force signal of the ankle PF and the center of pressure (COP) signal from the force plate were imported into the PC at a sampling rate of 1 kHz and were low-pass-filtered with a zero-lag fourth-order Butterworth filter at a cut-off frequency of 10 Hz for offline data processing (Ebisu et al., 2022). To evaluate the accuracy of the force tracking task, the root mean square errors (RMSEs) between the force target and force output value in the force tracking task was calculated by using the following formula:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(target\ value_i - output\ value_i)^2}$$

Reliability was assessed by calculating the intra-class correlation coefficient (ICC) with a 95% confidence interval using absolute agreement in a one-way analysis of variance and the results of a single measurement. ICC values were interpreted as follows: 'excellent' for ICC > 0.75, 'fair to good' for ICC between 0.40 and 0.75, and 'poor' for ICC < 0.40 (Pinsault, et al., 2009). The ICC $_{(1,\,1)}$ of the force tracking task in the current study was 0.583 (95% CI: 0.436, 0.714).

In this analysis, we used the 10-second data with a stable state during single-leg standing, which was confirmed by two examiners. Balance ability during single-leg standing was assessed with seven indices using a customized MATLAB program (MathWorks, Natick, MA, USA) as follows: 1) the total length of COP displacements (LNG); 2) the total length of COP displacements in the anterior-posterior direction (AP_{LNG}); 3) the average velocity of COP in the anterior-posterior direction (AP_{vel}); 4) the total length of COP displacements in the mediolateral direction (ML_{LNG}); 5) the average velocity of COP in the mediolateral direction (ML_{vel}); 6) the environmental area (ENV_{area}, Fig. 2D); and 7) the effective area (EF_{area}, Fig. 2E). The two area formulae are as follows.

$$ENV_{area} = \frac{1}{2}\sum_{i=1}^{n} |X_{i+1}Y_i - X_iY_{i+1}|$$

$$EF_{area} = \left(\sqrt{\frac{\sum_{i=1}^{n}\{(X_i - \bar{X})^2 + (Y_i - \bar{Y})^2\}}{n}}\right)^2 \times \pi$$

The ICC $_{(1,\,1)}$ of the single-leg standing balance test in the current study was 0.972 (95% CI: 0.950, 0.984).

Statistical Analysis

All statistical analyses were performed using SPSS Statistics (version 26.0; IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was performed to check for normality. An unpaired t-test was used to compare participant characteristics. A two-way repeated-measures analysis of variance (ANOVA) (two groups × three repetitions) was performed to assess the differences in the RMSEs and COP indices. Mauchly's test of sphericity was used to assess sphericity, and the Greenhouse–Geisser correction was applied in the absence of sphericity. After repeated-measures ANOVA, post hoc tests were performed according to results of interaction and main effects using the Bonferroni correction (Wei, et al., 2012). If normality was not observed, Friedman ' s test with pairwise comparisons using Bonferroni correction was used to compare between three repetitions for the RMSEs and COP indices in each group. The effect size for the ANOVA was calculated as partial eta-squared values (η_p^2) (Kasahara et al., 2021) and the effect size of Freidman test was measured by Kendall's *W* (Silva, et al., 2021). Statistical significance was set at a p-value of <0.05.

Results

Two-way analysis of variance showed that the maximum force during MVIC had no interaction or main effect (F [1.44, 23.10] = 2.537, p = 0.114, η_p^2 = 0.137). The absolute muscle strength of PF did not change in either group in this study.

For the force tracking test, ANOVA showed there was no significant interaction between group and time for the RMSEs (F [2, 32] = 0.566, p = 0.573, η_p^2 = 0.034). However, there were significant main effects of time (F [2, 32] = 26.676, p < 0.001, η_p^2 = 0.642) and group (F [1, 16] = 5.260, p = 0.036, η_p^2 = 0.247). The post hoc test showed that the RMSEs after training and one week were significantly smaller than those before training (both p < 0.001). Multiple comparison results did not show significant differences between the two groups at a specific time.

The single-leg standing balance ability in each group is shown in Table 2. Shapiro–Wilk tests showed that some variables in the COP data were not normality distributed. Therefore, Friedman' s test with pairwise comparisons using Bonferroni correction was performed for the COP data. In the block training group, there was a significant difference for ENV_{area} ($\chi^2(2)$ = 12.250, p = 0.002, Kendall's *W* = 0.766) between times and post hoc test showed that ENV_{area} in both post-training and after one week was smaller compared to pre-training. There were no significant differences for the LNG ($\chi^2(2) = 3.250$, $p = 0.197$, Kendall's $W = 0.203$), AP_{LNG} ($\chi^2(2) = 5.250$, $p = 0.072$, Kendall's $W = 0.328$), AP_{vel} ($\chi^2(2) = 3.800$, $p = 0.150$, Kendall's $W = 0.328$), ML_{LNG} ($\chi^2(2) = 0.000$, $p = 1.000$, Kendall's $W = 0.000$), ML_{vel} ($\chi^2(2) = 0.000$, $p = 1.000$, Kendall's $W = 0.000$), and EF_{area} ($\chi^2(2) = 0.4750$ $p = 0.093$, Kendall's $W = 0.297$) between times in the block group.

In the randomly trained group, there were significant differences for LNG ($\chi^2(2) = 8.359$, $p = 0.015$, Kendall's $W = 0.418$), AP_{LNG} ($\chi^2(2) = 8.600$, $p = 0.014$, Kendall's $W = 0.430$), AP_{vel} ($\chi^2(2) = 8.486$, $p = 0.014$, Kendall's $W = 0.424$), ML_{vel} ($\chi^2(2) = 6.158$, $p = 0.046$, Kendall's $W = 0.308$), and ENV_{area} ($\chi^2(2) = 16.800$, $p < 0.001$, Kendall's $W = 0.840$) between times. Post hoc test showed LNG ($p = 0.016$), AP_{LNG} ($p = 0.011$),and AP_{vel} ($p = 0.016$) after one week was smaller compared to pre-training in the randomly trained group and that ENV_{area} in both post-training ($p = 0.022$) and after one week ($p < 0.001$) was smaller compared to pre-training. For ML_{vel}, there was no significant difference between pre-training and after one week ($p = 0.057$) in the randomly trained group. There was no significant difference for ML_{LNG} ($\chi^2(2) = 5.000$, $p = 0.082$, Kendall's $W = 0.250$) and EF_{area} ($\chi^2(2) = 3.081$ $p = 0.214$, Kendall's $W = 0.154$) among times in the randomly trained group.

Discussion

We focused on force control training and applied the motor learning theory to investigate whether training ankle muscle force control with randomized loads would enhance the transfer and retention of standing balance stability compared to repetitive training at a single force level. The results indicated that training with a randomized order had a positive retention effect on force control accuracy in part. Additionally, it contributed to balance stability metrics such as LNG and ENV area without significant increases in maximum muscle strength. These findings supported our hypothesis that muscle training using variable and randomized forces enhances both the retention of the force control accuracy and the transfer effect for standing balance. The outcomes observed in this study could be explained by the contextual interference (CI) effects in the motor learning theory (Hernández-Guillénet al., 2022; Ivusza et al., 2022). Constant training typically results in low CI, enhances task specificity, and promotes motor skill acquisition (Ivusza et al., 2022; Nachmani et al., 2021). Conversely, training in a randomized order is more difficult than constant training and follows an irregular and unpredictable order, resulting in a high CI effect (Hodges et al., 2022; Nachmani et al., 2021). Moreover, training in a randomized order is considered to have divergent effects, resulting in improved adaptive processes and facilitating transfer to variable tasks (Coelho et al., 2018; Shea et al., 1979). Single-leg standing is intrinsically less stable than bipedal standing owing to its smaller support base, rendering it challenging to anticipate this instability. The ankle strategy is particularly important for anterior-posterior postural control in humans, according to the inverted-pendulum model of postural control (Kasahara et al., 2021). Thus, varied ankle force controls are essential for postural stability during single-leg standing. Compared to the constant training (0.5 Hz), RMSEs of force tracking were enhanced in the random training, involving frequencies of 0.2, 0.5, and 1.0 Hz. Consequently, the enhanced performance in the randomly trained group suggests an augmentation in the redundancy of force control. On the other hand, CI was low in the constant training group, and one force output (i.e., 0.5 Hz) was emphasized, whereas other force outputs may have been slightly overlooked. Therefore, random training may contribute to the generalizability of motor learning and improve the overall force output control of the PF (Schmidt et al., 2011).

For any training, it is natural to desire that its positive effects persist. When aiming to increase maximum strength through muscle training, withdrawal of strength training or loading inevitably results in a loss of gains in strength or motor performance (Kasper, 2019; Vigelsø et al., 2015). According to previous studies regarding the CI effect (Magill et al., 1990; Shea et al., 1979), training in a randomized order is known to have a retention effect on motor learning (Hodges et al., 2022; Ivusza et al., 2022; Nachmani et al., 2020); however, such training has not verified in basic training (e.g., stretching, muscle training, etc.). In this study, both the random and block training groups showed significant immediate and retention effects on force control, demonstrating that both types of training are effective. However, contrary to our hypothesis, no significant differences in RMSE were observed between the two groups in terms of retention effects in this study. Similar to results in this study, several previous studies reported no differences in retention between randomized and blocked practice (Buszard et al., 2017; Magelssen et al., 2022; Ruano et al., 2022). Researchers in these studies considered that the divergence from scientific findings that the randomized practice was of benefit for the retention compared with the blocked practice, which resulted from the characteristics of the force control task and the manipulation of the CI (Buszard et al., 2017; Magelssen et al., 2022; Ruano et al., 2022). Improvement in retention was observed in the CI between skills (Hall et al., 1994) and not in the CI between variation of the same skill (Buszard et al., 2017; Magelssen et al., 2022) like the current study. Also, similarities between force control tasks for training and assessment may affect improvement in retention. Russell and Newell (2007) concluded that randomized practice is essential if the future performance occurs in an open environment, in which the task varies from trial to trial, and the blocked practice is as beneficial as the randomized practice if future performance would occur in a closed environment in which the task remains constant. Therefore, the block and random training groups exhibited comparable outcomes immediately after training.

We prepared two different trainings (constant and random) for ankle strength control to improve balance instability. Both the constant and random training groups demonstrated improvements in balance stability. However, compared to the block training group, the random training group exhibited significant improvements in a greater number of balance-related parameters (Table 2). This finding same as the conclusions of Russell and Newell (2007), who emphasized the necessity of random practice in more open and variable environments. The results of our study further corroborate previous research (Ebisu et al., 2022), highlighting that, compared to block training, random training is more effective in transferring training in simple environments (e.g., ankle strength control) to complex, high-level functional tasks such as balance control. Regarding retention effects, most studies, along with the present study, commonly incorporate retesting sessions after one day or one week to evaluate the retention effect (Cross et al., 2007). Motor memory consolidation refers to offline processes that occur 4–6 hours after training and help stabilize motor memory (Kantak et al., 2010). Kantak et al. suggested that the neural substrate of motor memory consolidation differs depending on the practice structure (constant vs. random) (Kantak et al., 2010). Motor memory consolidation during the randomized order, which is more cognitively challenging, relies on higher-order motor areas, such as the dorsolateral prefrontal cortex (Kantak et al., 2010). Newly established motor neural networks associated with motor memories are consolidated at the cellular/synaptic level for minutes or hours after encoding (synaptic consolidation) (Thomas et al., 2016). Post-encoding reorganization, which involves structural and network changes, occurs over days or years (system consolidation) (Thomas et al., 2016). These suggestions may partially explain our results after one week, where stabilized motor memory may have been used in other motor tasks based on the motor schema (or generalized motor program) theory of motor learning. This perspective is beyond the scope of our study and should be explored in future studies.

There were several limitations in this study. First, our participant pool consisted exclusively of young, healthy individuals who inherently possess high and well-maintained balance abilities. Consequently, the observed positive effects might be attributed, in part, to participants' baseline proficiency in balance. Therefore, these results and training methods should be used with caution for older participants or patients undergoing rehabilitation. Second, only the frequency of the sine waves was manipulated in our training, and the other parameters were fixed. However, velocity is considered the most reliable parameter for postural and motor control (Kasahara et al., 2021). Third, the retesting period of one week may have influenced our results, as participants' daily activities (such as work, sports, and habits) could not be completely controlled due to ethical considerations regarding prolonged monitoring. Nonetheless, participants reported no significant changes in their physical or mental conditions during the week.

In conclusion, our findings in the current study revealed that the nature of the training array plays a pivotal role in the retention and transfer effects of submaximal force control training. Random training in variable and unpredictable situations may be more beneficial for balance performance than constant training.

Acknowledgments

The authors gratefully acknowledge all the participants in this study. We would like to thank Editage (www.editage.jp) for English language editing.

Disclosure Statement

The authors declare that they have no competing interests.

Funding

This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (18K10703 and 22K11321).

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Tables

Table 1. Characteristics of participants

Group	Constant (n = 8)	Randomized (n = 10)	P-value
Age (years)	24.5 ± 2.5	24.0 ± 2.6	0.59
Sex (female/male)	3 / 5	5 / 5	none
Height (cm)	167.6 ± 6.7	168.9 ± 8.4	0.347
Weight (kg)	62.0 ± 12.6	63.2 ± 9.8	0.434

Values are shown as mean ± SD.

Table 2. Comparisons of center of pressure (COP) measurements in each group

	Constantly trained group			Randomly trained group		
	Pre	Post	1 week	Pre	Post	1 week
LNG (cm)	46.1 (38.6, 61.0)	42.8 (36.2, 58.7)	41.2 (33.6,53.6)	48.9 (37.8, 63.4)	44.5 (39.7, 59.1)	41.5 * (35.4, 45.8)
AP_{LNG} (cm)	23.2 (20.9, 31.8)	24.3 (22.4, 40.9)	23.0 (19.4, 31.7)	26.4 (21.4, 37.9)	24.3 (21.5, 35.9)	23.5 * (20.0, 25.1)
AP_{vel} (cm/s)	2.3 (2.1, 3.2)	2.4 (2.2, 4.1)	2.3 (1.9, 3.2)	2.6 (2.1, 3.8)	2.4 (2.1, 3.6)	2.3 * (2.0, 2.5)
ML_{LNG} (cm)	33.8 (28.3, 42.5)	29.7 (25.4, 35.7)	29.4 (22.2, 37.5)	35.5 (27.9, 44.5)	33.8 (30.6, 39.4)	29.7 (25.0, 31.4)
ML_{vel} (cm/s)	3.4 (2.8, 4.2)	3.0 (2.5, 3.6)	2.9 (2.2, 3.8)	3.6 (2.8, 4.5)	3.4 (3.1, 3.9)	3.0 (2.5, 3.1)
ENV_{area} (cm^2)	13.2 (9.6, 20.7)	4.6 * (3.5, 7.1)	3.2 * (2.4, 4.0)	16.8 (12.1, 22.1)	4.5 * (4.0, 6.2)	3.3 * (2.4, 4.7)
EF_{area} (cm^2)	2.6 (1.6, 4.0)	2.8 (2.2, 5.6)	2.2 (1.5, 2.7)	3.5 (2.2, 3.9)	2.6 (2.3, 3.1)	2.0 (1.3, 2.7)

Values are presented as median (first quartile, third quartile) deviation. LNG, the total length of COP displacements; AP, anterior-posterior; ML, mediolateral; ENV_{area}, environmental area; EF_{area}, effective area. * represents significant differences from pre-training values ($p < 0.05$).

Figure legends

Figure 1. Experimental setup and procedure.

(A) Participants on Biodex performed an online force-tracking task with plantar flexors. (B) Visual feedback information regarding the target force and the actual isometric muscle force was supplied online to participants from a PC monitor. Note that the vertical scale was removed to avoid the prediction and memory of the force pattern for the participants. PF: plantar flexors.

Figure 2. Force order and COP trajectory during single-leg standing.

(A) The force tracking test includes three randomized cycles. (B) Constant training includes nine cycles at 0.5 Hz. (C) Typical random training includes 3 × 3 cycles arrayed at three frequencies at 0.2, 0.5, and 1.0 Hz randomly. (D) and (E) Representative environmental and effective areas (thick line) during single-leg standing. The thin line represents the COP trajectory. COP: center of pressure, PF: plantar flexion, AP: anterior-posterior, ML: medial-lateral.

Fig.1

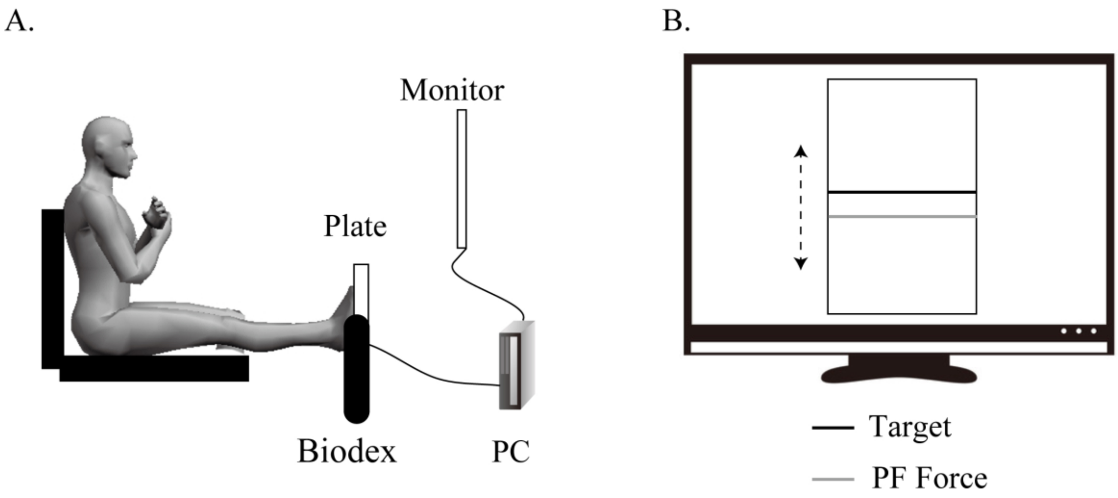
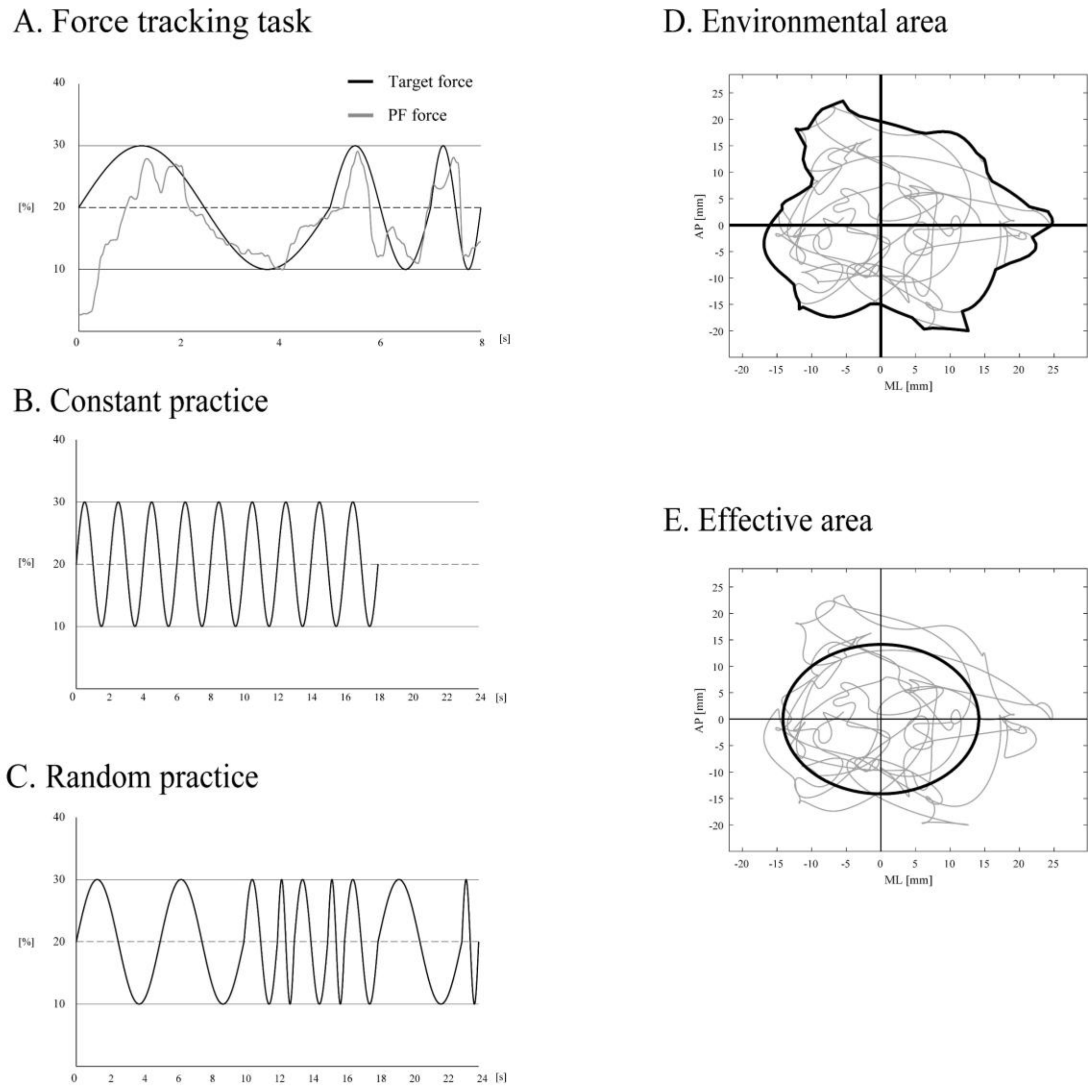


Fig.2


A. Force tracking task
Target force
PF force
[%]
[s]
B. Constant practice
[%]
[s]
C. Random practice
[%]
[s]
D. Environmental area
AP [mm]
ML [mm]
E. Effective area
AP [mm]
ML [mm]