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Plantar intrinsic foot muscle activity and its relationship with postural sway during single-legged and bipedal tiptoe standing in ballet dancers

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During tiptoe standing, especially with the single-legged support, the foot joints in ballet dancers are heavily loaded. Thus, the activity of the plantar intrinsic foot muscles (PIFMs), which stabilize the foot joints, may be important in reducing postural sway during tiptoe standing. We compared PIFM activity during single-legged and bipedal tiptoe standing and examined its relationship to postural sway in dancers. In 11 female ballet dancers, the electromyography (EMG) amplitudes of PIFMs and the center of pressure (COP) data were recorded during single-legged and bipedal tiptoe standing tasks. The EMG amplitudes were normalized to those during the maximal voluntary contraction, and PIFM activity level and its coefficient of variation over time (EMG-CV$_{time}$) during the task were assessed. From the COP data, standard deviations in the anteroposterior (COP-SD$_{AP}$) and mediolateral (COP-SD$_{ML}$) direction, velocity, and area were calculated. PIFM activity level and COP velocity were 2–2.5-fold higher in the single-legged than bipedal task ($p \le 0.003$). Significant correlations were found between PIFM activity level and COP velocity ($r = 0.666$, $p = 0.025$) and between EMG-CV$_{time}$ and COP-SD$_{AP}$ or COP-SD$_{ML}$ ($r \ge 0.738$, $p \le 0.010$) only in the single-legged task. These results suggest that PIFM activity is associated with postural sway, especially during single-legged tiptoe standing in dancers.

Keywords High-density electromyography, Temporal variability, Postural sway, Center of pressure, Foot

Reducing postural sway during tiptoe standing ("demi-pointe" in ballet terminology) is essential for ballet dancers (hereafter referred to as "dancers")[1,2]. In particular, single-legged tiptoe standing (STS) is frequently employed in ballet choreography because the unsupported leg can be used for a variety of expression. During STS, dancers are required to maintain a high and stable foot arch structure in the supported leg, which is also aesthetically desirable[3,4]. In situations of unloaded or minimal loading, the foot arch structure is primarily supported by passive and non-contractile components (e.g., bones, ligaments, plantar fascia, etc.)[5]. However, in situations of high postural demands or heavy foot loading, stabilization of the foot arch structure is not achieved sufficiently by these passive components alone, and muscle-generated forces play an important complementary role[6,7]. In addition, during STS, where the base of support is very narrow, excessive loads are placed on the foot—the sole point of contact with the floor, and this may increase the risk of overuse injuries such as stress fractures or tendinopathy[4,8]. Given that the foot joints of dancers are particularly characterized by hypermobility[9,10], the activity of the muscles that contribute to joint stability may play a critical role in controlling postural sway during STS.

The plantar intrinsic foot muscles (PIFMs), which originate and insert within the foot, function in the stability or mobility of the foot joints[5,6,11–13]. Electromyography (EMG) studies in non-dancers have shown that PIFM activity increases or decreases in response to postural demands or foot loading; PIFM activity level is significantly higher in single-legged standing, bipedal tiptoe standing (BTS), and STS compared to bipedal standing[6,14]. Recent studies also suggest that the primary role of PIFMs during standing is to stabilize the foot joint (i.e., indirectly contribute to postural control) due to their short moment arms[5,15,16]. Although proximal

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muscles around the hip joint and trunk contribute to postural control during tiptoe standing[17], there is little information on how PIFMs activity is associated with postural sway during tiptoe standing performed by dancers. Our previous study showed that dancers had much less postural sway and lower level/variability of PIFM activity during BTS, compared to non-dancers[18]. This suggests that BTS is not a high postural demand or load for dancers and that low and steady PIFM activity is associated with less postural sway. However, due to the wide base of support in BTS, PIFM activity may play a less dominant role in postural control compared to STS. Comparing STS and BTS for postural sway and PIFM activity as well as their relationships may provide insights into a specific role of PIFMs during STS that dancers often perform.

The tiptoe standing that dancers perform in daily practice and on stage requires a large ankle plantar flexion (PF) angle, which is not achievable in non-dancers, and this is even more so during STS[9,10,18]. When comparing muscle activity between individuals/conditions and examining its relationship to other parameters such as postural sway, a well-controlled task setting with the specified/same joint angle is appropriate[19,20]. In fact, our previous study found that PIFM activity and postural sway during BTS differed among different ankle PF angles, and the relationships between these variables were also different depending on the ankle PF angle[18]. Thus, comparing PIFM activity between STS and BTS, as well as examining its relationship with postural sway, at a large and specified ankle PF angle will shed light on dancers' postural control during tiptoe standing. However, this has never been studied. Some previous studies have used intramuscular EMG to examine PIFM activity[6,7,14], but there are difficulties in using this technique due to its invasive nature, especially considering its potential detrimental effect on the dancers' subsequent performance. This study therefore adopted high-density EMG using a grid with multiple surface electrodes, which can noninvasively record PIFM activity across a large region of the plantar foot[15,18,21].

The objectives of this study were to compare PIFM activity and postural sway as well as their relationship between STS and BTS in dancers. We hypothesized that (1) PIFM activity (its level and temporal variability) and postural sway would be significantly higher during STS than during BTS, and (2) PIFM activity would be associated with postural sway during both STS and BTS but especially the former.

Methods

Participants

Eleven female ballet dancers (age: 25.1 ± 2.3 y, height: 163.9 ± 6.3 cm, body mass: 47.9 ± 4.9 kg, BMI: 17.8 ± 1.2 kg/m^2) were enrolled in this study. The participants were the same as those in our recent publication[18], which compared postural sway and PIFM activity during BTS in dancers versus non-dancers ($n = 14$ vs. 13). This study reports original data for STS that was performed by eleven dancers only, while deriving the data from our previous study for BTS performed by the same eleven dancers. Although a power analysis was not performed, the exploratory nature of the study and the limited pool of eligible dancers led us to consider a sample size of 11 as both practical and sufficient. Dancers needed to have an at least 10 years of ballet experience and still receive at least 7.5 h of ballet training per week. None of the participants had a history of injury or surgery in the ankle and foot joints within the past 3 months or 1 year, respectively. All participants self-reported that they were right-dominant. The study protocols complied with the principles of the Declaration of Helsinki and were approved by the Ethics Committee of Ritsumeikan University (BKC-LSMH-2021-048), and all participants provided written informed consent.

Experimental protocol

The postural control task consisted of BTS for 30 s and STS (right leg) for 10 s, both at ankle PF 60°[15,18,21–23]. The ankle PF 60° was selected in this study after pilot experiments confirmed that all dancers who participated in the study were able to achieve this angle or a close to it in trials. Electric goniometers (SG110, Biometrics, UK) were applied to measure ankle PF angles during the postural control tasks. The stationary arm of the goniometer was aligned with the long axis of the fibula in the sagittal plane, while the moving arm was aligned with the plantar plane on the side of the little toe (i.e., fifth metatarsal bone) and attached to both feet. Note that the ankle PF angle is the sum of the talocrural joint and several foot joints (Chopart's joint, Lisfranc's joint, etc.). The visual feedback of the goniometer data of each foot was provided in real time via two 16-bit A/D converters (PowerLab 2/20; ADInstruments, Australia) and on two PC monitors located at participants' eye level, approximately 1 m in front of them (Fig. 1A)[18,22]. During the STS task, the goniometer on the left (unsupported) leg was removed. Participants initially stood on a force plate (SS-FP40AO-SY, Sports Sensing, Japan). In the BTS task, they began tiptoe standing while holding the bar in front of themselves with their hands, and then removed their hands from the bar after they were able to maintain the PF angles of both feet at the specified angle as much as possible by watching the monitor so that the body mass on both feet was equal. During the BTS task, they kept both feet parallel at a comfortable stance width, with the knees fully extended, and hands relaxed on the sides of the body. In the STS task, participants started the right leg tiptoe standing with both hands holding the bar, and when they were able to maintain the PF angle at the specified angle as much as possible while watching the monitor, they removed their hands from the bar. During the STS task, the right leg was maintained in optimal turnout (i.e., external rotation of the lower limb), the left leg in retiré (i.e., the left small toe on the knee joint of the right leg), and the upper limb in en avant (i.e., the upper limbs in a circular position with both fingertips in front of the trunk) (Fig. 1B). Considering the degree of postural demand, trials were performed in the order of the BTS task and then STS task, as performing STS first could induce fatigue and affect subsequent performance. To minimize potential order effects, familiarization trials were conducted beforehand, and participants performed three trials per task with at least 1 min of rest between trials. The average data from three successful trials were used in the data analysis. A successful trial was defined as one in which the participant was able to maintain the specified angle without grasping the bar or stepping out during the trial.

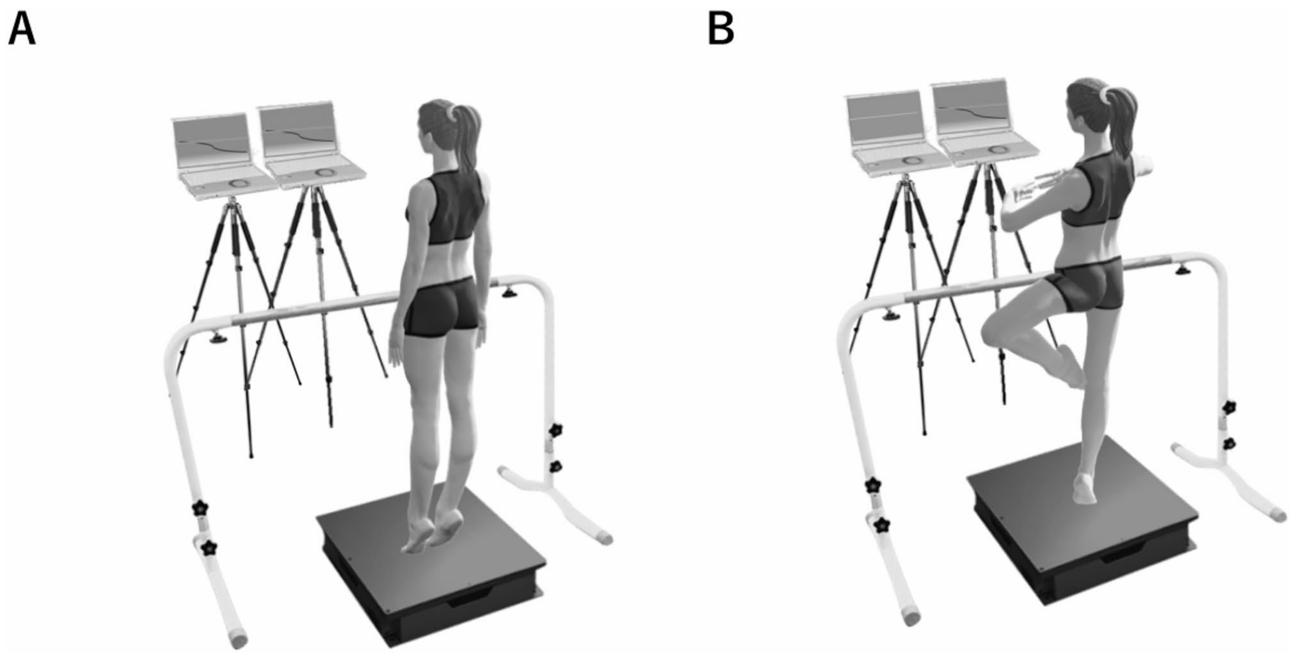

Fig. 1. The experimental setup. **A** During bipedal tiptoe standing, the ankle plantar flexion angles of both feet, measured using goniometers, were shown as real time visual feedback on two PC monitors. **B** During single-legged tiptoe standing, the right leg was maintained in optimal turnout (i.e., external rotation of the lower limb, the left leg in retiré (i.e., left small toe on the knee joint of the right leg), and the upper limb in en avant (i.e., upper limb in a circular position with both fingertips in front of the trunk). The feedback of ankle plantar flexion angle during single-legged was only for the right leg.

Data acquisition

Monopolar surface EMG amplitudes from the PIFMs were acquired with a high-density grid of 64 channels (GR08MM1305, OT Bioelettronica, Italy) consisting of 13 rows and 5 columns (minus one electrode) with an 8 mm inter-electrode distance in both directions (Fig. 2A), in accordance with prior studies[15,18,21]. The right plantar skin was lightly rubbed with sandpaper and cleaned with alcohol. After palpation of the heel and metatarsal fat pads, a high-density grid was placed in the center of these areas, aligned with the long axis of the foot (i.e., second metatarsal) (Fig. 2B)[15,18,21]. The grid was reinforced with tapes to ensure consistent contact with the sole at any ankle PF angle during the tasks. Reference electrodes were placed around the right knee and left wrist. The acquired amplitudes were amplified using a 16-bit analog-to-digital converter (Quattrocento; OT Bioelectronica, Italy), with a sampling frequency of 2048 Hz and a bandpass filter of 10–500 Hz (Fig. 2C). During the tasks, the COP data were acquired using the force plate and a 16-bit A/D converter (PowerLab/16SP; ADInstruments, Australia) with a sampling frequency of 1000 Hz and a low-pass filter of 5 Hz. Additionally, participants performed 5-s maximum voluntary contractions (MVCs) against manual resistance provided by one researcher twice for each of toe flexion (all toes) and toe abduction (the great and little toes), during which EMG were recorded[14,18,24]. The reliability of the EMG measurements during MVC was assessed using the intraclass correlation coefficient (ICC), which ranged from 0.783 to 0.986 (ICC (3,1)), indicating high consistency.

Data analysis

The EMG amplitude and COP data were synchronized using a trigger from a 16-bit A/D converter (PowerLab/8SP; ADInstruments, Australia). The analysis interval was 20 s excluding the first 5 s from the start of the task in the BTS task and 5 s excluding the first 2.5 s from the start of the task in the STS task. EMG signals recorded from 64 electrodes were visually inspected, and channels showing noise were reconstructed based on the interpolation of the signals from neighboring channels[15,18,21]. For each channel, the EMG root-mean-square (RMS) values during the tasks were calculated and normalized to the highest value over a 500-ms time window during the MVC tasks. The normalized EMG values were averaged across 64-channels[15,18,21], and used as a criterion value for PIFM activity level (% MVC). From the EMG amplitude, the coefficient of variation over time (EMG-CV_{time}) during the tasks was also calculated to evaluate the temporal variability of PIFM activity level. This was calculated by dividing the standard deviation (SD) by the mean of the EMG amplitudes during the analysis interval for each channel and then averaging over all 64 channels[18,25,26]. From the COP data, the SD in the anteroposterior and mediolateral directions (COP-SD_{AP} and COP-SD_{ML}), average velocity (COP-Velocity), and area of a 95% confidence ellipse encompassing the COP (COP-Area) were further calculated for the analysis interval as indices of postural sway[18,27,28].

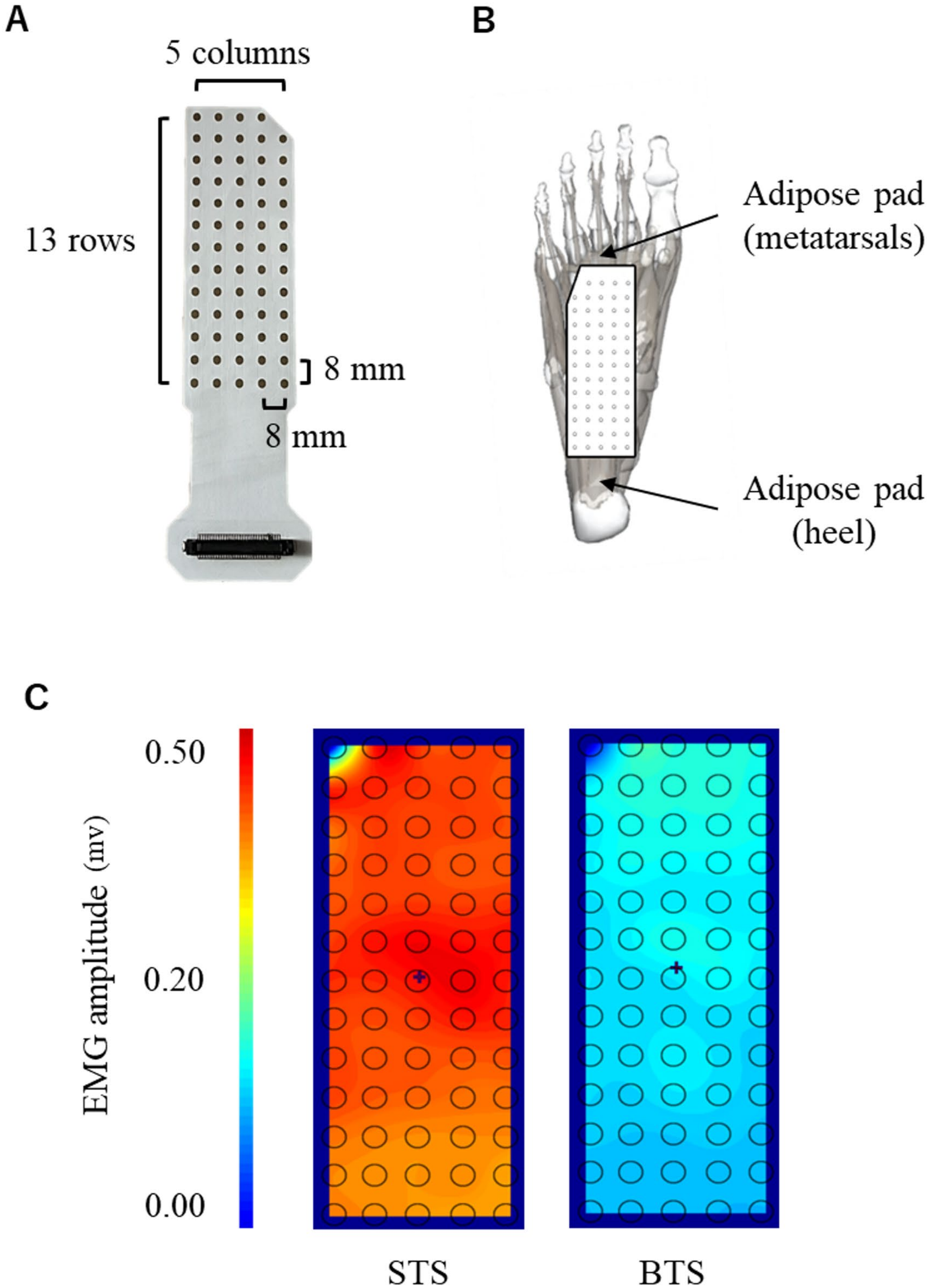

Fig. 2. High-density grid and its application position on the foot. **A** The high-density grid comprising 13 rows and 5 columns, with 8 mm distance between electrodes (except for one electrode at the apical corner on the little toe side). **B** The grid was placed between the metatarsal head and heel adipose pads on the plantar surface. The foot image was created using "BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan. **C** Color maps showing representative high-density EMG amplitudes in the single-legged tiptoe stranding (STS) and bipedal tiptoe standing (BTS). The point near the center of the color map (cross mark) indicates the barycenter of electromyographic activity.

Statistical analysis

For all variables, the Shapiro-Wilk test was applied to assess normality, which was confirmed for all variables except for PIFM activity level and EMG-CV_{time} in the BTS task, and COP-Area in the STS task. Therefore, between-task comparisons were made by Wilcoxon's signed rank test for these non-normally distributed variables, and by paired *t*-tests for the other variables. Effect sizes of between-task differences were calculated as Cohen's *d* values and were interpreted as trivial < 0.2; small 0.2–0.49; moderate 0.5–0.79; and large ≥ 0.8[29]. Additionally, their bootstrap 95% confidence interval (5000 samples, bias-corrected and accelerated) was assessed by using estimation statistics to improve statistical inference[30]. To evaluate the relationship between COP variables and EMG variables in each task, Pearson's correlation coefficient and Spearman's rank correlation coefficient were calculated for normally and non-normally distributed data, respectively. When EMG and COP variables showed a significant correlation in either task, the differences in the correlation coefficients between STS and BTS tasks were statistically assessed by an online resource (http://comparingcorrelations.org[31] in which Meng et al.'s[32] *z* test was used). Values were considered statistically significant at $p < 0.05$. All data were analyzed using SPSS software (SPSS Statistics 28, IBM, USA) unless otherwise stated.

Results

Compared to the BTS task, the STS task had significantly higher COP-Velocity (BTS vs. STS, 2.0 ± 0.3 vs. 5.1 ± 0.4 cm/s, $p<0.001$, $d = 8.77$, Fig. 3C) and PIFM activity level (11.4 ± 2.8 vs. 25.8 ± 7.8%MVC, $p = 0.003$, d = 2.47, Fig. 4A). There was no significant difference between tasks in the other variables ($p = 0.093$–0.941, $d =$ 0.05–0.61, Figs. 3 and 4).

In the STS task, significant correlations were found between PIFM activity level and COP-Velocity ($r = 0.666$, $p = 0.025$), between EMG-CV_{time} and COP-SD_{AP} ($r = 0.846$, $p = 0.001$), and between EMG-CV_{time} and COP-SD_{ML} ($r = 0.738$, $p = 0.010$) (Table 1). In the BTS task, no significant correlation was found between any combinations of the variables ($r = 0.097$–0.559, $p = 0.074$–0.778, Table 1). The magnitude of the correlation coefficient between EMG-CV_{time} and COP-SD_{AP} was statistically significantly different between STS and BTS (i.e., $r = 0.846$ vs. 0.097, $z = -2.185$, $p = 0.029$).

Discussion

The main findings of this study are as follows: (1) COP-Velocity and PIFM activity level were higher in the STS than BTS task, and (2) significant correlations were found between COP and EMG variables only in the STS task. These results partially support our hypothesis and suggest that foot loading and postural demands are increased during STS compared to BTS, and that PIFM activity is particularly associated with postural sway during STS in dancers.

In the present study, among the four COP variables, only COP-Velocity was significantly higher in the STS than in the BTS task, with an average difference of 2.6-fold, and this pattern was consistent across all dancers (Fig. 3C). COP-Velocity, which reflects the average displacement of the COP per second irrespective of direction, has often been interpreted as a general index of postural sway[27,28]. Given that tiptoe standing inherently restricts the base of support and alters the alignment of the center of gravity[33,34],the higher COP-Velocity during STS suggests elevated postural demands even for trained dancers. In contrast, no significant differences were found in COP-SD_{AP}, COP-SD_{ML}, or COP-Area between the tasks; some showed higher values, while others showed lower values during the STS than BTS task. This variability may reflect the diversity of individual adaptations in postural control to higher task difficulty, which may be influenced by differences in neuromuscular control patterns (e.g., ankle or hip strategies)[34] or foot shape and structure[35,36]. Although COP-Velocity may be useful as a general index of the amount of sway in such tasks as tiptoe standing, it does not capture the directional or temporal aspects of the sway. Future studies may therefore benefit from incorporating complementary indices

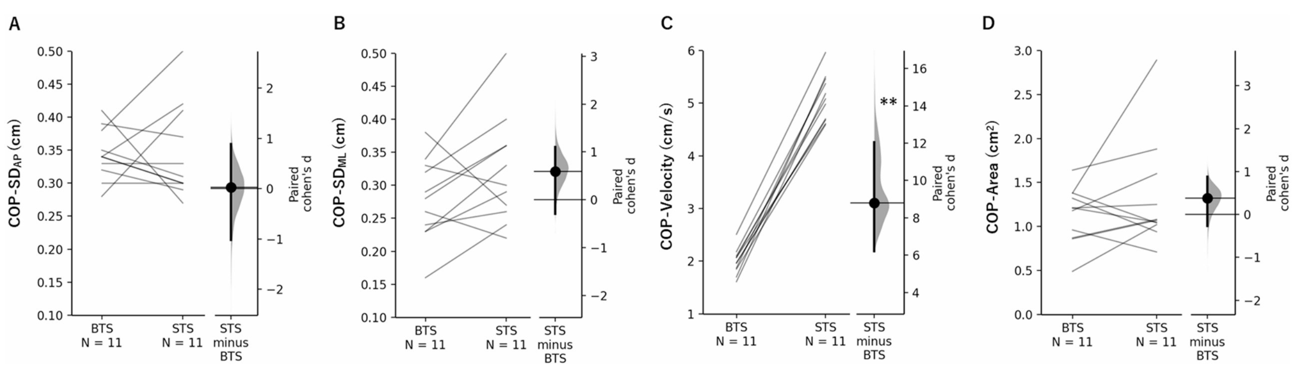

Fig. 3. Comparisons of COP variables (**A** COP-SD_{AP}, **B** COP-SD_{ML}, **C** COP-Velocity, **D** COP-Area) between bipedal tiptoe standing (BTS) and single-leg tiptoe standing (STS). On the right axes, paired Cohen's *d* values are plotted as boot strap sampling distributions. Mean Cohen's *d* values are depicted as dots with horizontal lines; 95% confidence intervals are indicated by the ends of the vertical error bars. Significant differences between groups are indicated as $^{**}p<0.01$. *COP* center of pressure; *SD* standard deviation; *AP* anteroposterior; *ML* mediolateral.

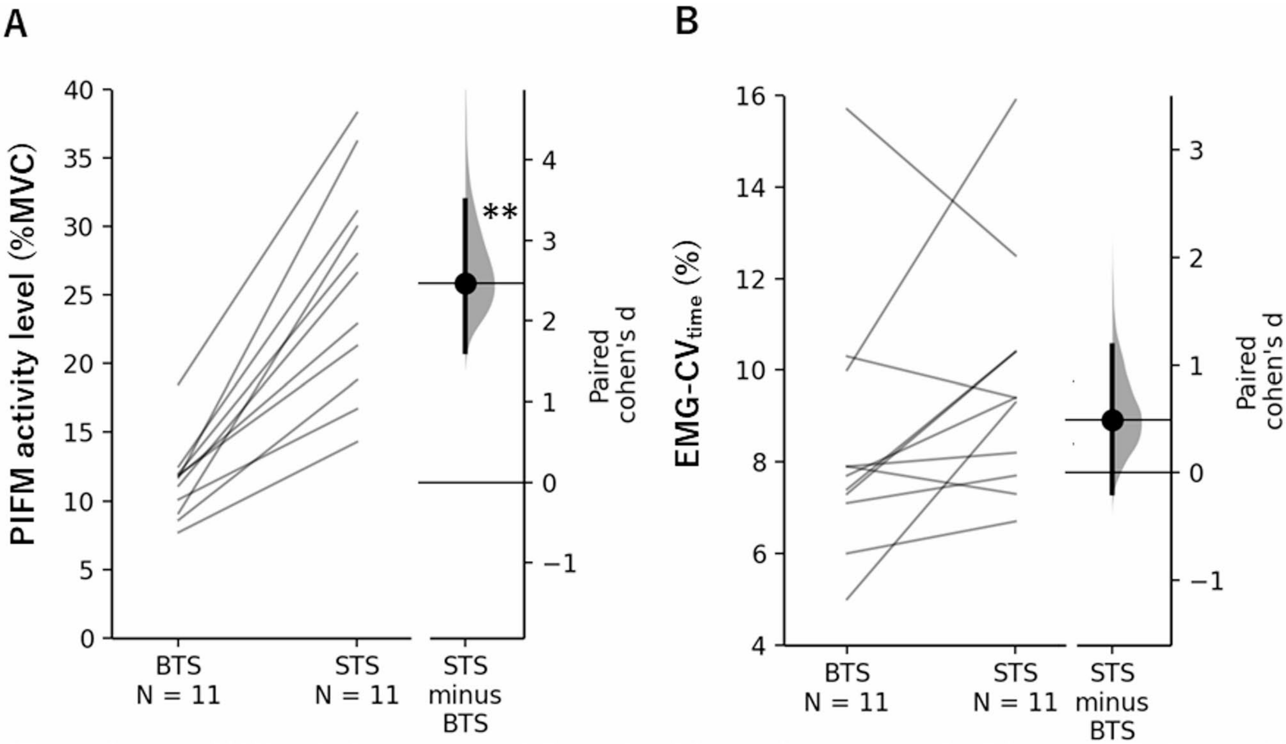

Fig. 4. Comparisons of EMG variables (**A** PIFM activity level, **B** EMG-CV$_{time}$) between bipedal tiptoe standing (BTS) and single-legged tiptoe standing (STS). On the right axes, paired Cohen's d values are plotted as boot strap sampling distributions. Mean Cohen's *d* values are depicted as dots with horizontal dashed lines; 95% confidence intervals are indicated by the ends of the vertical error bars. Significant differences between groups are indicated as $^{**}p<0.01$. PIFM, plantar intrinsic foot muscle; EMG-CV$_{time}$, temporal variability of EMG.

		PIFM activity level (%MVC)				**EMG-CV$_{time}$ (%)**		
COP	Position	*r*		*p*		*r*		*p*
SD_{AP} (cm)	BTS	0.174		0.608		0.097		0.778
	STS	0.083		0.808		0.846	**	0.001
SD_{ML} (cm)	BTS	−0.210		0.536		0.340		0.306
	STS	−0.037		0.913		0.738	**	0.010
Velocity (cm/s)	BTS	0.282		0.400		0.559		0.074
	STS	0.666	*	0.025		0.499		0.118
Area (cm^2)	BTS	0.000		1.000		0.362		0.275
	STS	−0.191		0.574		0.301		0.368

Table 1. Correlation coefficients between COP and EMG variables. Significance of Pearson's correlation coefficient and Spearman's rank correlation coefficient are indicated as follows: $^{*}p<0.05$, $^{**}p<0.01$. *COP* center of pressure; *SD* standard deviation; *AP* anteroposterior; *ML* mediolateral; *PIFM* plantar intrinsic foot muscle; *EMG-CV$_{time}$* temporal variability of EMG; *BTS* bipedal tiptoe standing; *STS* single-legged tiptoe standing.

such as boundary reaching time, which has been shown to be sensitive to changes in stability, especially in tasks with a reduced base of support[37].

PIFM activity level (% MVC) in the STS task was significantly higher than in the BTS task by 2.2-fold on average, and this was also consistent for all dancers (Fig. 4A). A study examining PIFM activity level in non-dancers reported that it was 1.5 to 1.7-fold higher in STS compared to BTS[14]. However, the tasks in that study were not compared robustly because the participants (all participants during STS and half during BTS) lightly touched a wall or other objects during postural control, and the ankle joint PF angle was not specified[14]. Since the body mass load on the foot is simply twice as heavy with the single-legged compared to bipedal support, it makes sense to assume that most of this difference in PIFM activity level is related to the greater foot loading. On the other hand, the correlation analysis showed that PIFM activity level was positively correlated with COP-

Velocity ($r=0.666$) only in the STS task, suggesting that activity level was indeed associated with postural sway particularly during STS. Due to the short moment arm of PIFMs, they do not generate joint torques in response to large perturbations (i.e., they are not a direct factor in reducing postural sway), and it has been suggested that they are mainly involved in stabilizing the arch structure of the foot[5]. Previous studies have also shown that higher PIFM activity is associated with greater postural sway[6,14,18]. Therefore, this result supports the findings of previous studies that PIFM activity is associated with postural sway.

Contrary to our expectations, EMG-CV_{time} did not significantly differ between tasks ($p=0.142$), although STS on average had a 1.2-fold higher value with a borderline small/moderate effect size (d = 0.49) (Fig. 4B). Higher and lower values of EMG-CV_{time} reflect greater neuromuscular fluctuation and greater steadiness[25,26], respectively, and therefore we expected it to be higher for STS than BTS. These results suggest that in dancers, although PIFM activity is higher during STS than BTS, its activity is similarly steady during both STS and BTS at their respective levels. It is worth mentioning that our previous study[18] also found no significant differences in EMG-CV_{time} during BTS performed at 20°, 40°, and 60° in dancers, while PIFM activity level was significantly higher for 60° than 20°, which is in line with the EMG findings of this study.

Also, EMG-CV_{time} showed a strong positive correlation with COP-SD_{AP} and COP-SD_{ML} only in the STS task ($r=0.846$ and 0.738, Table 1). These may suggest that PIFM activity is associated with postural sway in both directions during STS in dancers, and that these indices are sensitive to each other in the STS condition, although caution is needed when interpreting the results as correlation does not imply causation. A previous study has shown that PIFM activity during single-legged standing (with the heel on the floor) in non-dancers is synchronized with COP sway only in the mediolateral direction[6]. The reason for this discrepancy may be partly attributed to the participants being dancers vs. non-dancers, but may also be explained by the combined motion of foot joints and the function of windlass mechanism due to the difference in the limb position. The foot joints have a flexibly shape-changing structure[5,38], and in single-legged standing, each joint responds in a coordinated manner to postural sway, primarily in the frontal plane (i.e., mediolateral direction). For example, eversion of the subtalar joint in the hindfoot causes the combined motion such as inversion of the Chopart's and Lisfranc's joint in the mid/forefoot (and vice versa), resulting in a lowering/collapse of the medial longitudinal arch[13,39,40]. In tiptoe standing, on the other hand, the plantar fascia covering the calcaneus to the toes is tensed as the metatarsophalangeal joint is extended, resulting in the windlass mechanism that raises the medial longitudinal arch and increases joint stiffness of the foot; when this mechanism functions, the joints of the foot are unified, thus the aforementioned combined motion is reduced[41]. Although we do not have any data regarding these potential mechanisms, the present findings support recent suggestions that PIFMs are more actively involved in the windlass mechanism than previously considered[11,42–44], and add that their less variable (i.e., steadier) activity is associated with less postural sway during STS in dancers.

Limitations

This study had a relatively small sample size ($n=11$), due to difficulty in recruiting professional/high-level dancers, potentially reducing statistical power. For example, our previous study[18] with a slightly larger sample size ($n=14$) than this study found EMG-CV_{time} to be positively correlated with COP-Velocity in the BTS task, which was not the case in either task in this study. However, importantly, even with the small sample size of this study, we found significant differences between BTS and STS for all the main variables (i.e., PIFM activity, postural sway, and their relationship), and we consider that the main findings would remain the same if more dancers had been recruited. Nevertheless, more work with a much larger sample size is needed especially when examining inter-individual variability in neuromuscular and postural control measures.

Furthermore, both tasks in this study were compared only at the ankle PF joint angle of 60°, and it is unknown whether the results are generalizable to other PF joint angles. Future research should address this issue from multiple perspectives, including kinematics and kinetics, and independently evaluate the loading effect to clarify the contribution of PIFM to the stabilization of the foot arch structure. Moreover, incorporating assessments such as joint stiffness, plantar fascia tension, and the windlass mechanism will be essential to verify whether the characteristics of PIFM activity during tiptoe standing represent dancer-specific adaptations. Finally, we expect that reducing postural sway during tiptoe standing may contribute to reducing the risk of lower limb injuries in dancers, and biofeedback training aimed at controlling postural sway[45] and muscle activity[46] appears a promising strategy. Future research should be directed towards exploring this longitudinally.

Conclusion

In summary, PIFM activity level and postural sway were higher during single-legged than bipedal tiptoe standing in dancers, likely due to increased foot loading and postural demands. The findings of the correlations between EMG and COP variables provide new evidence that PIFM activity is associated with postural sway during tiptoe standing in dancers, especially performed on a single leg.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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H.F. and S.M.: Investigation, Resources, Writing original drafts. Y.K. and T.I.: Formal analysis, Visualization, Formal analysis. Data curation.

Declarations

Competing interests
The authors declare no competing interests.

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