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Recruitment of the plantar intrinsic foot muscles with increasing postural demand

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ABSTRACT

Background: The aim of this study was to determine the difference in activation patterns of the plantar intrinsic foot muscles during two quiet standing tasks with increasing postural difficulty. We hypothesised that activation of these muscles would increase with increasing postural demand and be correlated with postural sway.
Methods: Intra-muscular electromyographic (EMG) activity was recorded from abductor hallucis, flexor digitorum brevis and quadratus plantae in 10 healthy participants while performing two balance tasks of graded difficulty (double leg stance and single leg stance). These two standing postures were used to appraise any relationship between postural sway and intrinsic foot muscle activity.
Findings: Single leg stance compared to double leg stance resulted in greater mean centre of pressure speed (0.24 m s^{-1} versus 0.06 m s^{-1}, respectively, $P \leq 0.05$) and greater mean EMG amplitude for abductor hallucis ($P \geq 0.001$, ES = 0.83), flexor digitorum brevis ($P \leq 0.001$, ES = 0.79) and quadratus plantae ($P \leq 0.05$, ES = 0.4). EMG amplitude waveforms for all muscles were moderate to strongly correlated to centre of pressure (CoP) medio-lateral waveforms (all $r \geq 0.4$), with muscle activity amplitude increasing with medial deviations of the CoP. Intra-muscular EMG waveforms were all strongly correlated with each other (all $r \geq 0.85$).
Interpretations: Activation of the plantar intrinsic foot muscles increases with increasing postural demand. These muscles are clearly important in postural control and are recruited in a highly co-ordinated manner to stabilise the foot and maintain balance in the medio-lateral direction, particularly during single leg stance.

1. Introduction

Upright stance has been described as an unstable inverted pendulum, where continuous small fluctuations in body position (postural sways) are accompanied by bursts of lower limb muscle activity (Tokuno et al., 2007). The majority of muscular activity during quiet stance appears to occur in the ankle plantar flexors and is associated with anterior–posterior body sway (Winter, 1995). However, given that weakness in the plantar intrinsic foot muscles has previously been implicated as a contributing factor to balance impairment (Menz et al., 2005; Mickle et al., 2009), it is likely that these muscles are also involved in maintaining balance and as such, they may be significant in postural control.

The plantar intrinsic foot muscles are a unique group of muscles, with both origins and insertions contained within the foot. It has been proposed that these muscles provide structural support for the medial arch of the foot (Basmajian and Stecko, 1963) however their precise function remains unclear (Kura et al., 1997). It has been proposed that weakness and dysfunction of these muscles can contribute to clinical pathologies such as plantar fasciitis (Wearing et al., 2006), hallux valgus (Arinci-Incel et al., 2003), and medial tibial stress syndrome (Senda et al., 1999), through a reduced ability to control foot pronation (Headlee et al., 2008).

Early intramuscular electromyographic (EMG) studies (Gray and Basmajian, 1968; Mann and Inman, 1964) suggested that the plantar intrinsic foot muscles act as a functional unit to stabilise the toes during the push off phase of gait, as well as providing resistance to subtalar joint pronation. These early reports provided valuable insight into the function of these muscles. However, evidence of electrode location and sufficient detail of the procedures used to acquire and process the EMG signals were not provided. More recently, surface EMG evaluation of the plantar intrinsic foot muscles has provided some evidence for their role in maintaining the height of the medial longitudinal arch (Fiolkowski et al., 2003) and reducing foot pronation (Headlee et al., 2008) during static stance. These studies are, however, limited by the inability of surface EMG electrodes to capture the individual activity of small, deep and underlying musculature. As such, their conclusions were drawn from the larger and more superficial abductor hallucis (AH). Given the methodological limitations of existing literature, combined with the lack of data pertaining to the role of the plantar intrinsic foot muscles in postural support, it is judicious to use ultrasound guided EMG to provide reliable and accurate recordings of these muscles during basic postural tasks.

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Therefore, the aim of this study was to determine the difference in activation patterns of three plantar intrinsic foot muscles, during two standing tasks with increasing postural difficulty. Recording of specific patterns of activation from these muscles was achieved using ultrasound guided intramuscular EMG. We hypothesised that these muscles would be active during stance and that their level of activation would be regulated in response to postural demand.

2. Methods

2.1. Participants

Ten healthy male participants (mean (SD) for age 33 (4) yr; mass: 76 (4) kg; height: 181 (4) cm) with no history of diagnosed neuromuscular disorder or lower limb injury in the previous six months volunteered to participate in the study. All subjects were informed of the study requirements, benefits and risks before giving written informed consent. All procedures conformed to the standards set by the Declaration of Helsinki and the protocol was approved by the scientific research ethics committee of ASPETAR, Qatar Orthopedic and Sports Medicine Hospital.

2.2. Experimental design

2.2.1. Postural tasks

Two quiet standing postures with varying degrees of difficulty (double leg stance, DLS; and single leg stance, SLS) were used to appraise any relationship between postural sway and intrinsic foot muscle activity, measured using fine-wire intramuscular electromyography (EMG). The DLS trial was performed once only, for a 120-s period, while the more difficult SLS trial was performed three times, each for a 60-s period.

2.2.2. Data collection

2.2.2.1. Balance measurements. The DLS and SLS postural trials were performed with the subject standing on a force platform (Type 9286AA Kistler, Zurich, Switzerland) facing forward with their eyes open and arms folded across their chest. Two strips of adhesive tape were placed on the force plate, measuring 15 cm apart and extending from the posterior to anterior edge. During the DLS trial, subjects were asked to align the medial aspect of their heel and forefoot (left and right foot) along the corresponding pieces of tape. For the SLS trial, subjects placed their foot in the middle of the force plate parallel with the previously mentioned strips of tape. This procedure was employed to maintain consistency of foot placement between subjects and trials.

2.2.2.2. Electromyography (EMG). Identification of the abductor hallucis, flexor digitorum brevis (FDB) and quadratus plantae (QP) muscles was conducted using real-time ultrasound imaging (12 Hz, linear array, Siemens Acuson Antares, USA) in the right foot of each subject. An acupuncture needle (0.3 × 50 mm, Seirin, Shizuoka, Japan) was inserted into the muscle of interest through the medial aspect of the foot, while continuously imaging the muscle. The acupuncture needle was used as a guide to determine the correct angle and depth for when the fine-wire electrode was to be inserted later. Unlike fine-wire delivery needles, the acupuncture needle could be retracted and repositioned with minimal discomfort to the participant, until the tester was satisfied that it was located within the appropriate muscle. Subsequently, bi-polar fine-wire electrodes (0.051 mm stainless steel, Teflon coated, Chalgren, USA) with a detection length of 2 mm and inter-electrode distance of approximately 2 mm were inserted using delivery needles (0.5 mm × 50 mm) into the bellies of AH, FDB and QP under ultra sound guidance, using the angle and depth of the acupuncture needle as a guide for correct placement. The size of the active area and separation between sites was chosen to give the best chance of recording representative activity from each muscle, while reducing the possibility of cross-talk from nearby muscles. Once the wires were positioned appropriately in each muscle, both the acupuncture and delivery needles were removed. The muscle was imaged once more to determine that the ends of the wires remained within the muscle after needle removal. This method has been shown previously to be an accurate and reliable method of fine wire placement (Carpenter et al., 2008). Sterile techniques were used for the insertion of all wires.

In two subjects, additional confirmation of electrode placement was made immediately after the experiment with the use of Computed Tomography (Siemens Somatom Sensation 40 Slice, Siemens, Malvern, PA, USA). Spiral blocks of 1–2 mm slice thickness were recorded through the region from the metatarsal heads to the calcaneus. These images were reconstructed in axial, coronal and sagittal planes to verify wire position. Risk of radiation exposure was reduced with the use of lead gowns.

EMG signal quality was assessed by asking the participant to flex their toes against manual resistance. In some cases when the signal appeared to be contaminated by artefact or crosstalk, the position of the fine-wire electrodes was adjusted by gently pulling on the exposed wires, withdrawing them approximately 1 mm. The quality of the signal was then reassessed and the procedure was repeated until an artefact free EMG signal was obtained.

EMG was continuously recorded from the right foot during all of the DLS and SLS trials. Ten seconds of EMG data was also recorded in a seated position, with the right foot unloaded and relaxed (REL). This procedure was undertaken in order to determine the level of resting base-line activity for each muscle.

2.2.2.3. Data acquisition and processing. All EMG signals were sampled at 5 kHz, amplified 1000 times and band pass filtered between 30 and 1000 Hz (MP35, Biopac Systems Inc., Santa Barbara, CA, USA). Data was subsequently exported to Spike2 (Cambridge Electronic Design, Cambridge, UK) for analysis. Each EMG signal had any DC offset removed prior to rectification and lowpass filtering at 5 Hz using a fourth order Butterworth filter. Mean EMG root mean square (RMS) signal amplitude was calculated for the entire duration of each postural trial, as well as for the 10s REL condition.

Centre of pressure (CoP) position in both the medio-lateral (ML) and antero-posterior (AP) directions was calculated for each sample from the vertical and horizontal forces recorded from the force plate. CoP path excursion in both AP and ML directions was calculated over the entire standing period for each DLS and SLS trial. Different task durations were employed in this protocol, as single leg stance is difficult to maintain for periods of longer than 60 s, while longer durations of quiet stance are typically employed to provide an accurate reflection of postural demand during double leg stance (Tokuno et al., 2007, 2009). Mean CoP speed in both AP and ML directions was also determined, in order to normalise the time periods for each task. The calculated CoP signal was additionally low pass filtered using a 5 Hz fourth order Butterworth filter. For the purpose of this study CoP was calculated to provide an indicator of postural sway. This assumption was made in accordance with previous literature (Gatev et al., 1999; Tokuno et al., 2008, 2009).

To enable changes in the EMG signal to be cross-correlated with changes in the force plate signals, the rectified and smoothed EMG data was down sampled to 50 Hz, the same frequency at which the force data was sampled. Synchronisation between both force plate and EMG signals was achieved with the use of an external trigger.

2.2.2.4. Statistical analysis. A repeated measures analysis of variance (ANOVA) was used to compare differences in mean EMG RMS amplitude between DLS, SLS and REL trials. Sphericity (homogeneity of covariance) was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure. Pair-

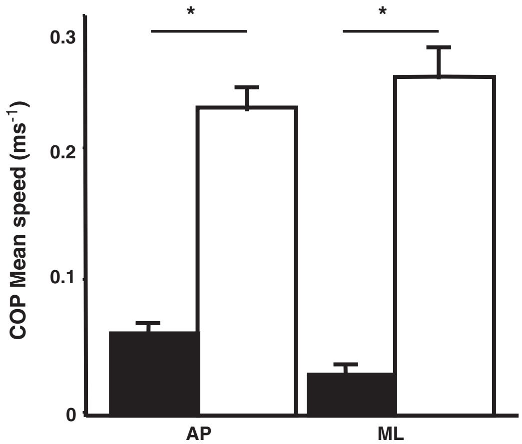

Fig. 1. Mean (SEM) speed of the centre of pressure (CoP) in antero-posterior (AP) and medio-lateral (ML) directions during double leg stance (DLS, solid) and single leg stance (SLS, open) trials. * Significantly different between conditions.

wise comparisons, including Bonferroni corrections, were applied as post-hoc analyses. Effect size (ES) was calculated using partial-eta squared, to determine the magnitude and the practical relevance of the significant findings. Differences in mean CoP speed between DLS and SLS trials were assessed using a paired *T*-test. For all analysis, the level of significance was set at $P \leq 0.05$.

A cross (waveform) correlation function was applied to compare correlations between rectified EMG and CoP path excursion (in AP and ML directions), as well as inter-muscular correlations. This analysis was conducted using SPIKE 2 software. Correlation (*r*) values were classified as follows; small ± 0.1–0.3, moderate ± 0.3–0.5, and strong ± 0.5–1.0 (Nelson-Wong et al., 2009).

3. Results

The single leg balance task induced a higher level of postural demand, as evidenced by a significantly greater mean CoP speed in both AP ($T_9 = 5.84$, $P < 0.001$) and ML ($T_9 = 7.84$, $P < 0.001$) directions (Fig. 1). Mean EMG RMS amplitudes were significantly higher in the SLS task (Fig. 2) in AH ($F_{2,18} = 44.3$, $P < 0.001$, ES = 0.83), FDB ($F_{2,18} = 32.2$, $P < 0.001$, ES = 0.79) and QP ($F_{2,18} = 5.45$, $P < 0.02$, ES = 0.40), compared to both DLS and REL. No significant differences in EMG RMS were found between DLS and REL tasks ($P > 0.05$). However, most subjects displayed intermittent recruitment of a small number of motor units, in one or more muscles, during DLS (Fig. 3). AH was the most commonly active muscle during DLS, displaying consistent recruitment in 7 of the 10 subjects.

Recruitment of AH (r = 0.62), FDB (r = 0.40) and QP (r = 0.40) was correlated to ML sway during the SLS task (Fig. 4), with increased recruitment during medial shifts of the CoP. No correlation was evident for AP sway and muscle recruitment (all $r < 0.2$), nor were there any significant CoP-muscle correlations during the DLS task (all $r < 0.2$). Strong correlations were observed between all muscles during the SLS task (all $r > 0.85$, Fig. 4).

Computed tomography images in two subjects confirmed the location of the fine wire electrodes within each respective muscle belly after the completion of the balance tasks. Thus, providing further evidence of correct electrode placement whilst also indicating that the electrodes remained in their correct location for the duration of testing period.

4. Discussion

The aim of this study was to describe the activation patterns of the plantar intrinsic foot muscles during standing, where task demand and loading varied. We hypothesised that activation of these muscles would increase with increasing postural demand, and that recruitment and activity of these muscles would be correlated with postural sway. Our results indicate that recruitment of the plantar intrinsic foot muscles is regulated in response to postural demands. These muscles are moderate to strongly correlated with ML postural sway, thus suggesting a function in balance control.

This is the first study to use ultrasound guided intramuscular EMG to describe the activation patterns of the plantar intrinsic foot muscles during quiet stance. Previous studies examining the EMG activity of the plantar intrinsic foot muscles have either been limited by the inability to confirm the exact location of fine wire electrodes (Basmajian and Stecko, 1963; Gray and Basmajian, 1968; Mann and Inman, 1964), or by the inability of surface EMG electrodes to record the individual activity of small, deep and underlying musculature (Fiolkowski et al., 2003; Headlee et al., 2008). Given that the physiological cross-sectional area of these muscles is quite small (Kura et al., 1997; Ledoux et al., 2001) and that the use of real-time ultrasound is now quite readily available for use in EMG studies, it is prudent to use these techniques to provide reliable and effective intra-muscular electrode recordings (Carpenter et al., 2008). In addition to real-time ultrasound guidance, we have used computed tomography (in 2 individuals) to confirm the location of our fine wire electrodes after the completion of the balance tasks.

Our results indicate that the plantar intrinsic foot muscles are active during quiet stance, increasing activation in accordance with

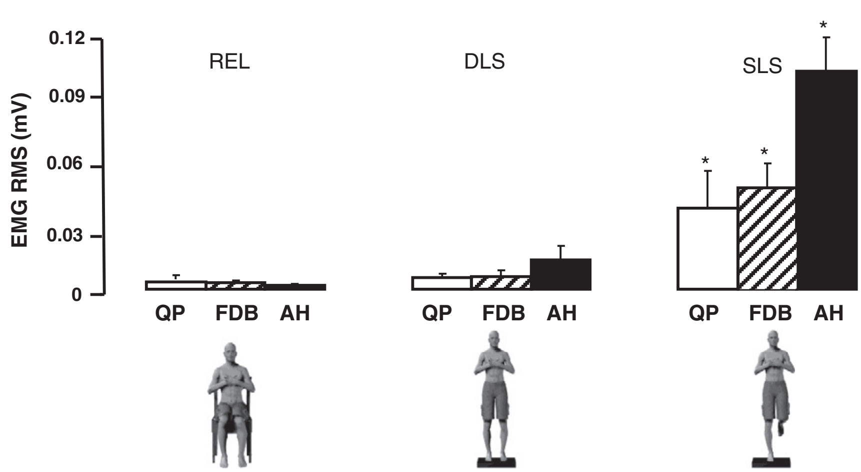

Fig. 2. Mean (SEM) EMG root mean square signal amplitude during relaxed sitting (REL), double leg stance (DLS) and single leg stance (SLS), for quadratus plantae (QP, white), flexor digitorum brevis (FDB, diagonal black stripes) and abductor hallucis (AH, black). * Significantly different from REL and DLS conditions.

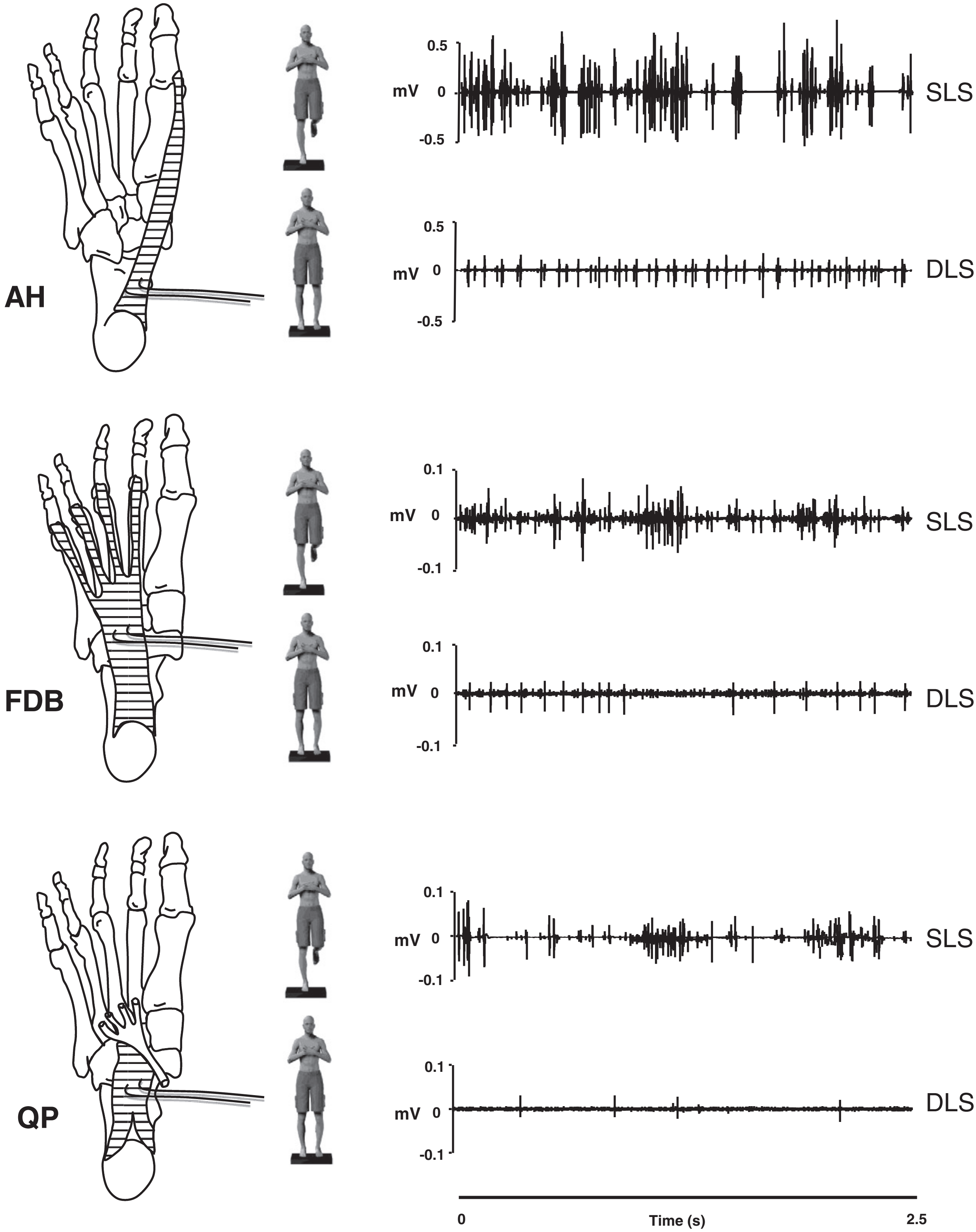

Fig. 3. Anatomical location of abductor hallucis (AH), flexor digitorun brevis (FDB) and quadratus plantae (QP) in a right foot, as well as a sample of EMG signal recorded during the single (SLS) and double (DLS) leg stance trials. Bi-polar fine wire electrodes have been drawn in the approximate recording region within each muscle. All recordings are taken from the same representative individual, with all SLS (upper trace) and DLS (lower trace) recordings taken from the same time period in each respective trial.

postural demand. An early study by Basmajian and Stecko (1963) involved incrementally adding weights to the legs of seated subjects. They reported that activation of these muscles increased with loading of the foot, providing secondary structural support to the medial longitudinal arch. The work of Fiolkowski et al. (2003) and Headlee et al. (2008), using surface electromyography reported reduced muscle activation in AH in association with increased medial arch deformation. Our study delivers evidence that the plantar intrinsic foot muscles provide postural support for the feet during quiet stance.

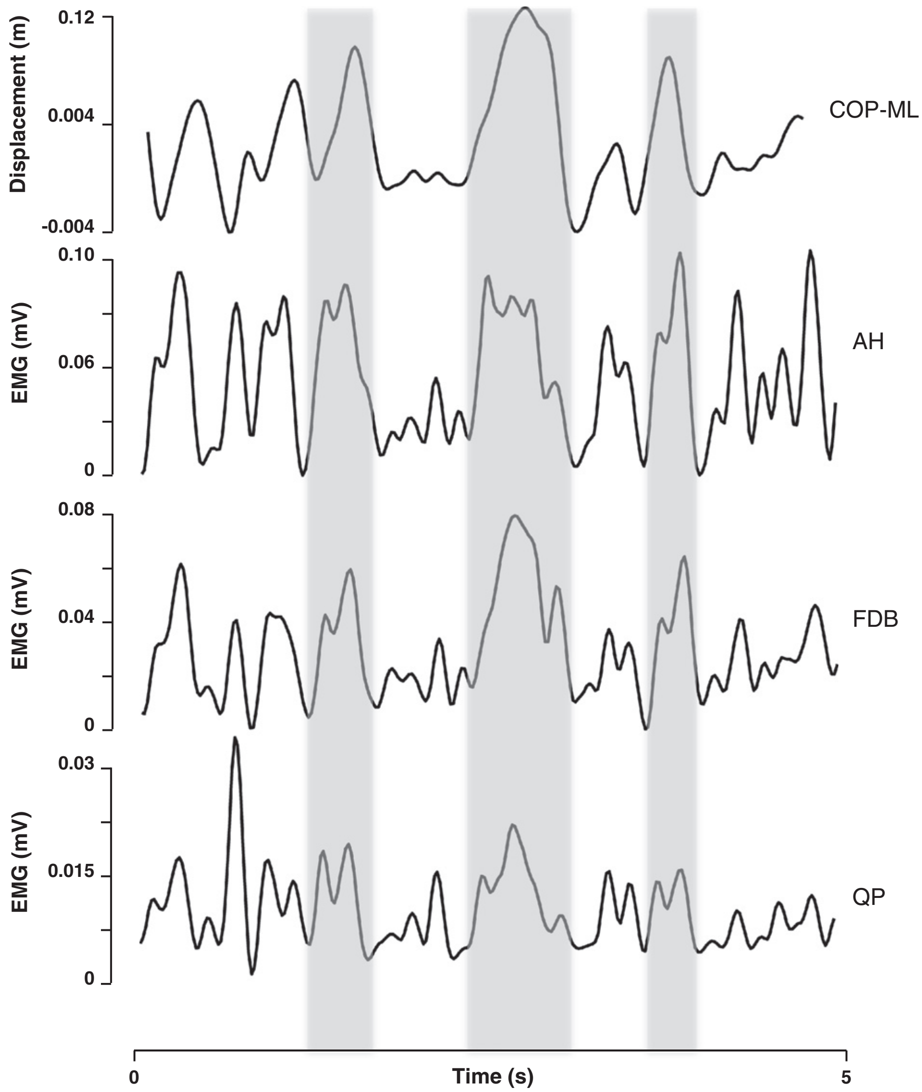

Fig. 4. Waveforms for medio-lateral centre of pressure (CoP-ML) and for EMG of abductor hallucis (AH), flexor digitorum brevis (FDB) and quadratus plantae (QP) during single leg stance (SLS) for a representative subject. Moderate to high correlations between CoP-ML and muscle activation in AH, FDB and QP (all $r \geq 0.4$). High inter-muscular correlations were observed between all muscles (all $r \geq 0.85$). Shaded areas show the synchronous EMG bursts that correspond to the CoP-ML excursion.

A major finding of this study was that plantar intrinsic foot muscle activation was strongly correlated with medio-lateral postural sway in single leg stance, with increasing activity observed during sway to the medial border of the foot. Additionally, these muscles display highly correlated inter-muscular activation patterns during standing. Cross (waveform) correlation functions have been used widely in research related to balance and posture (Nelson-Wong et al., 2009), establishing relationships between postural sway and muscle activation in the lower limb. Using these techniques, it has been established that the posterior lower limb muscles are recruited in response to AP body sway, with muscle waveform peaks occurring prior to the peak of anterior sway (Gatev et al., 1999; Winter, 1995). Suggestions have been made that a central balance control mechanism is responsible for the activation of posterior leg muscles, in response to anterior body sway (Gatev et al., 1999; Loram et al., 2011) and that recruitment of the posterior leg muscles may be dictated by common neural drive (Mochizuki et al., 2006). In the current study, plantar intrinsic foot muscle activity was positively correlated with medial shifts in CoP during single leg stance, with EMG waveform peaks occurring prior to that of peaks in medial CoP excursion. Thus, we suggest that a similar central mechanism may also be responsible for the highly synchronised recruitment of AH, FDB and QP, in response to medial sways in CoP. Although these muscles are relatively small in size compared to the extrinsic foot muscles (Kura et al., 1997; Ledoux et al., 2001), the synchronised manner in which they respond to ML sway may be an essential response to maintain balance. According to Mann and Inman (1964), the plantar intrinsic foot muscles function as a unit to resist subtalar joint pronation, observed as calcaneal eversion (frontal plane), combined with medial deviation (transverse plane) and reduced vertical height (sagittal plane) of the navicular (Razeghi and Batt, 2002). As foot posture and function are known to impact on single leg balance (Menz et al., 2005; Tsai et al., 2006), activation of the plantar intrinsic foot muscles may be utilised to help stabilise the foot, thereby improving balance. Our results also support the conclusions of Menz et al. (2005) and Mickle et al. (2009) who hypothesised that weakness in the intrinsic foot muscles is associated with poor balance and increased risk of falls in the elderly.

4.1. Limitations

The plantar intrinsic foot muscles are relatively small in size, thus there is always a risk of crosstalk from adjacent muscles when attempting EMG recordings (Solomonow et al., 1994). Within the current study we took care to use a recording area on the intramuscular electrode that was large enough to record representative muscle activity, while small enough to minimise the risk of crosstalk. Additionally, visual inspection of our data revealed periods during the balance tasks when only one muscle was active at a given time (Fig. 3), providing evidence that our electrodes were in fact recording electrical activity from different muscles.

5. Conclusion

This study investigated the function of the plantar intrinsic foot muscles during quiet upright stance. Our results indicate that recruitment of these muscles increases with increasing postural demand and that high levels of inter-muscular co-ordination occur in response to ML sway during single leg stance.

Conflict of interest statement

The authors declare no financial interest in any of the products used in this study.

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