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Regional recruitment and differential behaviour of motor units during postural control in older adults

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Abstract

Ageing is associated with neuromuscular system changes that may have implications for the recruitment and firing behaviours of motor units (MUs). In previous studies, we observed that young adults recruit sub-populations of triceps surae MUs during tasks that involved leaning in five directions: common units that were active during different leaning directions, and unique units that were active in only one leaning direction. Further, the MU sub-population firing behaviours (average firing rate (AFR), coefficient of variation (CoV_{ISI}) and intermittent firing) modulated with leaning direction. The purpose of this study was to examine whether older adults exhibited this regional recruitment of MUs and firing behaviours. Seventeen older adults (aged 74.8 ± 5.3 years) stood on a force platform and maintained their center of pressure leaning in 5 directions. High-density surface electromyography recordings from the triceps surae were decomposed into single MU action potentials. A MU tracking analysis identified groups of MUs as being common or unique across the leaning directions. While leaning in different directions did not affect the AFR and CoV_{ISI} of common units ($p > 0.05$), the unique units responded to the leaning directions by increasing AFR and $CoV_{ISI,}$ albeit modestly ($F = 18.51$, $p < 0.001$). The unique units increased their intermittency with forward leaning ($F = 9.22$, $p = 0.003$). The medio-lateral barycenter positions of MU activity in both sub-populations were found in similar locations for all leaning directions ($p > 0.05$). These neuromuscular changes may contribute to the reduced balance performance seen in older adults.

New and Noteworthy

In this study, we observed differences in motor unit recruitment and firing behaviours of distinct sub-populations of motor units in the older adult triceps surae muscle from those observed in the young adult. Our results suggest that the older adult central nervous system may partially lose the ability to regionally recruit and differentially control motor units. This finding may be an underlying cause in older adults balance difficulties during directionally challenging leaning tasks.

Keywords

High-density surface electromyography, ageing, motor units, firing rates, postural control

Introduction

The capacity to control standing balance is a requirement for performing many daily life activities and underlies the ability to maintain a mobile and independent lifestyle. Shifting the body weight in different directions during standing is fundamental for more complex motor tasks, and requires contributions from the musculoskeletal system, specifically the medial and lateral gastrocnemius (MG and LG) as well as the soleus (SOL) muscles (1-3).

In healthy young adults, the performance of multi-directional leaning tasks in standing is accomplished with minimal difficulty but with a large degree of complexity with regard to the recruitment and firing behaviours the MUs. That is, in our previous studies (4, 5) we found that two distinct two subpopulations of motor units (MUs) were recruited during a multi-directional leaning task: *common* MUs were recruited from the MG and SOL, presumably to meet the baseline torque requirements and as the force requirements for body stabilization changes, *unique* MUs in separate locations were recruited in the MG and SOL muscles. In addition to the recruitment location of the MUs, the distinct MU subpopulations exhibited different firing behaviours, suggesting that the CNS may have the capability to control these subpopulations separately. *Common* units were defined as MUs with waveforms that were indistinguishable from each other when matched across at least two different leaning directions. In contrast, *unique* units were MUs that could not be matched across leaning directions and had distinguishable waveforms (4-6).

However, with ageing, there is an age-related loss of muscle mass (7) and associated reduction in maximal muscle strength, power, and physical function, known as sarcopenia (8, 9), which may influence postural control (10). While the causes of sarcopenia are multifactorial (11, 12), one of the primary causes of sarcopenia is the structural changes at the neuromuscular level. During ageing, there is a loss of alpha motor neurons and degeneration of the peripheral nerves (13-16). This process begins gradually, early in life, and accelerates more rapidly from 60 years of age (17, 18), with more rapid declines in muscle function from 70 years of age (19-21). One consequence of the loss of alpha motor neurons is the denervation of the muscle fibres that they previously innervated (22). This can lead to a decreased number of muscle fibres, contributing to the loss of muscle mass. However, the surviving motor neurons possess the ability to reinnervate some of these recently orphaned fibres increasing the size of the innervated MUs proportional to the number of fibres rescued (13, 23, 24). These enlarged MUs are considered to be a positive adaptation as they compensate for declining motoneuron numbers and prevent muscle fibre loss (25). However, a consequence of this phenomenon may be altered MU recruitment in the aged neuromuscular system (26, 27). For example, recruitment thresholds are lowered and the dependency of firing rate on recruitment rank (i.e. the onion skin behaviour) is compromised in older adults (28). However, it remains unknown whether the MU remodelling process influences the regionally-specific recruitment pattern previously observed in young adults (4). Regional recruitment of MUs necessarily requires the muscle fibres belonging to a single MU to be localized within a small region (29). It is plausible that during the remodelling process, the new fibers reinnervated by the motor neuron are outside of the spatially localized region. If such a pattern occurred, regionally specific recruitment of MUs may be attenuated or even lost.

The recruitment of MUs is also influenced by whether the synaptic current distributes either uniformly or non-uniformly across the motoneuron pools of the triceps surae muscles. In young adults, non-uniform activation of the motoneuron pool has been demonstrated during standing balance (4, 30). In older adults, it has been observed that there is less localized activity in the gastrocnemius during quiet stance, which may suggest a reduced ability to flexibly recruit MUs in specific areas (31). Using coherence analyses, Semmler et al. (32) observed an increase of common drive in older than younger adults, suggesting that older adults have decreased flexibility in MU control. Flexible MU control is the ability of motor neurons to comply with various task constraints. This includes selective voluntary activation of single motor units (33, 34), exceptions to the size principle (35, 36) in addition to differential firing behaviours of distinct motoneuron populations (5). An overview of flexible MU control has been recently published by Hug et al. (37). As a flexible control strategy is important for the independent control of spinal motoneurons (37), it is possible that the decreased flexible control observed in older adults may influence the MU firing behaviour observed during directional leaning.

It appears that, in the young adult, the central nervous system (CNS) acquires and uses directionally specific force information to control balance in standing postural tasks. What remains to be investigated is how older adults respond to directional force challenges during standing balance. The present investigation, therefore, has two main goals: 1) to determine if older adults regionally recruit MUs, and 2) to evaluate whether the MU firing behaviour in the plantarflexor muscles of older adults modulated during a multi-directional leaning task. Due to the denervation and reinnervation of MUs, we hypothesized that there would be less regional activation of MUs in older adults than that seen previously in young adults. In addition, due to the decrease in flexible neural control, we expected that there would be less evidence of differential control of MU firing behaviours in older adults.

Methods

Participants

A total of 17 older adults (8 males and 9 females: mean ± SD: age 74.8 ± 5.3 years, body mass 75 ± 15.3 kg; height 171 ± 12.2 cm) participated in this study after providing informed written consent. Exclusion criteria included individuals under the age of 70, the presence of co-morbidity (specifically, known neuromuscular, neurological, or balance disorders), or lower limb injuries within the past 6 months. This study conformed to the standards established by the Declaration of Helsinki latest amendment and was approved by the Institutional Ethics Committee.

Experimental Protocol

The experimental protocol has been described in more detail in previous studies (4, 5). Briefly, participants were instructed to stand naturally in bipedal stance on a force platform (OR6-6 Advanced Mechanical Technology, Watertown, MA, USA) in front of a screen displaying their centre of pressure (CoP) (see Figure 1 in (4, 5)). Participants were allowed to stand stood in their natural bipedal stance, which allowed them to choose their foot position (approximately shoulder width apart). The position of the arms was instructed to remain at their sides during the duration of the trial. First, a 30 s quiet stance trial was recorded for each participant. Following that, each participant's limits of stability (LoS) were established by conducting a 4-way LoS test (38). Five targets at 0º, 30º, 60º, 90º, and 120º (counter-clockwise from lateral-right of the average CoP position computed during the quiet stance trial) were calculated and placed along an ellipse corresponding to 60% LoS (Figure 1A). The same procedure was completed for the 80% LoS. Given that the CoP distance from the ankle joint scales with the ankle torque (39), the 80% LoS condition required a greater contraction intensity. Only one target was displayed on the screen at any time and using visual feedback participants were instructed to move in a smooth and controlled manner until their CoP position reached the circular target and maintain the CoP position for 35s. A rest period of 15 s was provided between different target directions. Figure 1B provides an example of a single participant's CoP trace during the leaning protocol. The order of the target directions and LoS conditions was randomized for each participant. The duration of each trial was approximately 45 s, 5 s towards the target, 35 s within the target, and 5 s back to their natural bipedal stance. If a participant did not maintain the instructed body position, the trial was repeated. Only the trials with correct leaning posture were retained and analyzed. To familiarize themselves with the procedure participants first performed an unrecorded practice trial.

EMG Electrode Placement

Using an ultrasound imaging system (LogicScan 64 LT-1T; Telemed, Vilnus, Lithunia) as a guide, the High Density surface Electromyography (HD-sEMG) grids were placed on the MG, LG and SOL (OTBioelectronica, Torino, Italy). Detection of the medial and lateral edges of the gastrocnemius and SOL, the insertion of the MG and LG on the Achilles tendon, the fascial space between the MG and LG, and the distal edges between the two muscles were identified and marked on the skin with participants lying prone and the ankle in neutral position. The skin was cleaned and abraded prior to grid placement. A single 32-channel semi-disposable grid (interelectrode distance of 10mm) was placed over each of the MG and LG. The gastrocnemius grids were placed in the proximal region of the muscle 10mm above the distal edges of the superficial aponeurosis of the MG and LG. One 64 channel semi-disposable grid with an interelectrode distance of 10 mm was placed over the SOL muscle centered on the Achilles tendon, 10mm below the distal insertion of the MG. Bio-adhesive foam held the grids in place, and conductive paste was used to ensure optimal electrode skin contact. Three reference electrodes were placed on the patella (MG), the fibular head (LG) and the medial malleolus (SOL).

In surface EMG, the amount of muscle volume sampled and the information one can obtain depend on the arrangement of muscle fibers in relation to the skin rather than on the muscle architecture itself. We strived to sample from the largest possible fraction of the muscle volume, and thus represent the biggest possible number of motor units for the grid of electrodes we used. Increasing sensitivity in surface EMG requires placing each electrode in the grid on a different group of muscle fibers, ensuring minimal redundancy between different EMGs. Ideally, greater spatial resolution would be obtained from the sampling of the physiological cross-sectional area of a muscle, which is not possible from the skin surface. For in-depth pinnate muscles, greater spatial resolution is ensured by distributing surface electrodes over different locations covering the muscle aponeurosis (cf. Figures 2 and 3 in (40). Specifically for the soleus muscle, this would mean covering the muscle central region, over the Achilles tendon (41).

Data Analysis

HD-sEMG Signal Analysis

The HD-sEMG signal analysis has been described in detail in previous articles (4, 5). Briefly, HD-sEMG signals were collected in monopolar configuration. Signals were amplified 1000 times using an amplifier (128-channel EMG-USB with OTbioLab software v.2.05; OTBioelectronica, Torino, Italy) and digitized at 2048 Hz with a 12-bit analog to digital converter. After assessing the quality of the signals, monopolar signals were filtered (Butterworth, 2nd order, 20-350 Hz) and decomposed using the blind source separation method (42) implemented in the DEMUSE tool software. The decomposition was done for each target direction and LoS condition separately, over the central 20s of the 35s period when the CoP was maintained at the target location. The results of the decomposition were inspected visually for spurious units with propagating potentials, noisy waveforms and those with a pulse to noise ratio below 28 dB were discarded (43, 44). An example of a retained MU is shown in Figure 2 (top).

To determine spatial locations of the decomposed MU, the barycenter was computed for each MU. The barycenter is quantified from the cluster of channels with an average rectified value (ARV) above 70% of the maximum ARV (See (4, 30, 45) for more detail). The location of the peak activity was calculated as:

$$Barycenter = \frac{\sum ARV_{ch} POS_{ch}}{\sum ARV_{ch}}$$

With ‘ch’ being each channel in the cluster of channels with amplitude above 70% of the ARV, and ‘POS’ being their position along either rows (medio-lateral) or columns (proximo-distal) on the electrode matrix. The barycenter is the location on the muscle where the MU action potentials are more clearly represented.

The segmented activity maps of the HD-sEMG results in each channel representing a 1 cm^2 area (Figure 2). The number of channels with an amplitude above 70% ARV for the barycenter calculation was computed for each MU. This value is indicative of the area of muscle fibres being activated and is referred as the area of MU from this point.

For each retained MU, the average firing rate (AFR) was calculated as the number of firing instances divided by the time the MU was active. Interspike intervals (ISIs) < 25ms were excluded as they would have a large impact on the computation of average firing rate. We did not include ISIs >250 ms in the AFR calculation, as these are considered a de-recruitment of the MU, which would be captured in the intermittency index (see below). The coefficient of variation of the ISI (CoV_{ISI}) was calculated as the standard deviation of the ISI divided by the mean ISI.

A previously-established intermittency index (5) was used to determine whether the MUs were activated intermittently. To standardize the amount of intermittent activity for a single MU, we calculated the degree of intermittency:

$$Degree\ of\ Intermittency = \frac{Number\ of\ intermittent\ occurences}{Time\ MU\ was\ active\ (s)}$$

Where the "*Number of intermittent occurrences*" is the number of cases in which the MU firing rate drops below 4 Hz, and the "*Time MU was active*" is the total time the MU was actively recruited for. This procedure standardized the intermittency of MU activity and allowed comparisons between different MUs by evaluating the number of intermittent occurrences per second.

Motor unit tracking

To identify the subgroups of MUs, a MU tracking analysis was conducted separately for the 60% and 80% LoS conditions. Common MU action potentials between different leaning directions were identified. To identify common MUs, the retained MU ARV was calculated across 30ms epochs centered on individual action potentials. The action potentials of each pair of MUs were aligned in time by maximizing their cross-correlation function. The mean square difference was calculated between the two sets of time-aligned action potentials, averaged across channels, and then normalized with respect to the mean ARV of the two sets of MU. Finally, pairs of MU action potentials with a mean square difference smaller than 10% were considered common (4-6). The matching analysis provides a group of MUs that will be referred to as *common units* and a group of MUs not paired across directions which will be called *unique units* from this point on. See Figure 3 in (5) for more details.

Centre of Pressure Analysis

All CoP analyses were performed using MATLAB 2021b (The Mathworks, Inc., Natick, MA, USA). CoP position in the antero-posterior and medio-lateral directions was calculated from the force platform signals filtered with a fourth-order low-pass Butterworth filter (cut-off frequency = 50 Hz) and sampled at 2048 Hz using a 16-bit A/D converter. The mean CoP position, standard deviations in the X (medio-lateral) and Y (antero-posterior) directions, 95% confidence ellipse (CoP ellipse area), and path length were calculated over the central 20s of the 35s period where the CoP was maintained at the target location. These parameters were used to evaluate participant’s balance performance during each direction of the leaning task.

In addition, the CoP was recorded on the HD-sEMG system to synchronize the EMG and CoP signals. Signals were synchronized on the first, rising edge of CoP movement towards the targets.

Statistical Analysis

All statistical analyses were conducted on R (v.5.12.1, R Development Core Team, 2009). Analysis of the effects of leaning direction, LoS, muscle, MU subgroup (unique or common unit) and age group (young or older adult) on the medio-lateral and proximo-distal barycenter, area of the MU, firing rates, CoV_{ISI}, and degree of intermittency were conducted using separate linear mixed effects regression with the lme4 package (46). Data from the young adults were included from Cohen et al. 2020 and 2022 (4, 5), which used the same experimental protocol. A linear mixed effects approach was used to account for inter-individual differences in the dependent variables. Starting with a maximal random structure, including by-participant and by-item random slopes and intercepts, the structure was reduced to the optimal structure that could be supported by the data. The concatenated models were compared with likelihood ratio tests (LRT) to determine optimal model structure. This led to by-participant random intercepts and random slopes for direction and muscles in all five models. We could not include random slopes of leaning direction or LoS because of singular fit violations (i.e. multiple collinearities).

Diagnostic plots of the residuals from all models were inspected for violations of the assumption of normality and homoscedasticity. The AFR and CoV_{ISI} and barycenter values met the assumptions, however, the degree of intermittency did not (violations of homoskedasticity and normality of residuals). The intermittency values were normalized by a log $(x + 1)$ transformation for the data to fit the assumptions of the model.

Five linear-mixed effect models were conducted separately for the dependent variables (medio-lateral barycenter, proximo-distal barycenter, AFR, CoV_{ISI}, and degree of intermittency). Statistical significance of fixed effects was determined using type III Wald F tests with

Kenward-Rogers degrees of freedom with the ANOVA function from R's *car* package (v. 3.0.12). Effect sizes (Cohen's d) were calculated using the lme.dscore function from the R *EMAtools* package (v. 0.1.4). We quantified small (Cohen's d > 0.2), moderate (Cohen's d > 0.5), and large effect sizes (Cohen's d > 0.8) with the conventional cut-off thresholds (Cohen 1988). Post hoc pairwise comparisons (with Bonferroni's correction) were performed using the estimated-means contrast, as employed in R's *emmeans* package (v. 1.7.2). Post hoc comparisons were applied between each target direction (all-pairwise comparisons), and within the same target direction for the LoS condition, muscle group, and MU subgroup. Confidence intervals around the parameter estimates were calculated via parametric bootstrapping with 5000 iterations. The post hoc results are reported with the mean estimate difference (M), 95% confidence intervals (CI) and adjusted *p*-values.

To determine if the participant's balance performance during the leaning task differed across the target directions and LoS conditions, the CoP parameters (CoP standard deviations in the medio-lateral and antero-posterior directions, 95% ellipse area, path length, and mean velocity) were analyzed in 5 separate linear mixed effect models. Diagnostic plots determined if the CoP parameters met the assumptions for the linear mixed effects regressions. Using LRT we determined the optimal model structure: using the fixed effect of directions and LoS, with the random intercepts of subject. We could not include random slopes of leaning direction or LoS because of singular fit violations (i.e. multiple collinearities). The same post hoc analysis used for the MU firing parameters determined the differences across directions and LoS.

Results

The total number of identified motor units for each muscle per LoS condition in the older adult group can be found in Table 1. Approximately 55% (1756/3175) of the decomposed MUs in the older adults were determined to be common. Whereas the young adults had approximately 25% (892/3569) of their decomposed units determined as common (see Table 1 in Cohen et al., 2020). A further breakdown of the proportion of common units decomposed within each muscle by direction in the older adult *(See Figure 3).* To see a comparison between the young and older adult data, please see the supplementary material, https://doi.org/10.6084/m9.figshare.24352786.

Barycenter Locations

Within the older adults, the multi-directional leaning task did not have an effect on the location of the barycenter in medio-lateral direction for both unique and common units in all three muscles at any of the leaning directions (*p* values ranging from 0.27 to 0.69). There was a statistical difference in the proximal-distal position of the barycenters that was dependent on the MU subgroup demonstrated by the interaction of Direction by MU Subgroup (F = 2.745, $p = 0.02$, Cohen's d = 0.31). The unique units shifted more proximally during the 30º (M = 27 mm), 60º (M = 33 mm) and 120º (M = 52 mm) whereas there was no change in the position of barycenter in the common units (Table 2). Between the older and young adult groups, there was an Ageing effect that was dependent on the MU subgroup and Muscle as indicated by the Age Group x MU Subgroup x Muscle interaction (Proximo-distal: $F = 11.837$, $p < 0.001$, Cohen's d = 0.54; medio-lateral: $F = 3.864$, $p < 0.04$, Cohen's d = 0.64). Post hoc analysis determined that the older adults unique units shifted significantly less than the young adults in both the medio-lateral and proximo-distal directions during the 60º (proximo-distal: M = 8mm; medio-lateral: M = 15) and 120º (Proximo-distal: M = 7.8 mm; medio-lateral: M = 25mm) directions of the MG and SOL.

Area of the MUs

Within each of the age groups, the leaning direction did not have an effect on the area of the MUs for both unique and common units in all three muscles (P values ranging from 0.56-0.89). There was a significant effect of MU subgroup (young adults: F = 3.42, $p < 0.001$, Cohen's d = 0.56; Older adults: F = 2.76, $p < 0.03$, Cohen's d = 0.28), with the unique units occupying larger areas compared to the common units (M = 4.8 cm). The between group differences of the older adults and young adults determined an ageing effect that was dependent on the MU subgroup, indicated by the Ageing x MU subgroup interaction (F = 5.67, $p < 0.036$, Cohen's d = 0.55). Post hoc results determined that the older adults common units occupied larger areas compared to the younger adults in the MG (M= 2.3 mm), LG (M= 3.4 mm), and SOL (M= 3.2 mm) muscles (Table 2). No other statistical differences were identified.

Average Firing Rate

Individual MU Average Firing Rates (AFRs) and associated MU distributions for the MG, LG and SOL during the 5 leaning directions are depicted in Figure 3. The AFRs of the common units for all plantarflexors are distributed unimodally (with a rightward skew) with a peak of 8 - 10 Hz. Similarly, the AFRs of the SOL unique units were distributed unimodally (with a rightward skew) but with a larger number of units firing at higher rates (15 - 25 Hz) compared to the common units. The AFRs of the gastrocnemii unique units, conversely, had a relatively uniform distributions across firing rates (10 - 25 Hz) without very distinctive peaks.

The estimates of the AFR for each muscle are reported in Figure 4. The AFR increased across directions (F = 18.51, $p < 0.001$, Cohen's d = 0.16) dependent on the MU subgroup, as indicated by the Direction x MU Subgroup interaction (F = 5.61, $p < 0.001$, Cohen's d = 0.51). There were no directional effects in the common units for any of the three muscles. Post hoc tests of the within age group differences (within the older adults) determined that the AFR increased in the MG, LG and SOL unique units during the 30º (from 0º: M = 0.92 Hz, and from 120º = 2.79 Hz) leaning direction whereas the common units remained relatively constant (Figure 4). The AFR of the unique units was significantly higher than the common units (F = 42.63, $p <$ 0.001, Cohen's d = 0.99) among all directions in all 3 muscles (0º: M = 4.31 Hz, 30º: M = 5.13 Hz, 60º: M = 4.72 Hz, 90º: M = 4.09 Hz, 120º: M = 3.44 Hz). The muscle effect (F = 15.70, $p <$ 0.001) determined higher firing rates in the gastrocnemii compared to the SOL (MG: M = 2.54 Hz, LG: M = 2.57 Hz). There were no statistical differences between the LoS conditions ($p =$ 0.19). There was a main effect of age on the AFRs, that was dependent on the Muscle and MU Subgroup as indicated by the Muscle x MU Subgroup x Age Group interaction (F = 3.35, $p =$ 009, Cohen's d = 0.33). Post hoc tests between the older and younger age groups determined that older adults unique and common units firing rates were significantly lower than the young adults across all directions in the MG (M = 2.3 Hz) and SOL (M = 3.5 Hz). In addition, the common units of the older adults did not modulate across directions, whereas the young adults did (M = 2.1 Hz).

Coefficient of Variation

The estimates of the CoV_{ISI} are presented in Figure 5. The CoV_{ISI} values increased across leaning directions (F = 10.35, $p < 0.001$, Cohen's d = 0.09). Similar to the AFR, the directional effect was dependent on the MU subgroup, indicated by the interaction between Direction and MU Subgroup (F = 8.48, $p < 0.001$, Cohen's d = 0.92). There were no directional effects in the common units for any of the three muscles. Post hoc tests determined that the CoV_{ISI} increased in the MG, LG and SOL unique units during the 30º (from 0º: M = 3.2%, 90º: M = 5.5%, and 120º: M = 5.5%) and 60º (from 0º: M = 2.2%, 90º: M = 4.3% and 120º: M = 4.3%) leaning directions. The $\mathrm{CoV_{ISI}}$ of the unique units was significantly higher than the common units (F = 42.63, $p < 0.001$) among all directions in the MG (M = 12.3%), LG (M = 11.3%) and SOL (M = 13.5%). The muscle effect (F = 15.70, $p < 0.001$, Cohen's d = 2.52) determined higher $\mathrm{CoV_{ISI}}$ values in the gastrocnemii compared to the SOL (MG: M = 9.5%, LG: M = 8.4%). There was a main effect of age on the $\mathrm{CoV_{ISI}}$, that was dependent on the MU subgroup and the Muscle type indicated by Muscle x MU subgroup x Age Group interaction (F = 6.23, $p < 0.001$, Cohen's d = 0.82). Post hoc analysis between the older and younger age groups determined that the $\mathrm{CoV_{ISI}}$ of the unique units of the older adults were higher across all leaning directions in the MG (M = 5.3%) and LG (M = 4.8%).

Degree of intermittency

The estimates of the degree of intermittency are displayed in Figure 6. The degree of intermittency changed dependent on the MU subgroup across direction, indicated by the Direction x MU Subgroup interaction (F = 9.22, $p = 0.003$, Cohen's d = 0.32). Interestingly, the unique units increased their intermittency from the 0º and 120º directions to the 30º (0º: M = 0.084, 120º: M = 0.07) and the 60º (0º: M = 0.098, 120º: M = 0.089) whereas the common units showed a decrease in their intermittency from those comparators. In addition, the unique units had significantly more intermittent activity across all directions compared to the common units (M = 0.11 – 0.19). Additionally, there was a main effect of muscle (F = 9.23, $p < 0.001$, Cohen's d = 0.47) with the MG MUs (M = 0.29-0.37) having more intermittent activity compared to the SOL. There was a main effect of age on the degree of intermittency, that was dependent on the MU subgroup and Direction as indicated by MU Subgroup x Direction x Age Group interaction (F = 6.23, $p < 0.001$, Cohen's d = 0.53). Post hoc tests between the older and younger age group determined that the unique units of the older adults increased during the 30º (M = 0.244) and 60º (M = 0.278) leaning directions, whereas the unique units of the young adults decreased.

Balance Performance

The estimated means and CIs calculated from the linear mixed effect models for the CoP outcome measures are displayed in Table 3. There was a main effect of direction for both CoP path length and mean velocity (path length: F = 5.40, $p = 0.0003$; mean velocity: F = 7.54, $p < 0.0001$. Post hoc tests determined that there was higher CoP path length and mean velocity during the 60º (M = 6.75 cm; M = 0.39 cm/s), and 90º (M = 9.08 cm; M = 0.51 cm/s) leaning directions as compared to the 0º leaning direction. Additionally, there was a main effect of LoS for both CoP path length and mean velocity (path length: F = 6.13, $p = 0.014$; mean velocity: F = 10.49, $p = 0.0014$), however, after post hoc corrections were applied the effect was found to be not statistically significant ($p = 0.064$ and $p = 0.065$ for the path length and velocity, respectively). No other CoP parameter had statistically significant differences between leaning directions or LoS conditions (*p* values range 0.23-0.91).

Discussion

The ability of older adults to differentially recruit and control MUs was evaluated during a multi-directional leaning task. The main findings were that a majority of the MUs decomposed in the older adults in this study were considered common (55.4%). In addition, the common units in the older adults occupied significantly larger muscle volumes compared to the young adults with moderate effect sizes. Second, the medio-lateral positions of the barycenter in older adults of both unique and common units were found in similar locations for all leaning directions; while, the unique units shifted in different locations in the proximo-distal aspect of the muscle with direction, albeit with small effect sizes. However, a moderate effect size was found between the two age groups MU barycenter's with the older adults barycenter's shifting significantly less than the young adults. While leaning in different directions did not affect the AFR and CoV_{ISI} of common units, the unique units firing behaviour responded to the leaning directions with increasing AFR (albeit in only the 30° leaning direction with a small effect size), and CoV_{ISI} . The CoV_{ISI} of the older adults was significantly higher than the young adults across all directions and MU subgroups, with large effect sizes. Additionally, while the unique units were observed to increase their intermittency during diagonal leaning directions, the common units were observed to decrease it in the older adults. This is in contrast to those in the young adults, where common units are observed to decrease their intermittent behaviour during diagonal and forward leaning directions. Finally, older adults had higher CoP mean velocity and an increase in the CoP total path length in the 60 ° and 90 ° directions than during the 0°. Taken together, this study suggests that older adults may have difficulty controlling directionally-specific leaning tasks in standing.

Relative constant AFRs across leaning directions

The unique and common units in older adults were observed to behave differently from each other. Across the leaning directions, the unique units discharged at higher AFRs compared to the common units (Figure 4) with moderate effect sizes. Our previous study in young adults also found similar findings regarding the separation between the AFR of unique and common units (5).

However, contrary to the findings in young adults, the modulation of the AFRs of older adults across directions is modest. The common units maintained a constant AFR across all leaning directions, and the unique units had a statistically significant increase but only in one leaning direction (30º) with minimal practical significance (Cohen's d < 0.2). This contrasts findings from young adults, where modulation occurs in both common and unique units across the diagonal and forward-leaning directions (30º-90º). Previous studies have observed older adults exhibiting a reduced capacity for rate coding in a variety of force tasks (28, 47-49). Multiple mechanisms contribute to the decreased rate coding seen in older adults (50-53). Due to the decreased capacity to modulate the firing frequencies of MUs, older adults may utilize MU recruitment for force production; however, recruitment may also be impaired because of the smaller proportion of unique units (compared to young adults) and the difficulty to maintain their activity (see below).

The decreased modulation in older adults observed in this study may also indicate a decreased ability to flexibly control MUs with selective neural signals. Several studies have demonstrated that there is increased common synaptic input with ageing. Semmler et al., 2003 (32) observed that older adults demonstrate greater strength of coherent MU activity, and therefore, a high amplitude of common input, compared to young adults during low-intensity contractions of the first dorsal interosseous. Furthermore, it has been shown that older adults have a greater degree of variation in force fluctuations in the wrist extensors in voluntary than evoked contractions, indicating that the variance in synaptic input is greater for older adults than for young adults (54). In the lower limb, Castronovo et al. 2018 (77) found that declines in force steadiness during isometric contractions of the tibialis anterior seen in older adults were associated with an increase in the power of the common input to motor neurons. Taken together, the greater strength of the common modulation may diminish the ability to flexibly control MUs. With a larger common unit signal, there may be decreased independent synaptic inputs to the different MU subgroups.

The consequence of the decreased flexible control and/or the utilization of limited MU recruitment may be decreased force output leading to an increase in the CoP parameters seen during the 60º-90º directions, where force requirements are highest.

Differential Behaviour of the Degree of Intermittency

The unique units of older adults become more intermittent across directions. In stark contrast to young adults (5), the older adults unique units displayed increased intermittency during more forward directions (i.e. 30º-60º) with moderate effects (Cohen's d > 0.5). It has previously been shown in young adults that during forward sway MUs in the ankle plantarflexors become less intermittent (5, 55), whereas during backward sway MUs become more intermittent (55). It is presumed that one of the main mechanisms driving intermittent MU activity in young adults is the ability to leverage the pull of gravity to maintain balance, providing an economical solution to standing posture (55). MUs have been shown to de-recruit below a physiological threshold of 4 Hz during backwards translations of the body suggesting that the CNS allows the force of gravity to 'pull' the body to equilibrium rather than actively producing force (55). By allowing the body to essentially fall back to equilibrium, the MUs are not required to be constantly active, thus providing an energy efficient solution to maintaining standing balance. The observation that an opposite outcome was found in older adults may be indicative of two things. First, it may be illustrating that older adults have difficulty recruiting and maintaining activation of the higher threshold unique units. This may derive from the established increased motor unit recruitment thresholds (28, 56) and/or the decreased voluntary activation seen during ageing (57). With a decreased ability to recruit and maintain activation of the unique units, older adults may not able to achieve the firing rates to maintain continuous activity.

A second explanation for the increased intermittency could derive from the deterioration of the aged sensory system resulting in the reduced ability to detect CoP positional changes. This hypothesis fits well with the literature suggesting decreased sensory feedback in older adults (58, 59). Previous research has determined intrinsic sensory factors such as decreased cutaneous sensation in the feet (60, 61), and muscle spindle deterioration (62-65) occurring in the older adult which may lead to postural instability (61, 66). One may assume that with decreased sensory feedback, the older adult's CoP positional sense would be less responsive to CoP positional changes. Accordingly, perhaps older adults cannot detect the pull of gravity to the same extent as young adults to provide an economical neural solution to the unstable body, providing additional information regarding older adult's efficiency during postural control.

The common units of the older adults became less intermittent across leaning directions. This result is consistent with previous reports on intermittency (55), and is also similar to what has been observed in young adults; a decrease in the common units degree of intermittency was observed but was found to be non-statistically significant (5). Taken together, the intermittent responses of the common units of older adults appear to be similarly sensitive to the positional changes during forward translations as the young adults.

Regional recruitment – Barycenter positions

During the leaning protocol, older adults were found to recruit unique units in distinct locations in the proximo-distal direction with small effect sizes (Cohen's d < 0.5), but not in the medio-lateral direction (Table 2). The common units were found in similar locations in both proximo-distal and medio-lateral directions. Regional recruitment of MUs creates torques that are most efficient for the specific motor output by increasing the moment arm of the torque generated. While the triceps surae are conventionally thought to exclusively produce plantar flexion torques, it has been demonstrated that inversion and eversion torques are derived from these muscles (4, 30, 67, 68). As the relative degree of inversion and eversion increases at the ankle joint, so does the relative moment arm in the MG and LG. Accordingly, regional activation shifts in medio-lateral direction on the triceps surae can change the length of the moment arms producing more effective inversion and eversion torques required for maintaining balance during leaning. Accordingly, the CNS leverages MUs in the most optimal mechanically advantageous positions for force production (4, 30, 69, 70), by recruiting MUs in the medio-lateral direction for inversion-eversion torques, and proximally for plantar flexion torques. In this study, the older adults MUs were recruited only in the proximal direction, whereas young adults recruit MUs in both directions. In our previous research with young adults (4, 5), we postulated that common units are recruited to produce a baseline tonic level of force production. We inferred that the common MUs were smaller compared to the unique units, and thus were likely recruited first. Once the task exceeded the capabilities of the common units, the recruitment of unique units with fibres grouped in different medio-lateral and proximo-distal spatial locations was utilized to meet the force requirements of the task. The muscle fibres belonging to the unique units, recruited based on task demands, were situated in optimal positions to effectively contribute to the torque requirements. Similar observations in the older adults have been identified in this study: the unique units occupy larger muscle regions than the common units, with lower firing rates in the common units, which could suggest that a similar mechanism of recruitment could be utilized. However, the results of the current study continue to add to this understanding with three critical results. First, there are proportionally fewer identified unique units (compared to young adults) regardless of the spatial direction in the older adult populations. With likely fewer unique units available for recruitment, the ability of the CNS to leverage unique units situated in optimal positions may be suppressed. While speculative, this finding may be due to the MU remodelling process seen during ageing. As motoneurons degenerate, the surviving motoneurons re-innervate orphaned fibres. This process may increase the number of common units, putatively decreasing the number of unique units as the larger motoneurones are believed to degenerate first (23). Indeed, we did find that the area of the common units of the older adults was significantly larger than those in the young adults suggesting that these units have adopted the orphaned fibres. However, while this explanation may explain the proportional increase in common units, it does not provide an excellent explanation for the recruitment patterns. Older adults continued to utilize regionally selective MU recruitment in the proximo-distal direction (Table 2), suggesting there may be an alternative explanation for the regional recruitment observations.

Second, a more favourable explanation of the MU recruitment observed may derive from the physiological changes seen in older adults. As mentioned, many sensory deficits can affect postural control in older adults (60-65). If the CNS in older adults cannot identify the directional challenges the task demands, it may no longer utilize regional MU recruitment. Although there are a considerable number of factors that affect postural control performance in the older adult (71-74), the lack of regional recruitment may also contribute to the reduced task performance in this study. The lack of regional recruitment may be an underlying mechanism of motor control that has remained hitherto unexplored within the ageing literature. In this study, we did not observe regionally recruited MUs but we did observe increased CoP path length during the 60º and 90º leaning directions. During these leaning directions, there were significant medio-lateral shifts in young adult barycenter values (4), whereas in the older adults, there are no shifts (Table 3). Perhaps the consequence of older adults being unable to recruit MUs in optimal locations to effectively contribute to torque requirements may be the increased CoP path lengths and velocities.

A final consideration is that recruiting MUs in distinct locations was not necessarily required in the medio-lateral position of the muscles. The older adults had significantly smaller LoS distances in the medio-lateral direction compared to the young adults (unpublished findings, average distances: young adults = 22.24 cm, older adults = 17.85 cm, two-tailed *t*-test, p = 0.036). However, they had similar LoS distances in the anterior-posterior direction (average distances: young adults = 16.92 cm, older adults = 14.90, p = 0.10). With smaller medio-lateral LoS distances, there may be a reduced need for spatial recruitment in the medio-lateral position on the muscle. However, with similar anterior-posterior LoS distances achieved, the CNS continues to recruit units in spatial locations based on the highest mechanical advantage as a requirement for necessary force production.

Limitations

The older adult experimental groups recruited were relatively healthy, active participants, most of whom are not considered frequent fallers (defined as having had two or more falls within the last year (75, 76) (15/17 participants). Future studies should focus on recruiting specific demographics with frequent fallers to determine if there are further differences in the recruitment and MU control which may relate to falls.

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Figure Legends

Figure 1

A. A schematic of the experimental set up for the multi-directional leaning task. The grey circles denote the targets positioned at 0°, 30°, 60°, 90°, and 120° in respect to the position of the participant's center of pressure before the lean shown with the black circle. B. An example of a center of pressure trace of a single participant during the multi-directional leaning task.

Figure 2

Motor unit action potential and corresponding HD-sEMG motor unit activity map. A: An example of a lateral gastrocnemius motor unit waveform from a single participant during the 60º target direction. B: The corresponding averaged rectified value (ARV) activity map and barycenter location. The black circles indicate the channels included in the barycenter calculation (i.e. area), the larger gray circle is the resultant barycenter. Note the orientation of the axes: smaller values of the barycenter position indicate proximal (vertical axis) and medial (horizontal axis). IED = interelectrode distance.

Figure 3

Violin plots for each leaning direction of the average firing rate (AFR) distribution of the motor units (MUs) for all participants combined, identified during both 60% and 80% limits of stability conditions overlaid by the MU AFR for the unique (left column; A, B) and common (right column; C, D) units in the medial and lateral gastrocnemius (MG: white circles, LG: black circles; A, C) and soleus (SOL: white circles; B, D). The number of MUs for each direction are indicated under each violin plot. A small amount of swarm was added to the x-axis for clarity of display. The horizontal location of the individual MU AFR does not have an effect on the distributions of the violin plots. The proportion of common units in each muscle by direction is the following: *MG: 0°: 43%, 30°: 44% 60°: 53% 90°: 40% 120°: 43%; LG: 0°: 42%, 30°: 36%, 60°: 51%, 90°:42%, 120°: 41%; SOL: 0°: 63%, 30°: 66%, 60°: 69%%, 90°: 67%, 120°: 67%*

Figure 4

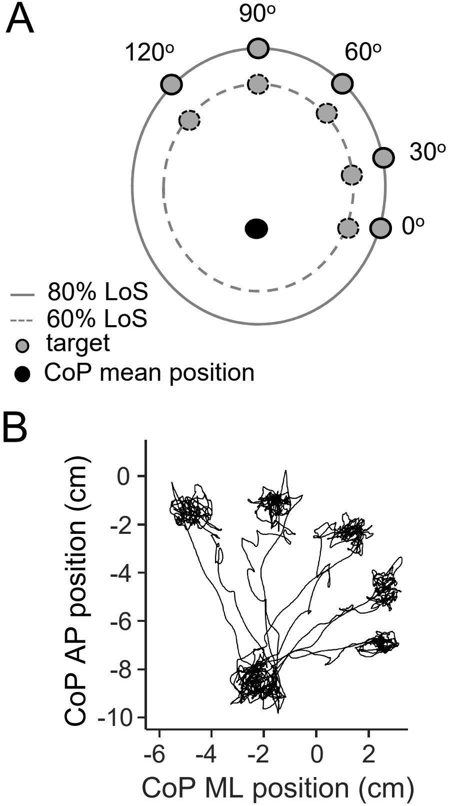
Average firing rates (AFR) for unique (circles) and common (triangles) motor units during 60% (grey) and 80% (black) limits of stability (LoS) reported for the medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SOL). The data are mean estimates and 95% confidence intervals calculated from the linear mixed model. * Indicates significantly different AFR from the 0° and 120° leaning directions for both 60% and 80% LoS conditions ($p < 0.001$). † Indicates significantly different AFR between unique and common units ($p < 0.001$).

Figure 5

Coefficient of variation of the interspike intervals (CoV_{ISI}) for unique (circles) and common (triangles) motor units during 60% (grey) and 80% (black) limits of stability (LoS) for the medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SOL). The data are estimated means and 95% confidence intervals calculated from the linear mixed model. * indicate significantly different CoV_{ISI} from the 0° and 120° leaning direction for both 60% and 80% LoS. † Indicates significantly different CoV_{ISI} between unique and common units.

Figure 6

Degree of intermittency for unique (top; black symbols) and common (bottom; grey symbols) motor units. The 60% (grey) limits of stability (LoS) data are depicted for the medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SOL). The 80% LoS condition had near identical values and have been omitted for clarity. The data are estimated means and 95% confidence intervals calculated from the linear mixed model for the log transformed values. Dotted line rectangles in both unique and common MUs enclose the intermittency values in all 3 muscles that are significantly different from the 0° and 120° leaning directions (* $p < 0.001$). † Indicates significantly different intermittency between MG and SOL ($p < 0.001$).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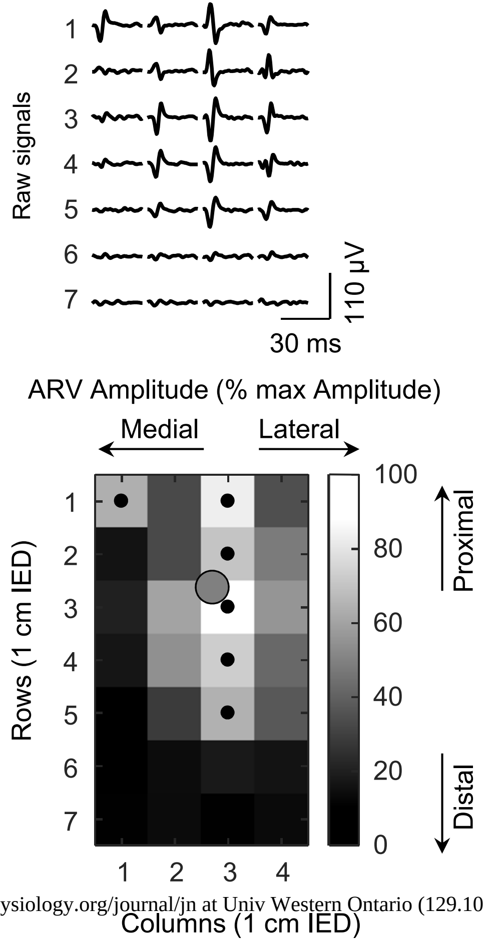
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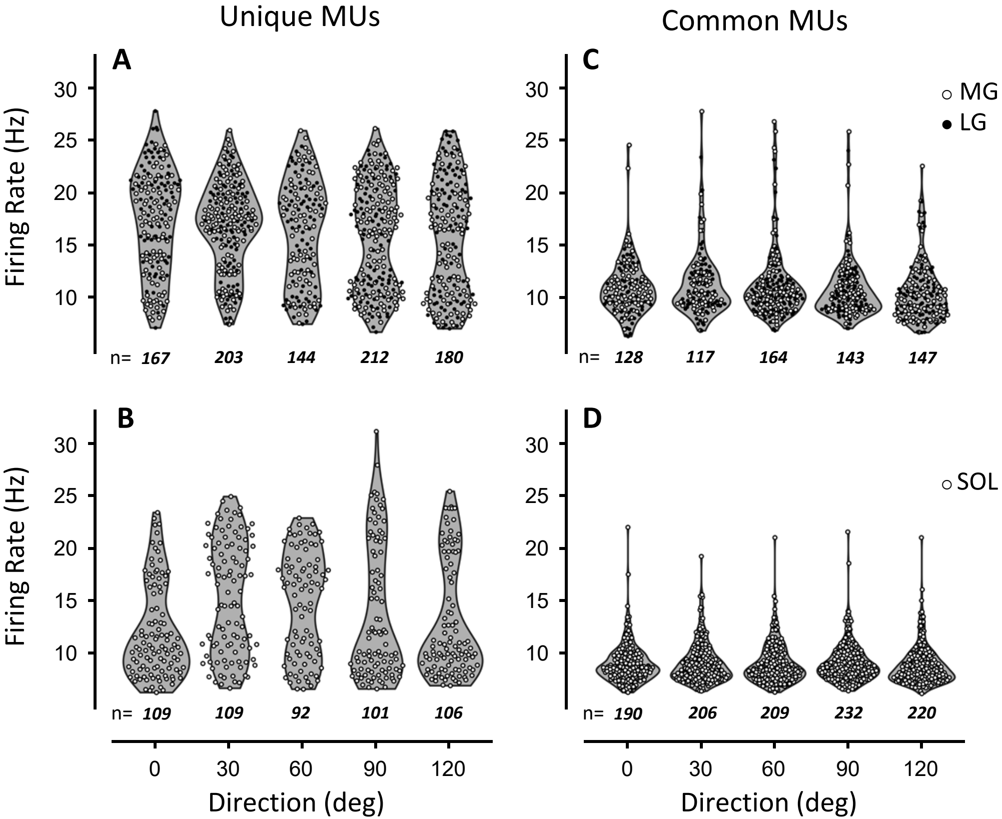
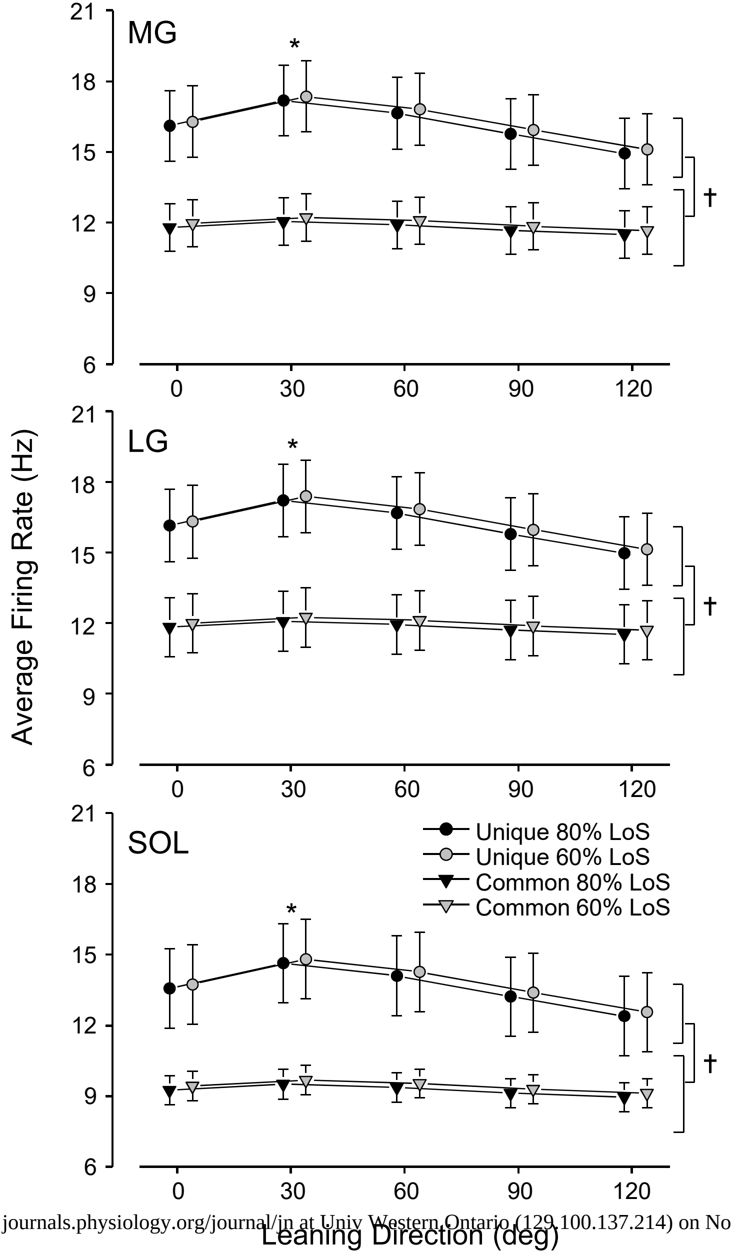
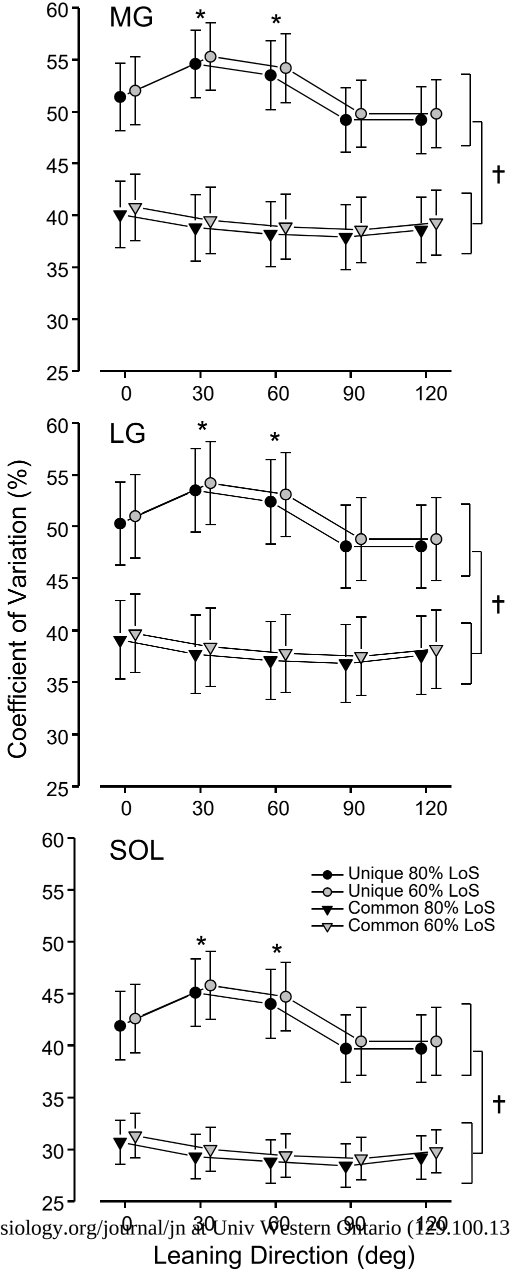
40
20
0
Proximal
Distal
1
2
3
4
Columns (1 cm IED)


Unique MUs
Common MUs
A
B
C
D
○ MG
● LG
○ SOL
Firing Rate (Hz)
30
25
20
15
10
n= 167 203 144 212 180
n= 109 109 92 101 106
n= 128 117 164 143 147
n= 190 206 209 232 220
0 30 60 90 120
Direction (deg)


MG
LG
SOL
*
†
Average Firing Rate (Hz)
Leaning Direction (deg)
6
9
12
15
18
21
0
30
60
90
120
Unique 80% LoS
Unique 60% LoS
Common 80% LoS
Common 60% LoS


MG
LG
SOL
Coefficient of Variation (%)
Leaning Direction (deg)
25
30
35
40
45
50
55
60
0
30
60
90
120
*
†
Unique 80% LoS
Unique 60% LoS
Common 80% LoS
Common 60% LoS

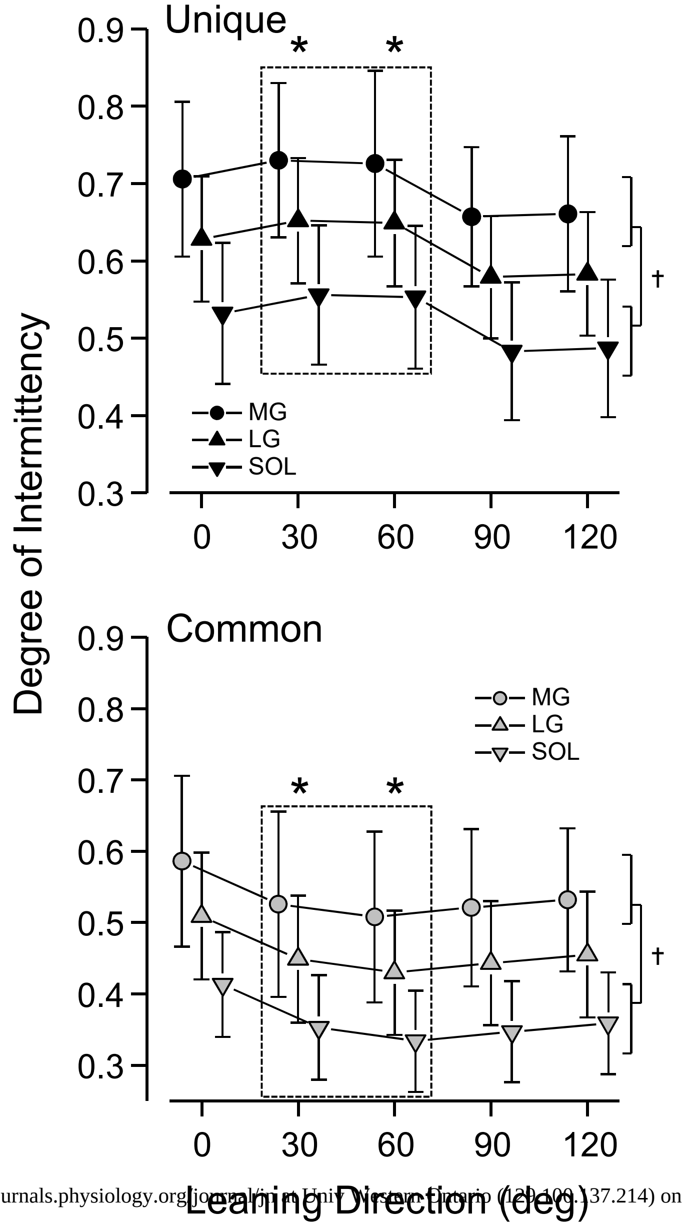

Unique
Common
Degree of Intermittency
0.9
0.8
0.7
0.6
0.5
0.4
0.3
*
*
†
MG
LG
SOL
0
30
60
90
120
Learning Direction (deg)

Table 1. Number of identified motor units (MUs) for all leaning directions

MUs	LoS	Medial Gastrocnemius	Lateral Gastrocnemius	Soleus
Total	60%	422 MUs, 25 ± 14 (7-89)	353 MUs, 21 ± 12 (2-48)	759 MUs, 48 ± 33 (12-130)
	80%	485 MUs, 30 ± 21 (6-90)	345 MUs, 20 ± 12 (2-45)	811 MUs, 44 ± 25 (8-145)
Unique	60%	224 MUs, 13 ± 9 (1-30)	188 MUs, 11 ± 9 (1-27)	261 MUs, 15 ± 12 (7-48)
	80%	290 MUs, 17 ± 7 (5-30)	204 MUs, 12 ± 8 (3-23)	252 MUs, 15 ± 10, (4-36)
Common	60%	198 MUs, 12 ± 10 (5-67)	165 MUs, 9 ± 9 (5-36)	498 MUs, 23 ± 20 (5-116)
	80%	195 MUs, 12 ± 9 (5-65)	141 MUs, 8 ± 10 (5-31)	559 MUs, 33 ± 22 (5 – 113)

Values are group totals, mean ± standard deviation and (minimum-maximum) range across participants. 60% and 80% correspond to limit of stability (LoS) condition.

Table 2. Estimated means of the barycenter position and area of MUs on the muscles of the older adults during the 60% limit of stability condition

MU group	Barycenter direction	Target Directions				
		0º	30º	60º	90º	120º
Medial Gastrocnemius						
Unique	ML(mm)	24.7 (23.0-26.4)	24.5 (22.8-26.1)	25.5 (23.8 – 27.2)	24.4 (22.8 – 26.1)	24.4 (22.7 – 26.1)
	PD (mm)	35.6 (32.8-38.5)	34.2* (32.7 – 38.4)	33.8* (33.1 – 38.8)	35.7 (32.9 – 38.6)	33.4* (35.0 – 4.02)
	Area (mm)	6.31 (5.89 – 7.82)	7.23 (6.23 – 7.99)	6.89 (5.87 – 7.21)	6.84 (5.33 – 7.45)	6.78 (5.28 – 7.43)
Common	ML(mm)	25.6 (23.7 – 27.5)	25.5 (23.6 – 27.4)	25.5 (23.6 - 27.3)	25.1 (23.2 – 26.9)	25.4 (23.5 – 27.3)
	PD (mm)	34.8 (30.4 – 36.5)	33. 5 (31.6 – 37.6)	33.3 (30.5 – 36.5)	35.8 (31.8 – 37.8)	34.8 (31.6 – 36.4)
	Area (mm)	**5.32** **(4.18 – 6.03)**	**5.12** **(4.23 – 5.91)**	**5.23** **(4.54 – 5.89)**	**5.18** **(4.04 – 5.97)**	**5.32** **(4.67 – 6.01)**
Lateral Gastrocnemius						
Unique	ML(mm)	28.6 (26.8 – 3.04)	28.4 (26.6 – 3.01)	29.4 (27.7 – 31.1)	28.4 (26.6 – 30.1)	28.3 (26.5 – 3.01)
	PD (mm)	38.1 (3.65 – 4.24)	36.6* (36.5 – 42.4)	36.3* (35.5 – 43.1)	38.2 (35.3 – 41.1)	35.8* (35.8 – 40.9)
	Area (mm)	6.02 (5.44 – 7.73)	8.02 (6.62 – 8.76)	7.32 (6.59 – 8.03)	7.35 (6.34 – 7.99)	7.02 (5.35 – 7.89)
Common	ML (mm)	29.5 (27.5 – 31.4)	28.4 (27.5 – 31.3)	29.4 (27.5 – 31.3)	29.0 (27.1 – 3.08)	29.3 (27.4 – 31.2)
	PD (mm)	37.2 (34.1 – 40.3)	35.9 (32.8 – 39.0)	35.7 (34.2 – 40.2)	34.4 (32.2-38.2)	35.2 (33.1 – 37.4)
	Area (mm)	**5.34** **(4.23 – 6.12)**	**6.33** **(4.54 – 6.89)**	**6.18** **(5.32 – 6.74)**	**6.27** **(5.43 – 7.05)**	**5.89** **(5.54 – 6.35)**
Soleus						
Unique	ML (mm)	44.3 (42.6 – 46.0)	44.1 (42.4 – 45.8)	45.1 (43.5 – 46.8)	44.1 (42.4 – 45.7_	42.3 (42.4 – 45.7)
	PD (mm)	39.4 (36.6 – 42.3)	38.0* (38.0 – 43.7)	37.6* (36.9 – 42.6)	39.5 (36.7 – 42.4)	37.1* (36.5 – 42.2)
	Area (mm)	6.89 (5.32 – 8.23)	7.67 (6.01 – 8.47)	7.46 (5.99 – 8.65)	7.89 (6.48 – 8.92)	8.04 (6.88 – 8.77)
Common	ML (mm)	45.7 (43.9 – 47.6)	45.7 (43.8 – 47.5)	45.6 (43.8 – 47.4)	45.2 (43.4 – 47.0)	45.5 (43.7 – 47.4)
	PD (mm)	38.6 (35.6 – 41.6)	37.3 (34.3 – 40.3)	37.1 (35.6 – 41.5)	35.8 (33.4 – 38.7)	36.6 (34.2 – 39.1)
	Area (mm)	**6.14** **(5.18 – 7.03)**	**6.35** **(5.23 – 6.89)**	**6.18** **(5.32 – 6.65)**	**6.34** **(5.13 – 6.92)**	**6.32** **(5.76 – 7.08)**

Values are mean estimates (confidence intervals) calculated from the linear mixed effect models. See Figure 2 for the orientation of the proximo-distal (PD) and medio-lateral (ML) axes. Statistical significant ($p < 0.05$) by direction is indicated with an (*) with 0 degrees as the comparator. **Bolded** indicates statistically significant ($p < 0.05$) by age group.

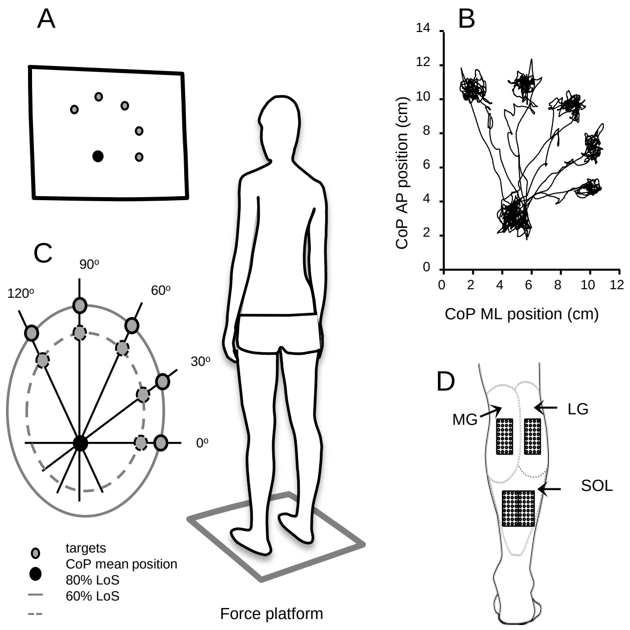
Table 3. CoP outcome measures in each leaning direction and limit of stability condition

CoP measure	Target Directions				
	0°	30°	60°	90°	120°
	60% Limit of Stability				
Path Length (cm)	27.0 (21.3 – 32.7)	29.8 (24.1-35.5)	33.7* (28.1 – 39.4)	36.0* (30.3-41.7)	32.8 (27.1 – 38.5)
Mean Velocity (cm/s)	1.27 (0.98 – 1.57)	1.47 (1.18 – 1.76)	1.67* (1.37 – 1.96)	1.78* (1.49 – 2.08)	1.58 (1.26 – 1.87)
95% Ellipse Area (cm^2)	1.47 (0.71 – 2.24)	1.98 (1.21 – 2.75)	1.71 (0.94 – 2.48)	2.04 (1.26 – 2.81)	1.75 0.98 – 2.52)
SD_{ML} (cm)	0.31 (0.23 – 0.39)	0.34 (0.26 – 0.42)	0.34 (0.25 – 0.41)	0.35 (0.27 – 0.43)	0.32 (0.25 – 0.40)
SD_{AP} (cm)	0.39 (0.32 – 0.47)	0.42 (0.34 – 0.50)	0.38 (0.30-0.45)	0.43 (0.35 – 0. 50)	0.41 (0.34 – 0.49)
	80% Limit of Stability				
Path Length (cm)	30.4 (24.6 – 36.1)	33.2 (27.5 – 39.0)	37.1 (31.4 – 42.9)	39.4 (33.7 – 45.2)	36.2 (30.5 – 42.0)
Mean Velocity (cm/s)	1.48 (1.19 – 1.78)	1.68 (1.36 – 1.98)	1.88 (1.58 – 2.17)	1.99 (1.70 – 2.29)	1.79 (1.49 – 2.09)
95% Ellipse Area (cm^2)	1.62 (0.84 – 2.39)	2.13 (1.35 – 2.90)	1.86 (1.08 – 2.63)	2.18 (1.40 – 2.96)	1.89 (1.12 – 2.67)
SD_{ML} (cm)	0.33 (0.25 – 0.41)	0.35 (0.27 – 0.43)	0.34 (0.27 – 0.43)	0.37 (0.29 – 0.45)	0.34 (0.26 – 0.42)
SD_{AP} (cm)	0.41 (0.33 – 0.49)	0.43 (0.36 – 0.51)	0.39 (0.31 – 0.47)	0.44 (0.36 – 0.52)	0.43 (0.35 – 0.51)

Values are mean estimates (confidence intervals) calculated from the linear mixed effect models. CoP = centre of pressure. SD_{ML} = standard deviation in the medio-lateral direction. SD_{AP} = standard deviation in the antero-posterior direction. * denotes significantly different ($p < 0.05$) from the 0° target direction.

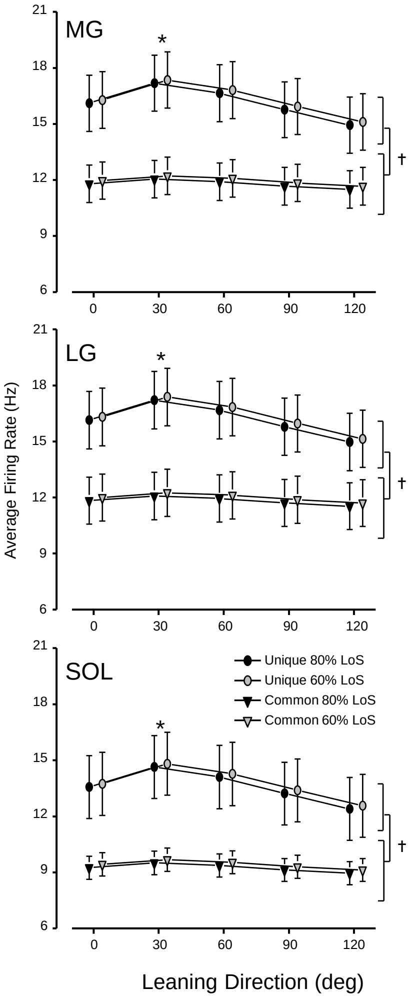
Regional recruitment and differential behaviour of motor units during postural control in older adults

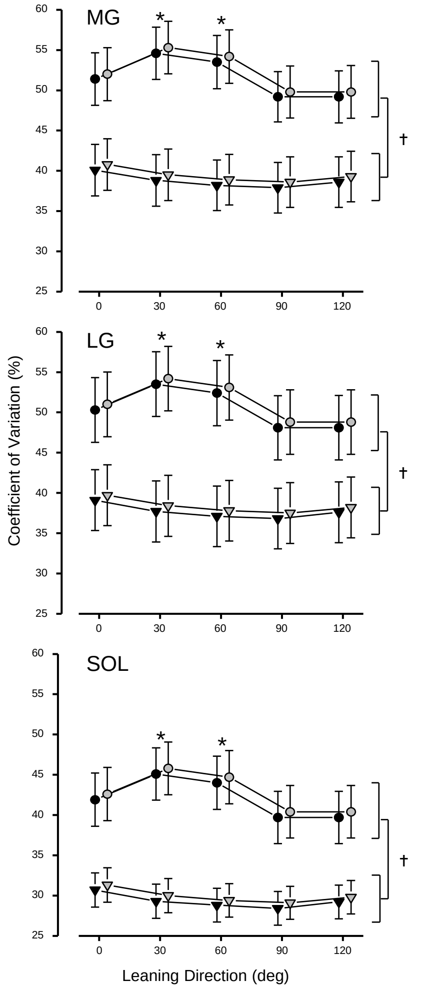
METHODS

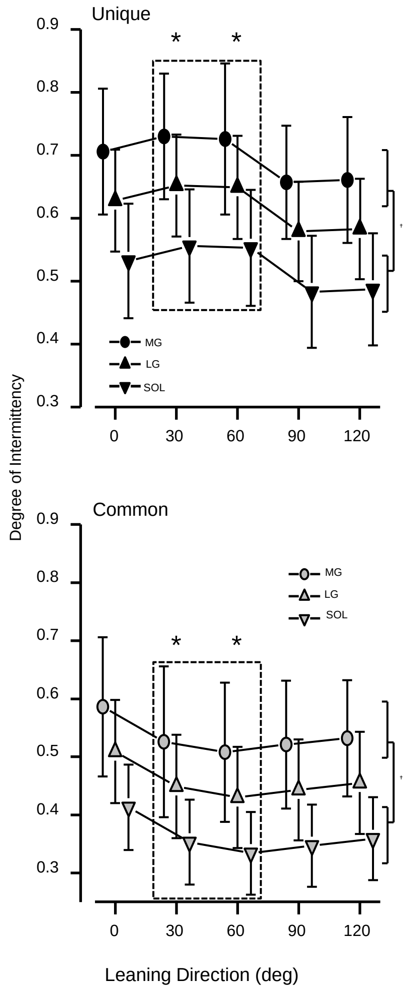


Purpose: To determine if older adults regionally recruit MUs, and to evaluate whether the MU firing behaviour in the triceps surae muscle of older adults modulated during a multi-directional leaning task

RESULTS







CONCLUSION

Older adult's central nervous systems may partially lose the ability to regionally recruit and differentially control motor units. This may be an underlying cause of balance difficulties