

Temporal organization of early post-contact lower-limb muscle activity under cognitive load in men with chronic ankle instability

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Research Article

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Abstract

Purpose

To determine whether chronic ankle instability (CAI) and concurrent cognitive loading alter the temporal organization of lower-limb muscle activity during the early post-contact stabilization phase of single-leg landing.

Methods

Sixty Tier 2–3 male athletes (30 with CAI and 30 controls) completed randomized single- and auditory 2-back dual-task single-leg drop landings. Surface electromyographic activity from 10 lower-limb muscles was examined over the first 200 ms after initial contact. Peak-normalized waveforms were analyzed using SPM1d and FPCA to characterize localized and distributed temporal features, respectively.

Results

SPM1d identified Group $\times$ Task interactions for the gluteus maximus at 120–126 ms and peroneus longus at 166–190 ms post-contact ($p = 0.017$ – 0.045 , $\eta^2 = 0.130$ – 0.158). Across tasks, CAI was characterized by a greater late gluteus maximus profile but lower early rectus femoris and lateral gastrocnemius profiles than controls ($p = 0.002$ – 0.037 , $\eta^2 = 0.128$ – 0.317). During dual-task landing, CAI also showed a greater late gluteus maximus profile than controls ($p = 0.003$, $d = 0.907$ – 0.950). FPCA identified task- and group-dependent differences in tibialis anterior and lateral gastrocnemius waveform structure ($p < 0.001$ – 0.034 , $\eta^2 = 0.106$ – 0.265).

Conclusion

CAI alters the temporal distribution of lower-limb muscle activity during rapid post-contact stabilization, whereas cognitive loading produces selective rather than generalized modulation of this neuromuscular response. These findings highlight the importance of temporal organization, in addition to activation magnitude, when characterizing neuromuscular control during landing.

1 Introduction

Lateral ankle sprain is one of the most common musculoskeletal injuries in physically active populations, yet its consequences frequently extend beyond the acute injury (Doherty et al. 2014; Gribble et al. 2016). Approximately 40% of individuals who sustain a first-time lateral ankle sprain may subsequently develop chronic ankle instability (CAI), characterized by recurrent sprains, episodes or perceptions of the ankle “giving way,” persistent symptoms, and reduced self-reported function (Herzog et al. 2019; Hertel and Corbett 2019). Rather than reflecting an isolated ligamentous deficit, contemporary models

conceptualize CAI as an interaction among pathomechanical, sensory-perceptual, and motor-behavioral impairments that can disrupt movement control across the lower extremity (Hertel and Corbett 2019). Emerging evidence also implicates neurocognitive function. A recent systematic review reported deficits in attention, inhibitory control, and visual memory in individuals with CAI, although evidence for working memory and processing speed remains mixed (Corlù et al. 2026). These interacting sensorimotor and neurocognitive impairments may become particularly relevant during rapid athletic tasks that require simultaneous postural stabilization and information processing.

Single-leg landing provides a demanding model for examining neuromuscular control in CAI because the lower extremity must rapidly attenuate impact while establishing stable single-limb support (Simpson et al. 2019; Maniar et al. 2022). The first 200 ms after initial contact represents a critical period of rapid neuromuscular stabilization, during which coordinated activation of distal and proximal lower-limb muscles contributes to impact attenuation, control of whole-body momentum, and establishment of stable single-limb support (Delahunt et al. 2006; Maniar et al. 2022). Previous landing studies have identified alterations in both distal and proximal neuromuscular control in individuals with CAI. Delahunt et al. (Delahunt et al. 2006), for example, examined muscle activity within 200-ms intervals surrounding IC and identified altered preparatory peroneal activity together with differences in landing mechanics. More recently, a meta-analysis specifically examining post-IC electromyographic responses during unilateral landing included 17 studies and 757 participants and reported lower activation of the peroneus longus, gluteus medius, and biceps femoris but greater soleus and rectus femoris activation in CAI than in healthy controls (Poor et al. 2026). Substantial heterogeneity was present for several muscles, however, indicating that CAI-related post-contact neuromuscular alterations are not expressed uniformly across studies or muscles.

This early neuromuscular response may be further challenged when landing is performed concurrently with a cognitive task. In sport, landing and postural stabilization frequently occur while athletes process environmental information, divide attention, or make movement decisions rather than under isolated and fully predictable conditions (González-Millán et al. 2024). This may be particularly relevant to CAI given emerging evidence of neurocognitive impairment in this population (Corlù et al. 2026). Nevertheless, current evidence does not support a generalized dual-task deficit. A systematic review and meta-analysis found no consistent overall deterioration under cognitive loading within CAI or between CAI and healthy control groups across studies largely involving balance and gait tasks, with variability partly attributed to differences in cognitive-task difficulty, motor-task demands, and CAI heterogeneity (Choi et al. 2023). More demanding landing paradigms may therefore reveal task-dependent cognitive-motor interference that is less apparent during balance or gait. During single-leg drop landing, He et al. (He et al. 2026) reported that an auditory working-memory task altered selected impact-loading, joint-mechanical, and lower-extremity surface electromyography (sEMG) outcomes in individuals with CAI, while several other measures remained unchanged. Collectively, these findings suggest that cognitive-motor interference during landing may be muscle-, outcome-, and time-dependent rather than reflecting a uniform deterioration in neuromuscular control.

An important methodological consideration is that several landing studies have characterized sEMG using discrete or predefined-window outcomes, including integrated activity, root mean square amplitude, or peak activation (Delahunt et al. 2006; He et al. 2026). Although these measures provide useful information about activation magnitude, they reduce a rapidly evolving signal to one or several scalar values and therefore provide limited information about when neuromuscular differences emerge or how activation is distributed across the post-contact period. Continuous waveform approaches may provide complementary information. One-dimensional statistical parametric mapping (SPM1d) enables statistical inference across registered biomechanical trajectories rather than at isolated time points and has identified time-specific lower-limb sEMG differences between individuals with CAI and healthy controls during gait (Pataky 2012; Moisan et al. 2021). Functional principal component analysis (FPCA) addresses a complementary aspect of waveform variation by representing inter-individual differences in continuous profiles using a reduced set of functional modes and participant-specific scores (Epifanio et al. 2008). Applications to human movement biomechanics further demonstrate that FPCA can identify dominant waveform features that may not be captured by conventional discrete analyses (Roach et al. 2021). Together, SPM1d and FPCA therefore provide complementary perspectives: the former identifies temporally localized differences, whereas the latter characterizes dominant modes of variation across the complete waveform. It remains unclear whether CAI- and cognitive-load-related alterations in early post-contact muscle activation are expressed primarily as localized temporal differences, broader changes in waveform structure, or both.

Accordingly, this study examined early post-contact lower-limb muscle activation profiles in men with unilateral CAI and side-matched healthy controls during single- and dual-task single-leg drop landings. Activation profiles from 10 distal and proximal lower-limb muscles were analyzed across the first 200 ms after IC. We hypothesized that: (1) individuals with CAI would exhibit altered early post-contact activation profiles across selected distal and proximal muscles compared with healthy controls; (2) cognitive loading would modify early post-contact activation profiles, with task-related responses differing between the CAI and control groups; and (3) dominant waveform modes would show group- and task-dependent differences that complement the temporally localized alterations identified by SPM1d.

2 Methods

2.1 Participants

A laboratory-based cross-sectional study with repeated single- and dual-task conditions was conducted using a convenience sample of male athletes to reduce sex-related heterogeneity. The required sample size was estimated a priori using G*Power software (Version 3.1.9.2; Heinrich-Heine-Universität Düsseldorf, Germany) for an ANOVA: repeated measures, within-between interaction model (Faul et al. 2007). Based on previous CAI studies examining landing-related and continuous sEMG outcomes, reported standardized effect sizes ranged from Cohen's $f = 0.20$ to 0.31 (Miao et al. 2024; Zhong et al. 2024). The effect size ($f = 0.20$) was therefore used for the a priori calculation. With $\alpha = 0.05$, power ($1-\beta$)

= 0.80, two groups, two repeated measurements, a correlation of 0.50 between repeated measurements, and a nonsphericity correction of 1.00, the minimum required sample size was 52 participants. Sixty men were included: 30 with unilateral CAI and 30 healthy controls. Participants were classified as Tier 2–3 athletes according to McKay et al. (McKay et al. 2022). The study was approved by the Institutional Ethics Committee of Jimei University (Approval No. 20260526001) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent before testing.

Eligibility criteria followed previous CAI research and the recommendations of the International Ankle Consortium (Gribble et al. 2014; He et al. 2026; Wang et al. 2026). Participants with CAI were required to have: (1) ≥ 1 significant lateral ankle sprain occurring ≥ 12 months before testing, with inflammatory symptoms and interruption of physical activity for ≥ 1 day; (2) ≥ 2 episodes of ankle giving way within the previous 6 months, with recurrent ankle sprains and/or perceived instability; and (3) a Cumberland Ankle Instability Tool (CAIT) score ≤ 24 . Healthy controls had no history of lateral ankle sprain, giving way, or perceived instability and had a CAIT score ≥ 28 . Exclusion criteria were bilateral CAI, previous lower-extremity fracture or surgery, acute lower-extremity musculoskeletal injury within the previous 6 months, current lower-extremity rehabilitation, or vestibular, visual, or neurological disorders affecting landing performance.

2.2 Testing procedures

Participants attended one laboratory session. Body height and body mass were recorded, body mass index (BMI) was calculated, and CAIT score was recorded before testing. The unstable limb was tested in the CAI group, whereas the tested limb in healthy controls was side-matched (left/right) to the unstable limb of a participant with CAI. After instrumentation and maximum voluntary isometric contraction (MVIC) testing, participants completed a standardized 15-min warm-up and sufficient familiarization with the landing and 2-back tasks. The single- and dual-task conditions were performed in randomized, counterbalanced order, with 3 min of rest between conditions. Three valid trials were collected per condition, separated by 30 s.

sEMG was recorded at 2000 Hz using a wireless system (Cometa Systems, Milan, Italy). Ground-reaction force was recorded at 1000 Hz using an embedded force platform (Type 9287CA; Kistler Group, Winterthur, Switzerland). The force-platform signal was used to identify IC and align the sEMG data.

2.2.1 Single-task drop landing

Following previous single-leg drop-landing protocols (Wang et al. 2026; Meng et al. 2026), participants stood on a 30-cm box with their hands on their hips. An unpredictable 800-Hz auditory beep lasting 500 ms cued them to step off with the designated test limb and perform a single-leg landing. Upward jumping and active push-off were prohibited, and participants were required to land fully on the force platform and maintain single-leg balance for ≥ 3 s. Trials were repeated if these criteria were not met.

2.2.2 Dual-task drop landing

The dual-task protocol was adapted from He et al. (He et al. 2026) and combined the same landing with a continuous auditory 2-back task (Kirchner 1958). A pseudorandom sequence of 25 letters (A-J) was presented (400-ms stimulus duration, 3000-ms interstimulus interval, 20% targets). Participants verbally answered “yes” or “no” to indicate whether each letter matched the letter presented two positions earlier. During the sequence, an unpredictable 800-Hz, 500-ms beep cued the landing while the 2-back task continued. Trials were repeated if cognitive-task accuracy was < 80%, a response was omitted, or the landing was invalid. Accuracy was calculated as the proportion of correct responses (Fig. 1).

2.3 Surface electromyography analysis

After hair removal when necessary, the skin was lightly abraded and cleaned before electrode placement. Ten wireless sEMG sensors were positioned over the tibialis anterior (TA), peroneus longus (PL), medial gastrocnemius (MG), lateral gastrocnemius (LG), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), semitendinosus (ST), gluteus medius (GMed), and gluteus maximus (GMax) according to SENIAM recommendations (Hermens et al. 2000). Three 5-s MVIC trials were recorded for each muscle, separated by 60 s. Standardized testing positions were seated knee extension for RF and VL, prone knee flexion for BF and ST, seated ankle dorsiflexion for TA, seated ankle eversion for PL, prone plantarflexion for MG and LG, side-lying hip abduction for GMed, and prone hip extension with the knee flexed to 90° for GMax. The highest peak of the processed linear envelope across the three trials was used as the MVIC reference (Burden 2010). Raw sEMG signals were demeaned, band-pass filtered at 20–450 Hz, notch-filtered at 50 Hz, full-wave rectified (Xuan et al. 2026), and low-pass filtered at 6 Hz using fourth-order zero-phase Butterworth filters to obtain linear envelopes, which were normalized to the corresponding MVIC reference (Rao et al. 2023; Wang et al. 2025).

IC was defined as the first instant at which vertical ground-reaction force exceeded 10 N (Cui et al. 2025). The 0-200-ms post-IC sEMG segment was extracted for each valid trial (Delahunt et al. 2006), and the three trials were averaged within each condition. For waveform-shape analysis, each condition-averaged profile was divided by its maximum within the 0-200-ms window and resampled to 101 points, yielding a 0–1 peak-normalized waveform spanning 0% (IC) to 100% (200 ms post-IC). Thus, subsequent analyses reflect relative waveform shape rather than activation magnitude.

2.4 Statistical analysis

Participant characteristics and cognitive-task accuracy were analyzed using SPSS Version 27.0 (IBM Corp., Armonk, NY, USA) and are presented as mean $\pm$ SD. Normality was assessed using Shapiro-Wilk tests and Q-Q plots and homogeneity of variance using Levene’s test. Between-group differences were assessed using independent-samples t-tests. Time-resolved sEMG profiles were analyzed using SPM1d in Python 3.10 (Pataky 2010, 2012). For each muscle, a 2×2 mixed SPM ANOVA was performed with Group (CAI vs. control) as the between-participant factor and Task (single vs. dual) as the within-participant factor, with the Group $\times$ Task interaction as the primary effect. Random field theory was used for cluster-level inference, and significant clusters were reported as percentages of the 200-ms post-contact window. FPCA was performed separately for each muscle in Python 3.10 using mean-centered

101-point profiles with trapezoidal quadrature weighting and no additional smoothing (Epifanio et al. 2008; Roach et al. 2021). fPC scores were obtained by projection onto the eigenfunctions, with components retained until cumulative explained variance reached $\geq 80\%$. Their scores were analyzed using 2×2 mixed ANOVAs with the same Group and Task factors. Within each muscle, p values across retained fPCs were Holm-adjusted separately for Group, Task, and Group $\times$ Task effects. Significant Group $\times$ Task interactions were followed by four simple-effect comparisons with Bonferroni correction. Effect sizes were reported as partial eta squared (η^2) for ANOVA effects and Cohen's d for simple effects; d was standardized using the pooled SD for between-group comparisons and the average SD of the two conditions for within-group comparisons (Lakens 2013). For significant SPM clusters, pointwise effect sizes were reported as ranges (Jones et al. 2025). Effect sizes were classified as small ($\eta^2 = 0.01$ to < 0.06 ; $d = 0.20$ to < 0.50), medium ($\eta^2 = 0.06$ to < 0.14 ; $d = 0.50$ to < 0.80), or large ($\eta^2 \geq 0.14$; $d \geq 0.80$) (Vermeulen et al. 2025). Statistical significance was set at $\alpha = 0.05$.

3 Results

3.1 Participant characteristics and cognitive-task performance

Table 1 presents participant characteristics. Groups did not differ in age, height, BMI, or dual-task accuracy ($p > 0.05$). The CAI group had lower CAIT scores than controls ($p < 0.001$).

Table 1. Demographic and Clinical Characteristics of Participants.

Characteristic	Control Group ($n = 30$)	CAI Group ($n = 30$)	p
Age (years)	20.2 $\pm$ 1.7	20.0 $\pm$ 1.2	0.658
Height (cm)	177.3 $\pm$ 2.7	176.1 $\pm$ 4.8	0.221
BMI (kg/m ²)	24.1 $\pm$ 1.6	24.9 $\pm$ 2.3	0.106
CAIT Score	29.6 $\pm$ 0.5	19.0 $\pm$ 2.6	<0.001
2-back accuracy (proportion correct)	0.97 $\pm$ 0.05	0.96 $\pm$ 0.05	0.529

Abbreviations: BMI, body mass index; CAI, chronic ankle instability; CAIT, Cumberland Ankle Instability Tool.

3.2 Time-resolved post-contact sEMG profiles

Significant Group $\times$ Task interactions were observed for GMax at 60-63% of the post-contact window ($p = 0.045$, $\eta^2 = 0.130$ - 0.132) and PL at 83-95% ($p = 0.017$, $\eta^2 = 0.130$ - 0.158). A separate simple-effect comparison identified a higher GMax profile in CAI than controls during the dual task at 85-95% ($p = 0.003$, $d = 0.907$ - 0.950); no PL simple-effect cluster survived Bonferroni correction. Group effects were identified for GMax at 79-99% ($p = 0.002$, $\eta^2 = 0.138$ - 0.260), RF at 0-6% ($p = 0.037$, $\eta^2 = 0.131$ - 0.154), and LG at 7-27% ($p = 0.005$, $\eta^2 = 0.128$ - 0.317), with CAI showing higher GMax but lower RF and LG

profiles than controls. No task main effects or other group or interaction clusters were detected (all cluster $p > 0.05$; η^2 at $F_{\max} = 0.009$ - 0.126) (**Figure 2**).

3.3 Functional principal component structure of post-contact sEMG

FPCA retained three fPCs for GMax, RF, VL, ST, TA, MG, and LG and four for GMed, BF, and PL, accounting for 80.1%-92.3% of cumulative waveform variance. Across muscles, fPC1, fPC2, fPC3, and fPC4 explained 30.5%-45.7%, 22.0%-33.7%, 13.2%-21.1%, and 10.8%-16.8% of the variance, respectively (**Figure 3**).

3.4 Group and task effects on functional principal component scores

A significant group $\times$ task interaction was observed for TA fPC1 ($F(1,58) = 7.50$, $p = 0.025$, $\eta^2 = 0.115$); under the single-task condition, CAI showed lower fPC1 scores than controls ($p = 0.027$, $d = 0.725$), whereas the remaining simple effects were nonsignificant ($p = 0.111$ - 1.000 , $d = 0.244$ - 0.595). A task main effect was observed for TA fPC3 ($F(1,58) = 6.86$, $p = 0.034$, $\eta^2 = 0.106$), with higher scores during the dual than single task. A group main effect was observed for LG fPC3 ($F(1,58) = 20.91$, $p < 0.001$, $\eta^2 = 0.265$), with higher scores in controls than in CAI. No other fPC-score effects remained significant after Holm correction ($p = 0.059$ - 1.000 , $\eta^2 < 0.001$ to $\eta^2 = 0.090$) (**Figure 4**). Detailed FPCA structure and statistical results are provided in **Supplementary Table S1**.

4 Discussion

This study examined whether CAI and concurrent cognitive loading alter the temporal organization of lower-limb muscle activity during the first 200 ms after single-leg landing and whether SPM1d and FPCA provide complementary information regarding these alterations. The first hypothesis was supported, as CAI was associated with selective time-localized differences in both distal and proximal muscle profiles. The second hypothesis was partially supported: cognitive loading did not produce a generalized Task effect across the time-resolved profiles, but Group $\times$ Task effects emerged for GMax and PL, and task-related differences were identified in TA waveform structure. The third hypothesis was supported, as SPM1d and FPCA captured partly distinct features of the post-contact response, with localized effects identified for GMax and PL, broader functional-mode differences for TA, and convergent evidence for LG. Overall, the findings indicate that CAI- and cognitive-load-related alterations in early landing control are muscle- and time-specific rather than uniformly expressed across the lower limb.

The group-related SPM1d findings indicate that CAI is associated with altered temporal organization of both distal and proximal muscle profiles across different portions of the early post-contact period. Relative RF and LG profile values were lower in CAI immediately or shortly after IC, whereas the relative GMax profile was greater later in the 200-ms window. Single-leg landing requires coordinated contributions from the ankle, knee, and hip musculature to attenuate whole-body momentum and

stabilize the lower extremity, with the gastrocnemius, quadriceps, and GMax contributing substantially to these functions (Maniar et al. 2022). Previous evidence likewise indicates that CAI-related landing alterations extend beyond the ankle, although the direction and magnitude of individual-muscle findings vary considerably across studies (Simpson et al. 2019; Dejong et al. 2020; Poor et al. 2026). Notably, Poor et al. (Poor et al. 2026) reported greater post-contact RF activation in CAI, whereas the present analysis identified a lower relative early RF profile. These findings are not directly contradictory because previous evidence largely reflects amplitude-based EMG outcomes, whereas the present analysis evaluated within-window peak-normalized waveform shape. Accordingly, the present results describe differences in when activity is relatively distributed within the post-contact profile rather than whether absolute muscle activation is greater or smaller.

The later GMax difference further indicates that CAI-related alterations are not restricted to ankle musculature or the earliest response after IC. GMax contributes substantially to hip extension control and the attenuation of downward momentum during single-leg landing (Maniar et al. 2022). The greater relative GMax profile observed later in the post-contact window may therefore reflect a different temporal contribution of proximal musculature to stabilization in CAI, consistent with evidence of proximal neuromuscular adaptations in CAI and greater GMax weighting under more demanding landing conditions (Dejong et al. 2020; Zhou et al. 2024). This interpretation is consistent with contemporary perspectives that CAI involves interacting impairments affecting movement behavior beyond the injured ankle rather than an isolated local ligamentous deficit (Hertel and Corbett 2019). However, whether this later GMax weighting represents effective compensation, maladaptive control, or simply an alternative coordination strategy cannot be determined from the present sEMG data. Such interpretations would require concurrent evidence from muscle force, joint kinetics, or intervention studies. The present finding should therefore be regarded as evidence of altered temporal organization of proximal muscle activity rather than a specific compensatory mechanism.

Cognitive loading produced a more selective pattern than initially hypothesized. No significant SPM1d Task main-effect cluster was identified in any of the 10 muscles, indicating that the auditory working-memory task did not impose a common time-localized alteration across groups. Instead, Group $\times$ Task interactions occurred for GMax and PL, while FPCA identified task-related changes in TA waveform structure. This pattern is consistent with evidence that cognitive-motor interference in CAI is context dependent rather than generalized; Choi et al. (Choi et al. 2023) found no consistent overall dual-task deterioration in CAI, whereas landing-specific studies have identified selective neuromuscular and biomechanical alterations under divided attention or working-memory demands (Lin et al. 2025; He et al. 2026). The present findings extend this selectivity to the temporal organization of post-contact sEMG. Cognitive-task accuracy was high and comparable between groups, indicating adequate task engagement after familiarization. However, because trials with accuracy <80% were repeated, accuracy should not be interpreted as cognitive dual-task cost.

The GMax interaction occurred at 60-63%, whereas the CAI-control difference during dual-task landing occurred later at 85-95%. Thus, the latter should not be interpreted as the directional source of the

interaction. Nevertheless, the interaction indicates task-dependent differences in GMax waveform organization without establishing a specific cortical or compensatory mechanism (Rosen et al. 2021; Corlù et al. 2026). The PL interaction requires even greater caution because none of the Bonferroni-corrected simple effects was significant. Therefore, no specific within-group task change or between-group directional difference should be assigned to the PL result. It is more appropriately interpreted as secondary evidence of task-dependent temporal modulation, consistent with evidence that landing anticipation and task context can substantially influence peroneal responses in CAI (Hou et al. 2024; Gong et al. 2025).

The TA findings demonstrate a different form of task-related adaptation. No localized TA cluster was identified by SPM1d, yet FPCA detected a Group $\times$ Task interaction for fPC1 and a Task main effect for fPC3. Inspection of the reconstructed fPC1 profiles indicates that this mode primarily distinguishes earlier- from later-weighted portions of the TA waveform; therefore, the lower fPC1 score in CAI than controls during the single-task condition reflects a different temporal distribution of activity rather than lower absolute activation. Because the corresponding group difference was not significant during dual-task landing and neither within-group task contrast survived Bonferroni correction, the interaction should not be interpreted as cognitive loading “normalizing” TA control in CAI. The fPC3 Task effect nevertheless indicates that cognitive loading altered an additional component of TA waveform organization across participants. Previous dual-task landing research reported task-related increases in peak TA activation in CAI (He et al. 2026), whereas the present FPCA findings address how TA activity is distributed through time rather than how much activity occurs. This distinction reinforces the value of separating activation magnitude from waveform structure.

The partial divergence between SPM1d and FPCA is therefore informative rather than inconsistent. SPM1d performs statistical inference continuously along registered one-dimensional trajectories and is suited to identifying localized temporal regions in which conditions differ (Pataky 2012; Yona et al. 2024); this approach has previously identified time-specific EMG differences in CAI during both gait and unilateral landing paradigms (Moisan et al. 2020, 2021). FPCA instead represents correlated variation across an entire waveform through a smaller number of functional modes and participant-specific scores (Epifanio et al. 2008; Warmenhoven et al. 2019; Roach et al. 2021). In the present study, GMax and PL exhibited localized SPM effects without corresponding significant fPC-score effects, whereas TA exhibited significant fPC effects without a localized SPM cluster; LG was identified by both approaches. These patterns indicate that restricted temporal differences can be detected by SPM1d without substantially altering a dominant whole-waveform mode, whereas distributed waveform variation can contribute to an fPC difference without forming a localized supra-threshold cluster. Consequently, the absence of an SPM cluster should not be interpreted as evidence that the overall waveform is invariant. The two approaches therefore characterize complementary dimensions of temporal neuromuscular organization.

From an applied perspective, these findings indicate that CAI-related neuromuscular control cannot be characterized solely by whether a muscle exhibits greater or lower average activation. The timing and

distribution of activity across the early landing response may contain information that discrete root mean square or peak measures do not capture, complementing conventional amplitude-based assessment (Delahunt et al. 2006; Poor et al. 2026). Likewise, the limited number of cognitive-load effects argues against conceptualizing dual-task landing as producing a uniform deterioration in neuromuscular control, consistent with current CAI dual-task evidence (Choi et al. 2023). Continuous waveform analysis may therefore complement conventional sEMG measures when the research question concerns how CAI or cognitive demands alter the temporal organization of landing responses. Cognitively demanding landing tasks may provide a useful experimental context for examining neuromuscular control under concurrent information-processing demands (González-Millán et al. 2024; Gong et al. 2025). Future longitudinal work should determine whether these temporal waveform characteristics are associated with recurrent sprain, perceived instability, or functional recovery. Longitudinal and intervention studies are required to determine whether the identified waveform characteristics are modifiable and whether they relate to recurrent sprain, perceived instability, or functional recovery.

Several limitations should be acknowledged. First, within-window peak normalization isolated waveform shape but removed absolute amplitude information; the findings therefore describe relative temporal organization rather than activation magnitude. Future studies should evaluate amplitude and waveform-shape outcomes together. Second, cognitive performance was assessed using accuracy alone, and trials below 80% were repeated; future studies should incorporate reaction time and cognitive dual-task cost. Third, inference was conducted separately across muscles, and the sample was limited to male Tier 2-3 athletes; replication in larger and more diverse cohorts is therefore warranted. Finally, the cross-sectional sEMG design cannot establish causality or identify the neural or mechanical mechanisms underlying the observed temporal profiles.

5 Conclusion

CAI was associated with selective alterations in the temporal organization of distal and proximal muscle activity during the first 200 ms of post-contact stabilization, while concurrent cognitive loading produced muscle- and time-specific rather than generalized modulation of this response. These findings indicate that the temporal distribution of muscle activity constitutes an important component of neuromuscular control during landing and may provide information beyond that obtained from discrete activation measures alone.

Abbreviations

CAI — Chronic ankle instability

CAIT — Cumberland Ankle Instability Tool

EMG — Electromyography

FPCA – Functional principal component analysis

IC – Initial contact

MVIC – Maximum voluntary isometric contraction

SPM1d – One-dimensional statistical parametric mapping

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

This study was performed in accordance with the Declaration of Helsinki and was approved by the Institutional Ethics Committee of Jimei University (Approval No. 20260526001).

Consent to participate

Written informed consent was obtained from all participants.

CRedit authorship contribution statement

ZW contributed to conceptualization, methodology, formal analysis, software, investigation, data curation, visualization, and writing of the original draft. HC contributed to investigation, data curation, validation, and review and editing of the manuscript. YH contributed to methodology, investigation, validation, and review and editing. WZ contributed to investigation, resources, and review and editing. XW contributed to conceptualization, supervision, project administration, resources, and review and editing. All authors read and approved the final manuscript.

Data availability

The de-identified data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figures

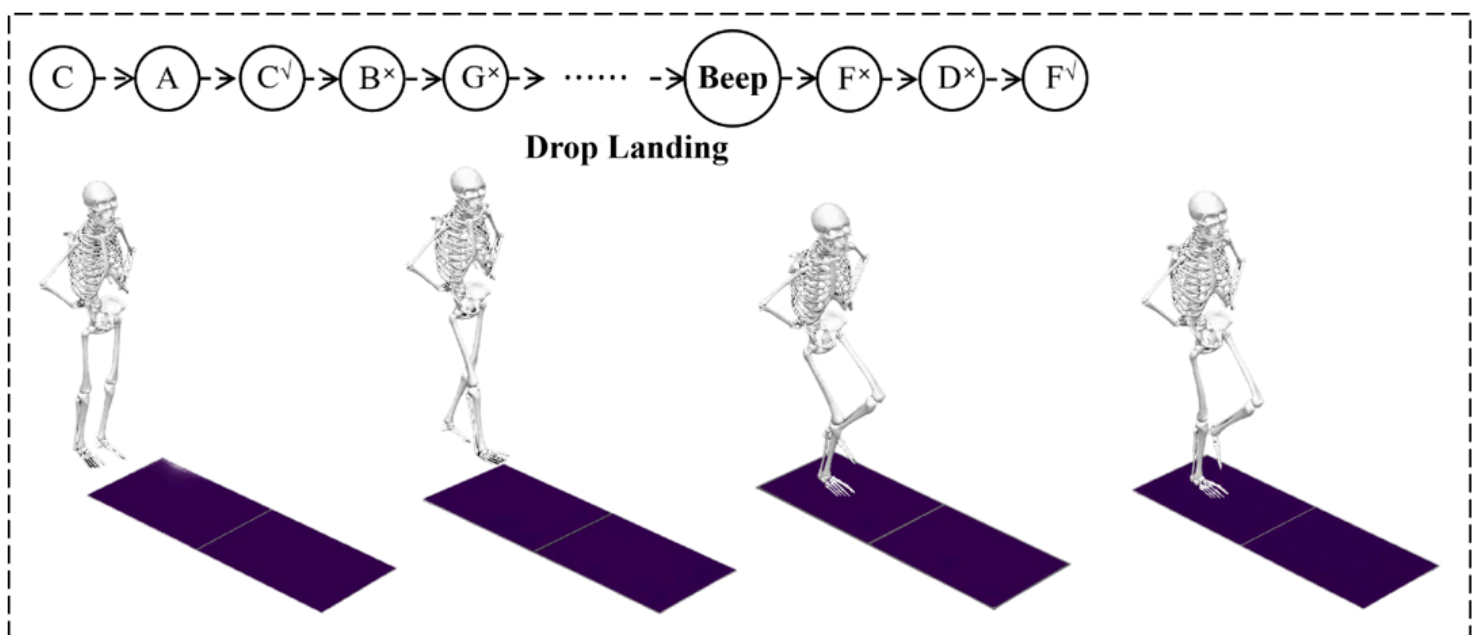


Figure 1

Schematic of the dual-task single-leg drop-landing protocol. The figure illustrates the experimental sequence for the dual-task single-leg drop-landing condition. Participants continuously performed an auditory 2-back task while standing on the 30-cm box and awaiting an unpredictable auditory cue. Letters were presented sequentially, and participants were required to verbally indicate whether the current letter matched the one presented two positions earlier. Check marks (✓) indicate target stimuli (2-back matches), whereas crosses (×) indicate non-target stimuli. An unpredictable 800-Hz, 500-ms beep cued the initiation of the drop landing. The lower panels depict the representative landing sequence from single-leg stance to post-landing stabilization on the force platform. The single-task condition used the same landing procedure without the concurrent auditory 2-back task.

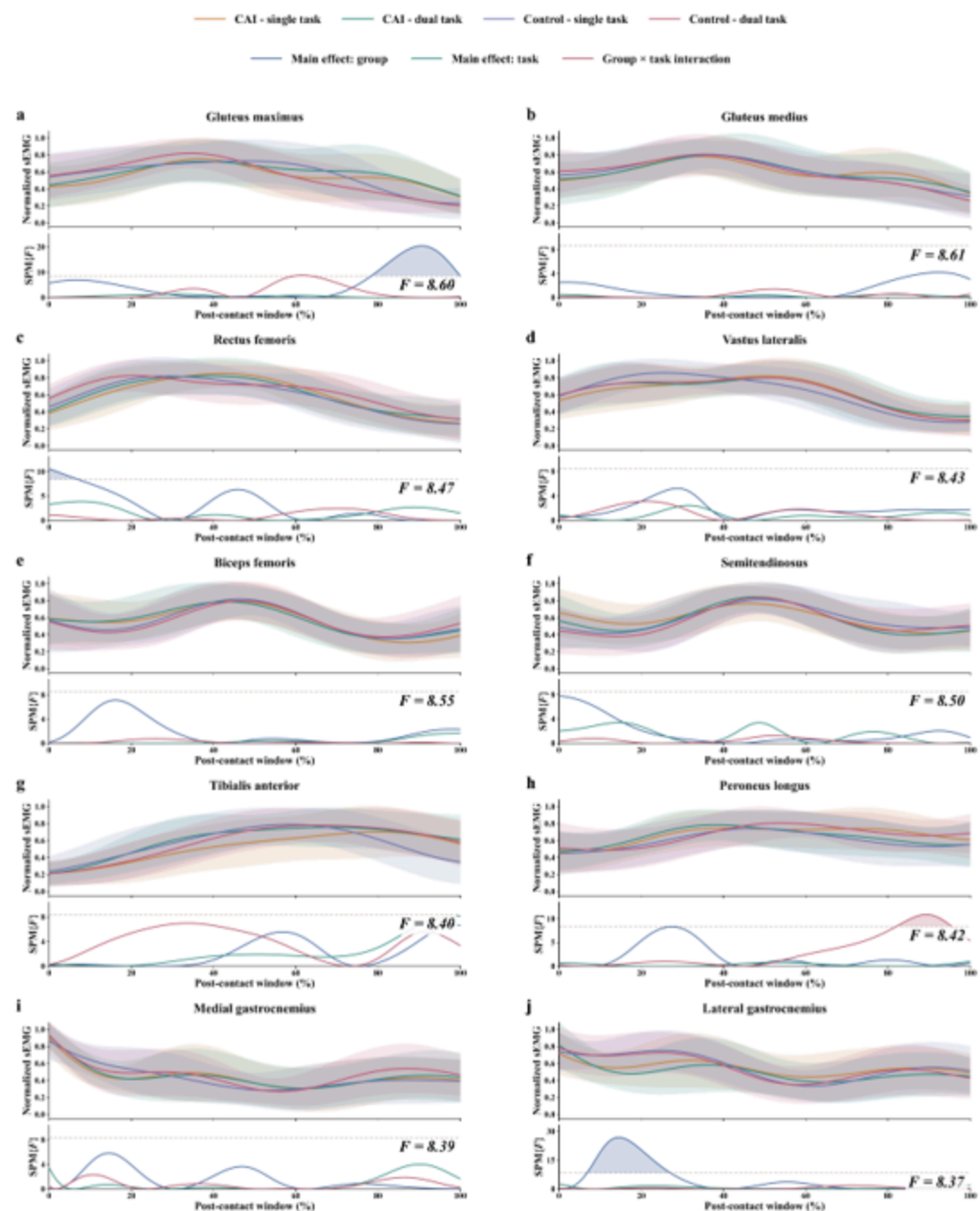


Figure 2

Time-resolved post-contact sEMG profiles and SPM1d results across the 10 lower-limb muscles. Mean peak-normalized sEMG profiles and one-dimensional statistical parametric mapping (SPM1d) results are shown for (a) gluteus maximus, (b) gluteus medius, (c) rectus femoris, (d) vastus lateralis, (e) biceps femoris, (f) semitendinosus, (g) tibialis anterior, (h) peroneus longus, (i) medial gastrocnemius, and (j) lateral gastrocnemius during the first 200 ms after initial contact. Orange, green, blue, and pink lines represent the CAI single-task, CAI dual-task, control single-task, and control dual-task conditions, respectively; shaded regions indicate ± 1 SD. The corresponding SPM $\{F\}$ trajectories show the main effects of group and task and the group $\times$ task interaction. Horizontal dashed lines indicate the random-field-theory critical $F_{\text{threshold}}$ at $\alpha = 0.05$, and shaded supra-threshold regions indicate significant clusters. The horizontal axis represents 0%-100% of the fixed 200-ms post-contact window, such that 1% corresponds to 2 ms. CAI, chronic ankle instability; sEMG, surface electromyography; SPM1d, one-dimensional statistical parametric mapping.

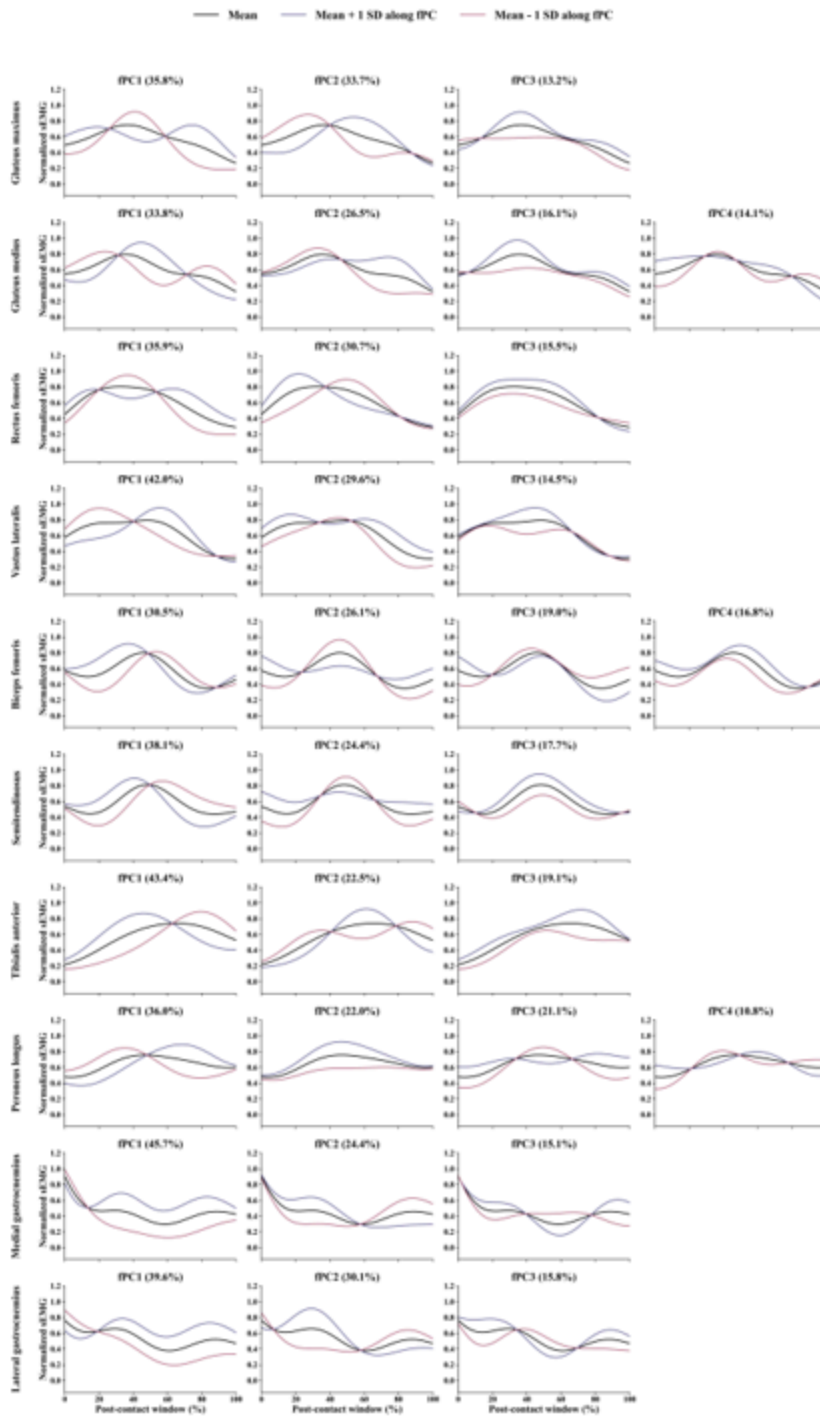


Figure 3

Functional principal component structure of post-contact sEMG profiles across the 10 lower-limb muscles. Retained functional principal component waveform modes are shown for the gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, biceps femoris, semitendinosus, tibialis anterior, peroneus longus, medial gastrocnemius, and lateral gastrocnemius. For each muscle, three or four fPCs were retained until the cumulative explained variance reached at least 80%. The percentage shown above each panel represents the proportion of total waveform variance explained by the corresponding fPC. Black lines represent the common mean waveform, whereas blue and pink lines represent the mean

waveform displaced by +1 SD and -1 SD, respectively, along the corresponding fPC direction. The horizontal axis represents 0%-100% of the fixed 200-ms post-contact window. fPC, functional principal component; sEMG, surface electromyography.

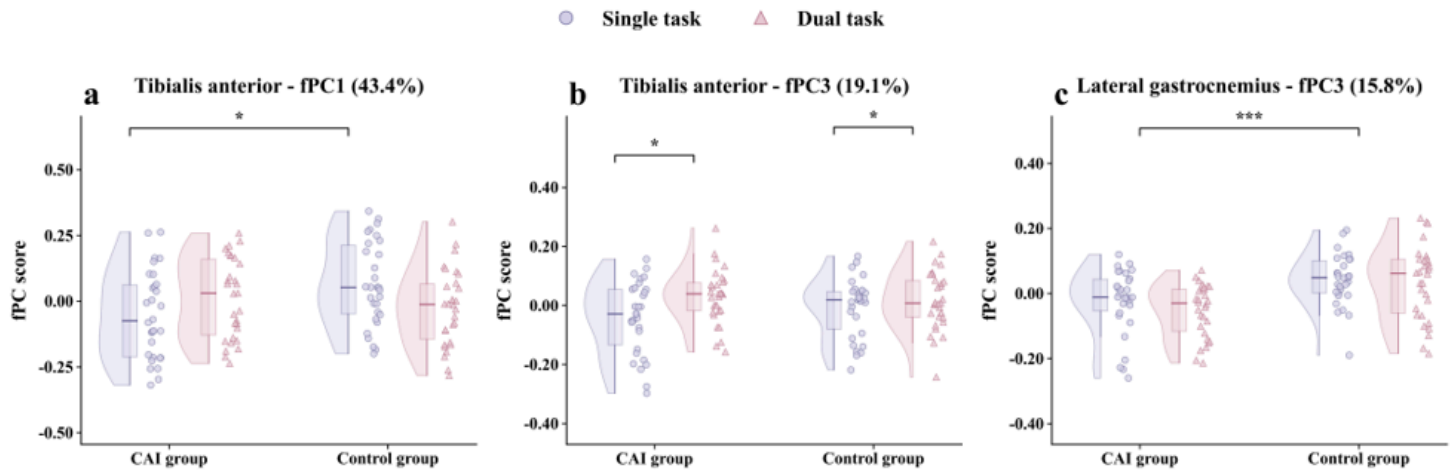


Figure 4

Group- and task-related differences in functional principal component scores. Participant-level fPC score distributions are shown for the components with significant Holm-adjusted effects: (a) tibialis anterior fPC1, explaining 43.4% of waveform variance; (b) tibialis anterior fPC3, explaining 19.1%; and (c) lateral gastrocnemius fPC3, explaining 15.8%. Circles and triangles represent the single- and dual-task conditions, respectively. Half-violin distributions, boxplots, and individual observations are displayed for the CAI and control groups. In (a), the bracket indicates the Bonferroni-adjusted simple effect following the significant group $\times$ task interaction. In (b), the annotation indicates the significant Task main effect. In (c), the bracket spanning the two groups indicates the significant group main effect. Asterisks indicate statistical significance (* $p < 0.05$, *** $p < 0.001$). CAI, chronic ankle instability; fPC, functional principal component.

Supplementary Files

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- [SupplementaryTableS1.docx](#)