Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics
Homepage: https://ijeeemi.org/; Vol. 8, No. 1, pp. 80-93, February 2026
e-ISSN: 2656-8624

RESEARCH ARTICLE

OPEN ACCESS

Influence of Visual Input and Surface Stability on Gastrocnemius Muscle Activation During Quiet Standing Using Multi-Feature EMG and Bilateral Assessment

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Abstract Postural stability depends on multisensory integration, yet most studies focus on a single EMG feature or sensory condition at a time. This creates a significant gap in understanding how multiple EMG features change when various sensory inputs are altered during quiet standing. To address this, the present study examined bilateral medial and lateral gastrocnemius activation using five EMG features: Mean Absolute Value (MAV), Root Mean Square (RMS), Waveform Length (WL), Integrated EMG (IEMG), and Total Power (PT) across four sensory conditions that combine visual input (eyes open or closed) and surface stability (stable or unstable). A one-way ANOVA revealed significant condition effects for RMS, MAV, WL, and IEMG ($p < 0.05$), while PT showed only a non-significant trend. Paired t-test results indicated that MAV significantly increased on the unstable surface with eyes closed compared to the stable surface ($t(4) = 4.793$, $p = 0.009$), WL increased in the right lateral gastrocnemius under the same condition ($t(4) = 3.976$, $p = 0.016$), and closing the eyes on a stable surface significantly increased WL in the right medial gastrocnemius ($t(4) = 6.209$, $p = 0.003$). Across features, the right gastrocnemius consistently showed greater modulation than the left, suggesting dominance-related asymmetry in neuromuscular control. This study provides one of the first bilateral multi-feature EMG characterizations of sensory perturbations during quiet standing. The findings demonstrate that the absence of vision increases neuromuscular demand even on stable surfaces, and that unstable surfaces further amplify activation, particularly in complexity-related features such as WL. These outcomes highlight the potential of EMG features, especially WL, as objective biomarkers for balance assessment. Clinically, the results may inform rehabilitation and fall-prevention programs by supporting the use of unstable surfaces and vision-restricted exercises to enhance proprioceptive and vestibular compensation.

Paper History
Received July 12, 2025
Revised August 20, 2025
Accepted January 23, 2026
Published Feb. 22, 2026

Keywords
Postural Control;
Surface Electromyography (sEMG);
Gastrocnemius Muscle Activation;
Balance Assessment

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I. Introduction

Maintaining postural stability is a crucial motor function for ensuring safety and efficiency in daily activities [1], [2]. This complex mechanism depends on integrating sensory information from the visual [3], [4], [5], [6], [7], vestibular [8], [9], [10], [11], [12], and somatosensory systems [13], [14], [15], [16], [17], [18], which coordinate muscular responses to sustain an upright stance [17], [19], [20], [21]. Among the lower-limb muscles, the gastrocnemius plays a critical role in stabilizing the ankle joint and maintaining postural control, particularly during perturbations [22], [23], [24]. As part of the triceps surae group, the gastrocnemius comprises medial and lateral heads that may contribute

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Digital Object Identifier (**DOI**): https://doi.org/10.35882/jeeemi.v8i1.297

differently depending on balance task demands. The activity patterns of these heads offer valuable insights into the neuromuscular strategies underlying balance maintenance.

Postural control is often explained through the frameworks of multisensory integration and mechanical stabilization [25], [26], [27]. According to sensory reweighting theory, the nervous system dynamically modifies its dependence on visual, vestibular, and somatosensory signals based on their reliability for maintaining balance. Biomechanical models, such as the inverted pendulum and spring–mass representations, complement this by depicting human posture as an actively stabilized, oscillating system that responds to internal and external disturbances through neuromuscular actions [28], [29]. These theoretical approaches help elucidate how visual deprivation or unstable surfaces can influence gastrocnemius muscle activation patterns during quiet standing. The essential role of the gastrocnemius in postural control has been demonstrated in studies examining the neurological correlates of muscle activity [7], [30], [31]. For example, one study reported intermuscular coherence across different frequency bands by capturing bilateral EMG signals from the anterior tibialis, medial gastrocnemius, and soleus muscles under varying stance conditions [32]. The findings showed stronger coherence in lower-frequency bands during more challenging postural tasks, supporting the hypothesis that intermuscular coherence involving the gastrocnemius may serve as a neural marker of postural stability. Surface electromyography (sEMG) has been extensively utilized to investigate neuromuscular contributions to movement and balance. An increasing number of studies have adopted multi-feature EMG analysis to extract complementary information beyond single descriptors such as Root Mean Square (RMS). For instance, features including auto-regressive (AR) coefficients, Mean Absolute Value (MAV), variance (VAR), RMS, waveform length (WL), and zero-crossings (ZC) have been effectively employed to classify lower-limb movements such as walking, sitting, and standing [33]. Systematic evaluations of time- and frequency-domain features have also identified both redundant and informative subsets among numerous proposed EMG features, offering practical guidelines for optimizing feature selection in EMG classification, though such analyses are rarely applied to postural balance contexts [34].

Previous research has explored the role of the gastrocnemius in maintaining posture through various analytical methods. Studies by Rosario and Jose (2021) [7], Saraiva et al. (2024) [30], and Vendramini et al. (2023) [31] focused on the neural connections of muscle activity using intermuscular coherence analysis. Ojha et al. (2023) [32], specifically recorded bilateral EMG signals from the anterior tibialis, medial gastrocnemius, and soleus under different stance conditions, discovering stronger coherence in lower frequency bands during more challenging postural tasks. While these studies effectively highlighted neural coupling between muscles, they offered limited insights into the activation dynamics of individual muscles and did not quantify muscle responses at the feature level under sensory challenges. Naik et al. (2018) [33] explored multi-feature EMG analysis by combining AR coefficients, MAV, VAR, RMS, WL, and ZC features to classify lower-limb movements like walking and sitting. This method demonstrated strong classification performance but was primarily designed for dynamic movement tasks, without considering sensory influences such as vision or surface stability. In the realm of balance control, Ward et al. (2022) [35] analyzed sway complexity measures as task difficulty increased, confirming their sensitivity to postural demand. However, their use of inertial measurement units and single-feature analyses limited the understanding of muscle-level neuromuscular mechanisms.

Expanding the analytical framework, Chen et al. (2023) [36] implemented a multi-feature EMG model that integrated spatial and time–frequency domain descriptors for hand gesture recognition, demonstrating the robustness of multi-feature techniques, though this approach was not extended to postural stability or sensory perturbation paradigms.

Similarly, Al Quraish et al. (2021) [37] applied multi-feature EMG analysis to classify lower-limb movement during seated ankle motion; while effective for controlled joint tasks, this approach did not encompass upright stance or sensory integration aspects relevant to balance control. Lastly, Huang and Xiao (2023) [38] examined postural control under visual manipulation (eyes open vs. closed) by analyzing gastrocnemius EMG activity using one or two features such as RMS and IEMG. Although their study provided insight into visual effects on muscle activation, it focused on a single muscle head and lacked a comprehensive, multi-feature, bilateral analysis. Building on previous methodologies, this study integrated five complementary EMG features: MAV, RMS, WL, IEMG, and Total Power. MAV and RMS are amplitude-based metrics that indicate the level of muscle activation, while IEMG measures the total energy used over time. WL assesses signal complexity and rapid changes, making it particularly responsive to neuromuscular

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adjustments caused by instability. Total Power reflects alterations in the frequency distribution of the EMG signal. Collectively, these features provide a comprehensive view of neuromuscular strategies that single-feature analyses cannot achieve.

Although multisensory integration is crucial for balance control, earlier research has mainly evaluated postural regulation using center-of-pressure or sway metrics, with fewer studies examining muscle-level responses through multi-feature EMG analysis. Force-based analyses offer whole-body insights but fail to capture the subtle neuromuscular adjustments essential for ankle stabilization. By utilizing multi-feature EMG under systematically varied visual and surface conditions, this study addresses a significant gap in understanding how sensory information influences muscle-level strategies during postural control. Collectively, these six studies have enhanced the understanding of neuromuscular mechanisms in postural control, but have notable limitations. Intermuscular coherence analyses reveal neural coupling but lack muscle-specific feature characterization; multi-feature EMG studies offer robust classification power but overlook sensory contributions; and visual manipulation experiments provide behavioral insights yet lack bilateral and multi-feature EMG analysis.

To address these limitations, the present study incorporates bilateral recordings from the medial and lateral gastrocnemius, applies a comprehensive set of time-domain EMG features (RMS, MAV, WL, IEMG, and Total Power), and systematically manipulates visual and surface stability conditions. This integrative framework provides a richer and more interpretable understanding of how sensory information influences gastrocnemius activation during postural control. Specifically, this study offers a significant contribution by quantitatively describing how visual stimuli and surface stability influence gastrocnemius muscle activation through a comprehensive EMG analysis. It identifies Waveform Length (WL) as the most responsive feature for detecting neuromuscular changes during sensory disturbances and uncovers bilateral differences in the activation of the medial and lateral gastrocnemius, emphasizing side-specific neuromuscular adaptations often neglected in earlier studies. These findings enhance the understanding of sensorimotor strategies for balance maintenance and offer valuable insights for rehabilitation and fall-prevention efforts.

This study is organized as follows: Section II presents the participant information, proposed methods, and statistical analysis procedures. Section III presents the descriptive statistical results across all sensory conditions, providing an overview of how postural and EMG measures varied between stable vs. unstable surfaces and eyes-open vs. eyes-closed states. Section IV offers an interpretation of the findings, compares them with previous studies, and outlines the study’s limitations. Finally, Section V delivers the conclusions, restating the research objectives, summarizing the key findings, and proposing directions for future work.

II. Method

A. Participants

This study involved five healthy adult participants, consisting of three women and two men, with an average age of 21.5 years (SD = 0.81). Anthropometric data were gathered, showing an average height of 157.2 cm and an average weight of 52.4 kg. To be included in the study, participants had to be free of musculoskeletal injuries, neurological disorders, or balance issues. Those with a history of lower-limb surgery, vestibular problems, or who were taking medications affecting balance or neuromuscular function were excluded. Prior to joining the study, each participant signed a written informed consent form. The study protocol received approval from the Institutional Ethics Committee and adhered to the guidelines of the Padjadjaran University Bandung's Research Ethics Committee (Ethical Approval No. 1010/UN6.KEP/EC/2025).

B. Apparatus

The balance performance was evaluated under both stable and unstable surface conditions. An unstable surface was generated using a custom-built wobble board constructed of laminated plywood measuring 45 cm in length, 25 cm in width, and 10 cm in height. The board features a curved base that enables tilting, posing difficulties in stability in the medial-lateral direction.

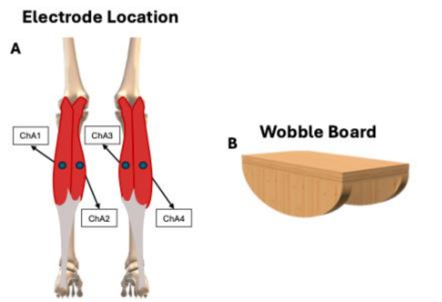

Fig. 1. EMG data collection a) Electrode placement on the medial and lateral gastrocnemius, adapted from SENIAM guidelines and prior EMG studies [39]. b) Wobble board used to create an unstable standing surface, consistent with approaches employed in earlier balance-control research [40], [41].

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Neuromuscular activity was measured using a BITalino wireless surface electromyography (sEMG) system (PLUX-Wireless Biosignals, S.A.) at a sampling rate of 1000 Hz and a resolution of 16 bits. sEMG electrodes were placed following guideline of SENIAM on the medial and lateral sides of both the left and right gastrocnemius muscles, which are important in the strategy for postural control. To ensure optimal signal quality, the skin was properly prepared to reduce impedance before placing four bipolar electrodes in the following configuration: A1 for the left lateral gastrocnemius, A2 for the left medial gastrocnemius, A3 for the right medial gastrocnemius, and A4 for the right lateral gastrocnemius (Fig. 1a). The gastrocnemius muscles were chosen due to their crucial involvement in the ankle-strategy mechanism, which serves as the main postural control method during quiet standing and moderate disturbances. Both the medial and lateral gastrocnemius are essential for managing plantarflexor torque and maintaining body stability during anterior-posterior sway, making them highly sensitive to variations in surface stability and sensory input. [32], [40], [42], [43]

C. Experimental Task

To minimize the order effects, the participants were instructed to complete four static balancing exercises in a random order. These included standing on a stable surface with eyes open (EOS) (Fig. 2a), standing on a stable surface with eyes closed (ECS) (Fig. 2b), standing on an unstable surface with eyes open (EOU) (Fig. 2c), and standing on an unstable surface with eyes closed (ECU) (Fig. 2d). Each task was completed for two consecutive minutes, with appropriate breaks between trials to prevent exhaustion. To standardize their posture, the participants stood barefoot and hip-width apart, with their arms relaxed at their sides. In eyes-closed situations, a blindfold was used to ensure complete visual deprivation. In this study, postural stability was assessed on two different surface conditions: stable and unstable. For the stable condition, participants stood barefoot on a solid, flat laboratory floor with their arms at their sides and feet positioned hip-width apart. In the unstable condition, participants stood on a wobble board, which consisted of a rigid rectangular platform measuring 45 cm in length and 25 cm in width. This platform was supported by two half-cylindrical curved bases along the underside of its longer edges. Each curve had a radius of about 10 cm, creating a rocker-like support surface that allowed controlled tilting in a single plane, with a usable tilt range of approximately 10–15°. Although wobble boards are commonly used in research on postural control and balance, there is no universally standardized set of dimensions or curvatures in the literature [44]; instead, studies typically use boards of similar size and shape to introduce controlled mechanical instability. Previous studies have demonstrated that tasks involving wobble boards have a strong correlation with force-plate center-of-pressure outcomes and consistently lead to increased neuromuscular and proprioceptive activity compared to stable surfaces, validating their use as models of unstable surfaces. Research on balance training with wobble boards has also shown that the curved base prompts continuous corrective adjustments, resulting in distinct sensorimotor strategies compared to standing on firm ground [45], [46], [47]. In this experiment, participants stepped off the wobble board between trials to reset their posture before each new condition.

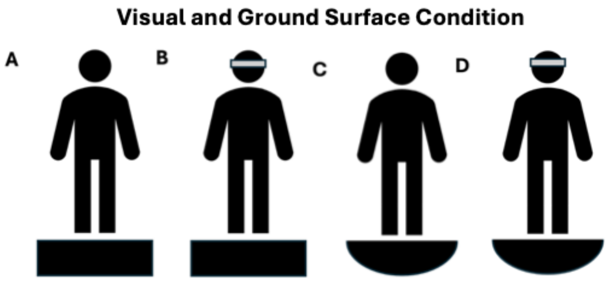

Fig. 2. Visual and ground Conditions: a) stable surface with eyes open (EOS), b) standing on a stable surface with eyes closed (ECS), c) standing on an unstable surface with eyes open (EOU), and d) standing on an unstable surface with eyes closed (ECU)

D. EMG Signal Processing

The raw EMG data were processed (Fig. 3) using MATLAB (R2024a, The MathWorks, Inc., Natick, Massachusetts, USA). The preprocessing pipeline used in this study is described explicitly here for reproducibility. Raw sEMG signals were first acquired through the system's built-in analog front end, which included the hardware pre-amplification integrated into the acquisition module. The signals were recorded in Analog-to-Digital Converter (ADC) units and subsequently converted into millivolts (mV) using a standard transfer function[48] (Eq. 1):

$$V_{signal} = \frac{ADC_{raw}}{2^{N-1}} \times V_{ref} \tag{1}$$

where N is the ADC resolution in bits and Vref is the system reference voltage. By applying this function, the signals were correctly scaled to the real voltage values, allowing for a consistent and quantitative examination in the subsequent phases. To ensure only steady-state muscle activity was analyzed, the first and last 10 seconds of each recording were removed to eliminate transitional artifacts. The trimmed signals were then

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filtered using a fourth-order Butterworth band-pass filter (20–450 Hz) to suppress low-frequency motion artifacts and high-frequency noise. No notch filter or rectification was applied, as the selected feature set did not require additional transformations. The resulting filtered signals were used directly for feature extraction. From the processed signals, various features were extracted to capture different physiological and mathematical aspects of muscle activity. Let x_i represent the EMG signal amplitude at the i^{th} sample, with N denoting the total number of samples.

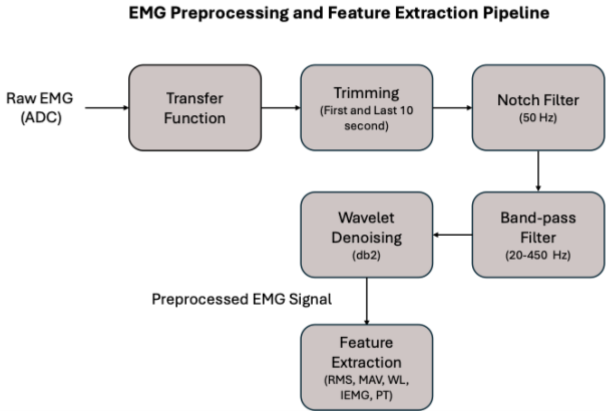

Fig. 3. EMG Preprocessing and Feature Extraction Pipeline

The Mean Absolute Value (MAV) [49] (Eq. (2)), which indicates the average level of muscle activity, is frequently employed to assess the overall intensity of muscle contraction. It is calculated as:

$$MAV = \frac{1}{N}\sum_{i=1}^{N}|x_i| \tag{2}$$

Where x_i is the i-th EMG sample, and N is the total number of samples. The Root Mean Square (RMS) [49] (Eq. (3)) quantifies the power content of a signal, offering insights into the strength and variability of muscle contractions. This is defined as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}x_i^2} \tag{3}$$

where x_i is the EMG amplitude at sample i and N is the number of samples. The Waveform Length (WL) [49] (Eq. (4)) quantifies the cumulative length of the signal waveform and is related to both frequency and amplitude changes, reflecting the complexity and smoothness of motor unit firing. It was computed using:

$$WL = \sum_{i=1}^{N-1}|x_{i+1} - x_i| \tag{4}$$

where x_i and x_{i+1} are consecutive EMG samples, and N is the total number of samples. The Integrated EMG (IEMG) [49] (Eq. (5)) quantifies the total rectified muscle activity over time, serving as a measure of overall muscle workload. It is defined as Eq. (5):

$$IEMG = \sum_{i=1}^{N}|x_i| \tag{5}$$

where x_i is the rectified EMG amplitude at the sample i, and N is the total sample count. Finally, the Total Power (PT) [49], [50] (Eq. (6)) was calculated from the power spectral density (PSD) using Welch's method. This metric estimates the total energy present in the EMG signal across all frequencies, capturing the overall activation energy during muscle contraction:

$$PT = \sum_f P_{xx}(f) \tag{6}$$

where $P_{xx}(f)$ is the PSD amplitude at frequency f, summed over all frequency bins. Features of amplitude (MAV, RMS), complexity (WL), cumulative activation (IEMG), and frequency-domain energy (PT) encompass various dimensions of muscle behavior, thereby offering a comprehensive depiction of neuromuscular control strategies during postural tasks.

E. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed to investigate the differences among the experimental conditions. ANOVA [51] divides the total variability into between-group and within-group variance, which is quantified as the Mean Square [52] (MS, Eq. (7)).

$$MS = \frac{SS}{df} \tag{7}$$

where SS denotes the sum of squares and df the degrees of freedom. The F-statistic [52] used to assess group differences is given in Eq. (8) as:

$$F = \frac{MS_{between}}{MS_{within}} \tag{8}$$

where $MS_{between}$ represents the variance between groups and MS_{within} represents the variance within groups. A significance level of $p<0.05$ was used to determine statistical differences. To further investigate the effects of vision (eyes open vs. eyes closed) and ground conditions (stable vs. unstable), paired t-tests [52] were performed. The paired t-statistic was determined using Eq. (9),

$$t = \frac{\bar{d}}{S_d/\sqrt{n}} \tag{9}$$

where the numerator is the mean of the paired differences $\bar{d}$ (Eq. 10),

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i \tag{10}$$

and the denominator is the standard error of the differences based on the standard deviation of differences S_d (Eq. 11)

$$S_d = \sqrt{\frac{\sum(d_i-\bar{d})^2}{n-1}} \tag{11}$$

Where $d_i - \bar{d}$ represents the deviation of each paired difference from the mean difference. When a significant main effect of condition was observed, post-hoc pairwise comparisons were conducted using Bonferroni-corrected tests to control for multiple comparisons across the six possible condition pairs. This correction was applied automatically through MATLAB's multcompare function using the Bonferroni adjustment.

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III. Result

The results showed a clear trend of increased muscle activation when the participants were subjected to more difficult balancing conditions. The average of the four muscle channels, A1, A2, A3, and A4, which correspond to the left lateral gastrocnemius, left medial gastrocnemius, right medial gastrocnemius, and right lateral gastrocnemius, respectively, increased systematically from the least challenging condition (eyes open on stable ground, EOS) to the most challenging condition (eyes closed on unstable ground, ECU) for all the EMG features (Table 1).

Table 1. Mean values of EMG features averaged across four gastrocnemius channels for each balance condition.

EMG Feature	Stable-Open	Stable-Closed	Unstable-Open	Unstable-Closed
RMS	0.010	0.011	0.018	0.024
MAV	0.007	0.007	0.011	0.014
WL	8.1×10^{2}	8.3×10^{2}	1.3×10^{3}	1.6×10^{3}
IEMG	1×10^{3}	1.1×10^{3}	2.1×10^{3}	2.6×10^{3}
PT	3×10^{-4}	3×10^{-4}	8×10^{-4}	1.1×10^{-3}

Table 2. Significant EMG feature differences ($p < 0.05$) between ground conditions in the eyes-closed visual condition. The bolded and italicized values indicate the lowest p-values observed.

Feat-ure	Stable Ground	Unstable Ground	t	p
	Right Medial Gastrocnemius (A3)			
RMS	0.015 ± 0.003	0.046 ± 0.017	4.5	0.011
MAV	***0.009 ± 0.002***	***0.027 ± 0.011***	***4.8***	***0.009***
WL	$1x10^{3} \pm 2x10^{2}$	$3x10^{3} \pm 1x10^{3}$	3.7	0.022
IEMG	$1.4x10^{3} \pm 3x10^{2}$	$4.3x10^{3} \pm 1x10^{3}$	4.8	0.009
	Right Lateral Gastrocnemius (A4)			
RMS	0.012 ± 0.006	0.018 ± 0.009	2.9	0.046
MAV	0.009 ± 0.004	0.012 ± 0.006	2.9	0.042
WL	***$9x10^{2} \pm 5x10^{2}$***	***$1.3x10^{3} \pm 6x10^{2}$***	***3.9***	***0.016***
IEMG	$1.3x10^{3} \pm 7x10^{2}$	$1.9x10^{3} \pm 9x10^{2}$	2.9	0.041

The most noticeable change was observed in channel A3, which represents the right medial gastrocnemius. A one-way repeated-measures ANOVA revealed significant condition effects for four EMG features: RMS (F(3,16) = 5.50, p = 0.013), MAV (F(3,16) = 4.89, p = 0.013), WL (F(3,16) = 3.38, p = 0.044), and IEMG (F(3,16) = 4.80, p = 0.014). In contrast, the Total Power (PT) feature showed a non-significant trend toward higher activation under more challenging conditions (F(3,16) = 2.58, p = 0.090), indicating that PT was less sensitive to surface and vision manipulations than the other four EMG features.

Table 3. Significant EMG feature differences ($p < 0.05$) between visual conditions on stable ground conditions. The bolded and italicized values indicate the lowest p-values observed.

Feat-ure	Open Eye	Closed Eye	t	p
	Right Medial Gastrocnemius (A3)			
RMS	0.01 ± 0.002	0.015 ± 0.003	-6	0.004
MAV	0.006 ± 0.002	0.009 ± 0.002	-4.6	0.009
WL	***$6.9x10^{2} \pm 2x10^{2}$***	***$1x10^{3} \pm 2.8x10^{2}$***	***-6.2***	***0.003***
IEMG	$9.4x10^{2} \pm 3x10^{2}$	$1.4x10^{3} \pm 3x10^{2}$	-4.9	0.008
PT	$9x10^{-5} \pm 4.4x10^{-5}$	$2x10^{-4} \pm 8x10^{-5}$	-4.7	0.009

Post-hoc analyses revealed that surface instability led to the most significant increases in postural sway. The most notable changes were observed when comparing a stable surface with eyes open (EOS) to an unstable surface with eyes closed (ECU), as indicated by RMS (+0.0368, p = 0.035), MAV (+0.0209, p = 0.040), WL (+2377.3, p = 0.083), and IEMG (+3418.5, p = 0.041). Conversely, the visual condition on an unstable surface had the least impact, as there were no differences in any features between the unstable surface with eyes open (EOU) and the unstable surface with eyes closed (ECU) (all Δ = 0, p = 1.0). These findings suggest that surface instability is the primary factor influencing sway changes, while the removal of vision has little effect when balance is already compromised.

We carried out additional examination to gain a deeper insight into how muscle activity reacts to visual and surface disruptions. Paired t-tests were employed to assess the primary impact of these disturbances. Initially, we evaluated the main effect of vision by comparing muscle activation when participants stood on both stable and unstable surfaces with their eyes either open or closed (Table 2). Subsequently, we assessed the main effect of surface stability by examining muscle activity in eyes-open versus eyes-closed scenarios on stable or unstable surfaces (Table 3). In terms of the main effect of vision, closing the eyes led to a significant increase in muscle activation on unstable surfaces compared to stable ones, especially in the right gastrocnemius muscle. Four EMG features from the

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Right Medial Gastrocnemius (A3) and Right Lateral Gastrocnemius (A4) were notably higher on the unstable surface (Table 2). The most pronounced differences were observed in the Mean Absolute Value (MAV) for A3 (Fig. 4, top; t(4) = 4.793, p = 0.009) and Wave Length (WL) for A4 (Fig. 4, bottom; t(4) = 3.976, p = 0.016), indicating increased muscle effort and signal complexity. However, no significant differences were detected in the PT or the Left Gastrocnemius muscles (A1 and A2), suggesting that the right leg is crucial for adjusting to balance disturbances under challenging conditions. Moreover, when the eyes were open, transitioning from stable to unstable surfaces did not result in significant changes in any EMG parameters (p > 0.05). This indicates that visual information effectively compensates for surface instability, reducing the need for muscle activity to maintain postural control.

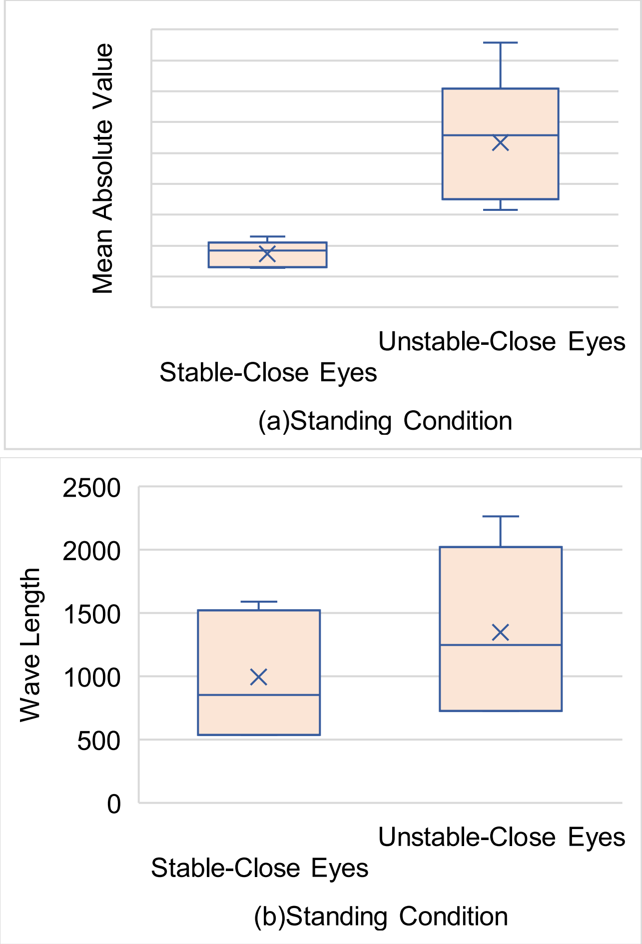

Fig. 4. Box plots of the most significant EMG features. A) Effect of ground conditions during eyes-closed trials for the right medial gastrocnemius (A3). B) Corresponding effect for the right lateral gastrocnemius (A4).

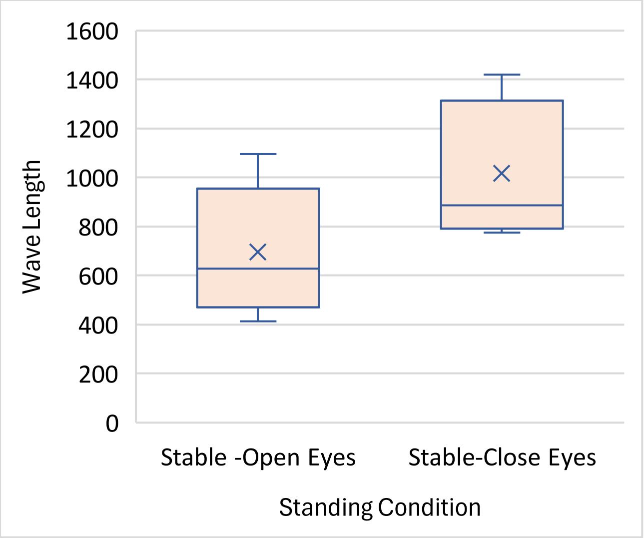

Fig. 5. Box plots showing the most significant EMG features affected by ground conditions

Regarding the main effect of surface stability, on a stable surface, closing the eyes significantly increased all EMG characteristics in the Right Medial Gastrocnemius (A3), as shown in Table 3. The most significant effect was noted for Wave Length (WL; Fig. 5, t(4) = 6.209, p = 0.0034), highlighting the importance of visual input in decreasing muscular demand during stable posture. However, under unstable surface conditions, no significant differences were observed between eyes-open and eyes-closed conditions (p > 0.05), suggesting that when postural challenges are already high due to surface instability, visual input plays a lesser role, and balance control may rely more on proprioceptive and vestibular input.

IV. Discussion

This study examined the effects of visual input and surface stability on gastrocnemius muscle activity during quiet standing using five time-domain EMG features: Root Mean Square (RMS), Mean Absolute Value (MAV), Waveform Length (WL), Integrated EMG (IEMG), and Total Power (PT). Several significant findings highlight how the neuromuscular system responds to sensory disturbances in balance control. The statistical analysis revealed significant differences in four of five EMG features across conditions. A one-way ANOVA showed significant effects for RMS (F(3,16) = 5.50, p = 0.013), MAV (F(3,16) = 4.89, p = 0.013), WL (F(3,16) = 3.38, p = 0.044), and IEMG (F(3,16) = 4.80, p = 0.014), with muscle activation increasing progressively from the least to the most challenging situations (EOS, ECS, EOU, and ECU, as depicted in Figure 2A–D). In contrast, PT (F(3,16) =

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2.58, p = 0.090) exhibited only a non-significant trend toward increased activation. These findings suggest that while overall energy expenditure remained relatively stable, variables related to amplitude, energy, and signal complexity were more sensitive to sensory manipulation. Among these, WL showed the greatest fluctuation, highlighting its value as an indicator of signal complexity and variability in motor unit recruitment [34].

Waveform Length (WL) captures both amplitude and timing variations in the EMG waveform, detecting rapid shifts and irregularities in muscle activity that amplitude-only features, such as RMS and MAV, might overlook. In recent EMG studies, WL is recognized as a sensitive indicator of signal complexity and temporal fluctuations, highlighting dynamic changes in motor unit recruitment patterns as task demands vary. In unstable or visually limited conditions, frequent corrective bursts and increased variability in motor unit recruitment produce sharper waveform transitions. These swift adjustments increase overall waveform length, making WL particularly sensitive to subtle shifts in neuromuscular control. I.

In this regard, labeling WL as “complexity-related” underscores its sensitivity to the temporal structure and irregularity of the EMG signal, which physiologically represents rapid modulation of firing rates, intermittent recruitment of additional motor units, and moment-to-moment corrective fluctuations typical of postural control under challenging sensory conditions. This contrasts with amplitude-based features, which mainly reflect the overall magnitude of muscle excitation rather than its temporal richness or dynamic variability.

Conversely, amplitude-based features like RMS and MAV primarily indicate the average magnitude of muscle excitation, which rises when the neuromuscular system compensates for reduced visual input or mechanical stability. IEMG, representing the cumulative area under the EMG curve, responds strongly to sustained increases in neural drive, especially during prolonged balance challenges. Collectively, these distinctions illustrate that RMS, MAV, and IEMG capture the overall level of neuromuscular effort, whereas WL uniquely reflects the complexity and frequency of corrective adjustments needed under more demanding sensory conditions.

An asymmetry in activation patterns between the left and right gastrocnemius muscles was also noted. The right gastrocnemius (A3 and A4) displayed more pronounced changes across both visual and surface conditions compared to the left gastrocnemius (A1 and A2). One possible explanation for this asymmetry is limb dominance. All participants in this study reported having a dominant right limb and engaged in everyday tasks, such as writing, using their right hand, which might lead to more consistent control on that side. Nonetheless, since no formal assessment of limb dominance beyond self-reporting was conducted, and no left-dominant individuals were included for comparison, this interpretation should be considered a plausible but unverified explanation rather than a definitive conclusion. Promsri (2022) [54] similarly reported that balancing on the non-dominant leg reduced the coupling between semitendinosus muscle activity and postural sway, with an effect size of –0.462, indicating a moderate dominance-related difference in neuromuscular coordination. These findings support the interpretation that the dominant limb contributes more actively to postural stabilization, providing greater adaptability across varying sensory and mechanical demands.

An independent analysis of the primary effects of vision and surface stability revealed consistent patterns. Regarding the main effect of vision, four EMG features (RMS, MAV, WL, and IEMG) were more pronounced on unstable surfaces compared to stable ones in A3 and A4, but only when the eyes were closed. The most significant features were MAV ($t(4) = 4.793$, $p = 0.009$) in the right medial gastrocnemius and WL ($t(4) = 3.976$, $p = 0.016$) in the right lateral gastrocnemius. With eyes open, these differences were not significant. This suggests that visual feedback effectively compensates for proprioceptive challenges on unstable ground, thereby reducing the need for heightened neuromuscular activation.

When individuals have their eyes open, they can utilize abundant visual information such as optic flow, visual landmarks, and motion signals to perceive their own body sway and make timely adjustments. This enables the central nervous system to maintain balance through visually guided control methods, even when proprioceptive input is less reliable. Consequently, muscle activation levels on unstable surfaces with open eyes become similar to those on stable surfaces, accounting for the absence of significant differences between surface conditions. This adaptive mechanism is consistent with the sensory-reweighting framework, where the CNS increases its dependence on the most reliable sensory input based on the environmental context.

A similar compensatory mechanism was observed in the findings of Sozzi et al. (2021) [55], who demonstrated that, when standing on a compliant (foam) surface, visual input reduced the center-of-pressure (CoP) ellipse area by approximately 61% and the CoP path length by 53% compared to the eyes-closed condition. Their spectral analysis further showed that vision lowered the median oscillation frequency by 63% in the mediolateral (ML) and 60% in the anteroposterior (AP) directions, reflecting a substantial stabilizing effect. Consistent with these observations, the present study found that removing

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visual input increased WL by roughly 45% under otherwise stable conditions, indicating that vision similarly reduces the need for rapid corrective bursts and dampens the temporal irregularity of muscle activation. Together, these results quantitatively demonstrate how vision mitigates instability-induced demands on the postural control system, supporting the sensory reweighting framework in which the central nervous system dynamically adjusts the weighting of sensory inputs based on contextual reliability.

In examining the primary effect of surface stability, it was noted that on a stable surface, all EMG features in A3 increased when the eyes were closed compared to when they were open, with the WL feature ($t(4) = 6.209$, $p = 0.003$) showing the most significant rise. This suggests that even with relatively low postural demands, the lack of vision requires greater neuromuscular effort.

In contrast, on the unstable surface, the absence of a significant difference between eyes-open and eyes-closed conditions suggests a ceiling effect: instability imposes such high sensory and neuromuscular demands that activation is already near the upper functional range required for balance, leaving limited capacity for further increases when vision is removed. In this scenario, both surface instability and vision loss push the system toward maximal corrective engagement, but instability dominates the sensory weighting.

Mademli et al. (2021) [56] similarly found that surface-related perturbations significantly impacted postural control, showing an average 12% increase in local instability across body segments from the ankle to the head when standing on unstable versus stable surfaces. Their use of local dynamic stability (sMLE) metrics based on kinematic data illustrated how instability propagates through the kinetic chain. Consistent with this, the present study also showed substantial surface-dependent changes: in right medial gastrocnemius, WL increased by approximately 200% when transitioning from the stable to the unstable surface, indicating a major rise in corrective neuromuscular activity under heightened stability demands. In the right lateral gastrocnemius, WL rose by about 44% across the same transition, reflecting a similar but comparatively smaller elevation. Collectively, these findings underscore that surface instability heightens sensorimotor demands and increases reliance on proprioceptive and vestibular feedback mechanisms to maintain balance.

Despite these significant findings, several limitations should be acknowledged. First, EMG recordings were limited to the gastrocnemius muscles, which restricts insight into the coordinated activation of other key postural muscles, such as the tibialis anterior or proximal stabilizers (e.g., quadriceps, gluteus medius). Since postural control depends on the coordination of multiple muscle groups, concentrating on just one group offers an incomplete understanding of the neuromuscular strategies involved in maintaining balance. Future research direction using multi-muscle EMG arrays could provide a more comprehensive analysis of these interactions.

Moreover, the relatively small sample size in this study might reduce statistical power and limit the applicability of the results to larger populations. The recruitment process also lacked detailed classification of limb dominance and gender-based analysis. As dominance and gender can affect neuromuscular control strategies, their omission might obscure potential differences in muscle activation related to side or demographic factors. Expanding the sample size and including these classifications in future research would enhance the interpretability and external validity of the findings.

The study also relied on surface EMG, which, while non-invasive, may be affected by cross-talk and skin impedance variability. Finally, the experimental setup simulated balance tasks under controlled laboratory conditions that may not fully capture the dynamic real-world postural challenges.

Although there are some limitations, this study presents valuable implications for both balance research and practical applications. By examining how sensory conditions and surface stability affect neuromuscular activation, it lays the groundwork for creating specific balance training and rehabilitation programs. For instance, using unstable surfaces or tasks that limit vision can be effectively employed to boost proprioceptive sensitivity, improve lower-limb coordination, and enhance strategies for maintaining posture. These methods are especially pertinent for older adults, those with balance challenges, or athletes aiming to optimize neuromuscular performance. Furthermore, monitoring muscle activity through EMG provides a useful means to objectively assess training progress or rehabilitation results, allowing clinicians or trainers to tailor interventions and track improvements over time.

V. Conclusion

This study aimed to explore the impact of visual input and surface stability on lower-limb muscle activation patterns during quiet standing, as measured through various EMG features. It quantified how sensory conditions shape neuromuscular responses and determined whether surface instability or visual deprivation produced greater changes in activation. The findings revealed distinct modulation of gastrocnemius activity driven by sensory input and surface conditions. Specifically, the Waveform Length (WL) increased by roughly 200% in the right medial

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gastrocnemius and by about 44% in the right lateral gastrocnemius when transitioning from stable to unstable surfaces, indicating a significant rise in neuromuscular corrective effort under heightened instability. Additionally, closing the eyes resulted in an approximate 45% increase in WL, highlighting the essential role of vision in stabilization. These results confirm that both surface instability and lack of visual input significantly heighten the demand on postural control systems through increased muscle activation.

The observed asymmetry in gastrocnemius activation indicates that limb dominance should be considered when evaluating postural control strategies. Clinically, these results could inform rehabilitation for individuals with compromised proprioceptive or visual systems, emphasizing the potential to enhance balance by targeting specific sensory modalities and considering limb dominance in therapeutic intervention design.

While these contributions are noteworthy, it is important to recognize certain limitations. The study's sample was composed of a small group of healthy young adults, which limits the ability to generalize the findings to older individuals or those with clinical conditions. Additionally, the research concentrated solely on static stance tasks and did not incorporate analyses like frequency-domain metrics or muscle synergy decomposition, which could provide more comprehensive insights into neuromuscular strategies. Future studies should aim to include larger samples (15–20 participants or more), encompass a wider range of populations, extend to dynamic balance tasks, and explore long-term training adaptations using multi-feature EMG methods.

From a practical standpoint, these findings suggest that EMG metrics, particularly WL, can serve as objective biomarkers for assessing balance and neuromuscular control. Rehabilitation and fall-prevention programs could benefit from incorporating training on unstable surfaces and in vision-deprived conditions to enhance proprioceptive and vestibular compensation. Monitoring changes in WL over time could provide a sensitive measure of progress, helping clinicians and trainers tailor interventions to individual needs.

Acknowledgment

The authors would like to express their sincere gratitude to the School of Electrical Engineering, Telkom University, for the invaluable support and resources provided throughout this research. The facilities, academic environment, and guidance from faculty members have greatly contributed to the successful completion of this work. This study would not have been possible without the department's dedication to fostering research and innovation in biomedical engineering.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contribution

Liana Nafisa conceptualized and designed the study, conducted data collection, and participated in data analysis and interpretation. Gloria Belinda, Ashila Ghaitsa, and Latifa Majesta contributed to data collection. Hesty Susanti conceptualized the study and provided critical feedback on the manuscript. All authors reviewed and approved the final version of the manuscript and agreed to be responsible for all aspects of the work to ensure its integrity and accuracy.

Declarations

Ethical Approval

The study protocol was reviewed and approved by the institutional ethics committee and conducted in accordance with the Research Ethics Committee of Padjadjaran University Bandung (*Ethical Approval* No.1010/UN6.KEP/EC/2025). Informed consent was obtained from all of participants, and confidentiality and anonymity of the participants were maintained throughout the research process. All procedures adhered to ethical guidelines for research involving human subjects.

Consent for Publication Participants.

Consent for publication was given by all participants

Competing Interests

The authors declare no competing interests.

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Liana Nafisa Saftari is a faculty member of the Biomedical Engineering Study Program, School of Electrical Engineering, Telkom University. She earned her Bachelor's degree in Biomedical Electronic Engineering from Universiti Malaysia Perlis in 2014 and received her Ph.D. in Biomedical Engineering from the Ulsan National Institute of Science and Technology (UNIST), South Korea. Her research interests include sensory processing, brain and cognitive science, and signal processing, with a focus on understanding neural and physiological mechanisms underlying human perception and performance. She actively integrates engineering, neuroscience, and experimental research

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methodologies to develop innovative tools and analytical approaches for cognitive assessment and biomedical applications.

Hesty Susanti is a faculty member of the Biomedical Engineering Study Program, School of Electrical Engineering, Telkom University. She earned her Bachelor's degree in Engineering Physics in 2008 and her Master's degree in Instrumentation and Control from Bandung Institute of Technology in 2010. Prior to her Doctoral study, she was a research fellow focusing on ultrasound for medical diagnostics in the Chair of Medical Engineering, Ruhr University, Germany, from 2011-2015. She received her Ph.D in Engineering Physics from Bandung Institute of Technology in 2020.

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Latifa Majesta Saputra obtained her Bachelor's degree in Biomedical Engineering from Telkom University in 2025. Her research interests include medical physics and biomedical instrumentation, with a particular focus on sport engineering and electromyography (EMG). Throughout her undergraduate studies, she developed a strong interest in applying biomedical engineering principles and physiological signal analysis to support musculoskeletal assessment, performance optimization, and rehabilitation in sports-related contexts. She has also explored the role of sensor-based measurement systems in improving training strategies and injury prevention. Her long-term goal is to contribute to the development of innovative tools and evidence-based methods to enhance clinical evaluation and athletic performance monitoring.

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Rerefences

[1] S. Lopes, M. Rodrigues, M. Lopes, R. Costa, and J. Alvarelhão, "Evaluating the Impact of Active Footwear Systems on Vascular Health and Static Balance: An Exploratory Study," *Sensors 2025, Vol. 25, Page 1724*, vol. 25, no. 6, p. 1724, Mar. 2025, doi: 10.3390/S25061724.

[2] H. Susanti, H. Mukhtar, D. Rahmawati, M. Arik Geraldy Fauzi, and S. Setiyadi, "Somatotype and Center of Pressure (CoP) Measurements with a Force Platform to Determine the Influence of Body Morphology on Standing Posture Balance," *Jurnal Otomasi Kontrol dan Instrumentasi*, vol. 14, no. 2, pp. 87–99, Oct. 2022, doi: 10.5614/JOKI.2022.14.2.3.

[3] Y. Okayama, M. Maekawa, and S. Daikuya, "Postural control strategies with alterations in visual input conditions in a standing position," *Eur. J. Appl. Physiol.*, vol. 125, no. 3, pp. 707–714, Mar. 2025, doi: 10.1007/S00421-024-05635-8/METRICS.

[4] L. N. Saftari and O. S. Kwon, "Ageing vision and falls: A review," *J. Physiol. Anthropol.*, vol. 37, no. 1, pp. 1–14, 2018, doi: 10.1186/s40101-018-0170-1.

[5] R. R. Onofrei and E. Amaricai, "Postural Balance in Relation with Vision and Physical Activity in

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Digital Object Identifier (**DOI**): https://doi.org/10.35882/jeeemi.v8i1.297

Healthy Young Adults," *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 5021*, vol. 19, no. 9, p. 5021, Apr. 2022, doi: 10.3390/IJERPH19095021.

[6] D. Lafleur and Y. Lajoie, "The impact of eye movement on postural control depends on the type of oculomotor behavior and the visual task," *Gait Posture*, vol. 100, pp. 65–69, Feb. 2023, doi: 10.1016/J.GAITPOST.2022.12.002.

[7] M. G. ROSARIO and A. JOSE, "The Impact of balance and visual feedback on tibialis anterior/gastrocnemius neuromuscular activation timing in healthy young adults," *Human Movement*, vol. 22, no. 4, pp. 46–55, Jun. 2021, doi: 10.5114/HM.2021.103289.

[8] N. I. Bohnen, P. Kanel, M. van Emde Boas, S. Roytman, and K. A. Kerber, "Vestibular Sensory Conflict During Postural Control, Freezing of Gait, and Falls in Parkinson's Disease," *Movement Disorders*, vol. 37, no. 11, pp. 2257–2262, Nov. 2022, doi: 10.1002/MDS.29189;WEBSITE:WEBSITE:MOVEMENTDISORDERS;JOURNAL:JOURNAL:15318257;REQUESTEDJOURNAL:JOURNAL:15318257;WGROUP:STRING:PUBLICATION.

[9] J. Esteban-Sanchez and E. Martin-Sanz, "Long-Term Evolution of Vestibular Compensation, Postural Control, and Perceived Disability in a Population of Patients with Vestibular Neuritis," *Journal of Clinical Medicine 2022, Vol. 11, Page 3941*, vol. 11, no. 14, p. 3941, Jul. 2022, doi: 10.3390/JCM11143941.

[10] M. Chepisheva, "The Vestibular System and Its Implications in Spatial Orientation and Postural Control," *SSRN Electronic Journal*, Dec. 2021, doi: 10.2139/SSRN.3988338.

[11] R. McLaren, P. F. Smith, R. L. Taylor, I. K. Niazi, and D. Taylor, "Scoping out noisy galvanic vestibular stimulation: a review of the parameters used to improve postural control," *Front. Neurosci.*, vol. 17, p. 1156796, May 2023, doi: 10.3389/FNINS.2023.1156796/BIBTEX.

[12] M. K. Chepisheva, "Spatial orientation, postural control and the vestibular system in healthy elderly and Alzheimer's dementia," *PeerJ*, vol. 11, p. e15040, May 2023, doi: 10.7717/PEERJ.15040.

[13] J. Nakamura *et al.*, "Effects of postural-control training with different sensory reweightings in a patient with body lateropulsion: a single-subject design study," *Physiother. Theory Pract.*, vol. 40, no. 11, pp. 2701–2711, Nov. 2024, doi: 10.1080/09593985.2023.2274943;REQUESTEDJOURNAL:JOURNAL:IPTP20;WGROUP:STRING:PUBLICATION.

[14] A. Kahveci, B. C. Cengiz, V. Alcan, S. Gürses, and M. Zinnuroğlu, "The effect of foot somatosensory loss in postural control during Functional reach test in patients with diabetic polyneuropathy: A controlled study," *The Foot*, vol. 59, p. 102097, Jun. 2024, doi: 10.1016/J.FOOT.2024.102097.

[15] Z. Chen, O. Tirosh, J. Han, R. Adams, D. El-Ansary, and A. Pranata, "Lower Limb Proprioception in Low Back Pain and Its Relationship With Voluntary Postural Control," *J. Mot. Behav.*, vol. 56, no. 6, pp. 760–771, 2024, doi: 10.1080/00222895.2024.2341712;SUBPAGE:STRING:FULL.

[16] E. Lirani-Silva, V. S. Beretta, A. M. F. Jimenez, and L. T. B. Gobbi, "Postural Control and Somatosensory Information: Effects of Aging and Parkinson's Disease," *Locomotion and Posture in Older Adults: The Role of Aging and Movement Disorders, Second Edition*, pp. 385–399, Jan. 2024, doi: 10.1007/978-3-031-74123-4_20.

[17] A. Marchant, J. Witchalls, S. B. Wallwork, N. Ball, and G. Waddington, "The Correlation Between Ankle Somatosensory Acuity and Sensory Organisation in Postural Stability," *Percept. Mot. Skills*, 2025, doi: 10.1177/00315125251343158/ASSET/940BE17D-6DF7-4BEE-B0FE-2D79A49ABE86/ASSETS/IMAGES/LARGE/10.1177_00315125251343158-FIG3.JPG.

[18] Z. Liu, Q. Wang, W. Sun, and Q. Song, "Balancing sensory inputs: somatosensory reweighting from proprioception to tactile sensation in maintaining postural stability among older adults with sensory deficits," *Front. Public Health*, vol. 11, p. 1165010, May 2023, doi: 10.3389/FPUBH.2023.1165010/BIBTEX.

[19] S. Nozu, K. A. Johnson, M. Takemura, and R. K. Shields, "Disrupted somatosensory input alters postural control strategies during the Star Excursion Balance Test (SEBT) in healthy people," *Gait Posture*, vol. 90, pp. 141–147, Oct. 2021, doi: 10.1016/J.GAITPOST.2021.08.023.

[20] K. O. Appiah-Kubi, A. Galgon, R. Tierney, R. Lauer, and W. G. Wright, "Concurrent vestibular activation and postural training recalibrate somatosensory, vestibular and gaze stabilization processes," *PLoS One*, vol. 19, no. 7, p. e0292200, Jul. 2024, doi: 10.1371/JOURNAL.PONE.0292200.

[21] P. Sung and P. Rowland, "Impact of sensory reweighting strategies on postural control using the sensory organization test in older adults with and without fall risks," *Physiotherapy Research*

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Digital Object Identifier (**DOI**): https://doi.org/10.35882/jeeemi.v8i1.297

International, vol. 29, no. 2, p. e2075, Apr. 2024, doi: 10.1002/PRI.2075.

[22] H. Yakut, V. A. Ayyıldız, Z. Bekar, M. Kayan, and S. Kutluhan, “The Relationship of Gastrocnemius-Soleus Muscle Architecture with Balance and Functional Strength in Acute Stroke Patients,” *J. Mot. Behav.*, vol. 56, no. 4, pp. 486–495, 2024, doi: 10.1080/00222895.2024.2329697.

[23] S. Y. Yi *et al.*, “Effects of Open Kinetic Chain Exercise for the Gastrocnemius and Tibialis Anterior Muscles on Balance,” *The Journal of Korean Physical Therapy*, vol. 33, no. 6, pp. 278–285, Dec. 2021, doi: 10.18857/JKPT.2021.33.6.278.

[24] G. Marcolin *et al.*, “Neuromuscular Fatigue Affects Calf Muscle Activation Strategies, but Not Dynamic Postural Balance Control in Healthy Young Adults,” *Front. Physiol.*, vol. 13, Jan. 2022, doi: 10.3389/FPHYS.2022.799565,.

[25] J. Ketterer, A. Gollhofer, S. Ringhof, L. Assländer, U. Granacher, and D. Gehring, “Effects of balance training with visual input manipulations on balance performance and sensory integration in healthy young adults: a randomized controlled trial,” *Scientific Reports 2024 14:1*, vol. 14, no. 1, pp. 28589-, Nov. 2024, doi: 10.1038/s41598-024-79736-x.

[26] T. C. K. Cheung and M. A. Schmuckler, “Multisensory and biomechanical influences on postural control in children,” *J. Exp. Child Psychol.*, vol. 238, p. 105796, Feb. 2024, doi: 10.1016/j.jecp.2023.105796.

[27] L. Asslander and R. J. Peterka, “Sensory reweighting dynamics in human postural control,” *J Neurophysiol*, vol. 111, no. 9, pp. 1852–1864, 2014, doi: 10.1152/jn.00669.2013.

[28] Y. YAMANAKA and K. YOSHIDA, “Modeling of human center of pressure using a viscoelastic-supported inverted pendulum,” *Mechanical Engineering Journal*, vol. 12, no. 3, pp. 24–00464, 2025, doi: 10.1299/mej.24-00464.

[29] A. M. Selvitella and K. L. Foster, “The Spring-Mass Model and Other Reductionist Models of Bipedal Locomotion on Inclines,” *Integr. Comp. Biol.*, vol. 62, no. 5, pp. 1320–1334, Dec. 2022, doi: 10.1093/icb/icac047.

[30] M. Saraiva, J. P. Vilas-Boas, and M. A. Castro, “Postural Control and Muscle Activity during Dual-Task in Young Adults,” *Behavioral Sciences 2024, Vol. 14, Page 403*, vol. 14, no. 5, p. 403, May 2024, doi: 10.3390/BS14050403.

[31] I. C. Vendramini, C. Papcke, P. S. da Veiga Neto, C. F. dos Santos, R. A. de Pinho, and E. M. Scheeren, “Older Adults with Pre-sarcopenia/Sarcopenia have Increased Gastrocnemius Muscle Activity to Maintain Upright Postural Control at Stance Perturbation,” *J. Med. Biol. Eng.*, vol. 43, no. 4, pp. 437–445, Aug. 2023, doi: 10.1007/S40846-023-00808-W/METRICS.

[32] A. Ojha, G. Alderink, and S. Rhodes, “Coherence between electromyographic signals of anterior tibialis, soleus, and gastrocnemius during standing balance tasks,” *Front. Hum. Neurosci.*, vol. 17, p. 1042758, Apr. 2023, doi: 10.3389/FNHUM.2023.1042758/BIBTEX.

[33] G. R. Naik *et al.*, “An ICA-EBM-Based sEMG Classifier for Recognizing Lower Limb Movements in Individuals With and Without Knee Pathology,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 3, pp. 675–686, Mar. 2018, doi: 10.1109/TNSRE.2018.2796070.

[34] A. Phinyomark, P. Phukpattaranont, and C. Limsakul, “Feature reduction and selection for EMG signal classification,” *Expert Syst. Appl.*, vol. 39, no. 8, pp. 7420–7431, Jun. 2012, doi: 10.1016/J.ESWA.2012.01.102.

[35] N. Ward *et al.*, “The Specificity of Cognitive-Motor Dual-Task Interference on Balance in Young and Older Adults,” *Front. Aging Neurosci.*, vol. 13, no. January, pp. 1–13, 2022, doi: 10.3389/fnagi.2021.804936.

[36] P. Zhang, Y. Li, Y. Zhuang, J. Kuang, X. Niu, and R. Chen, “Multi-level information fusion with motion constraints: Key to achieve high-precision gait analysis using low-cost inertial sensors,” *Information Fusion*, vol. 89, pp. 603–618, Jan. 2023, doi: 10.1016/J.INFFUS.2022.09.009.

[37] M. S. Al-Quraishi, I. Elamvazuthi, T. B. Tang, M. Al-Qurishi, S. Parasuraman, and A. Borboni, “Multimodal Fusion Approach Based on EEG and EMG Signals for Lower Limb Movement Recognition,” *IEEE Sens. J.*, vol. 21, no. 24, pp. 27640–27650, 2021, doi: 10.1109/JSEN.2021.3119074.

[38] Z. Huang and X. Xiao, “Characteristics of the postural stability of the lower limb in different visual states of undergraduate students with moderate myopia,” *Front. Physiol.*, vol. 13, Jan. 2023, doi: 10.3389/FPHYS.2022.1092710.

[39] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, and G. Rau, “Development of recommendations for SEMG sensors and sensor placement procedures,” *Journal of Electromyography and Kinesiology*, vol. 10, no. 5, pp. 361–374, Oct. 2000, doi: 10.1016/S1050-6411(00)00027-4.

[40] P. X. Fuchs, A. Fusco, T. Y. Shiang, C. Cortis, and H. Wagner, “Wobble Board Performance: A Practical and Useful Quantification in Balance Assessment,” *Applied Sciences 2024, Vol. 14,*

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Digital Object Identifier (**DOI**): https://doi.org/10.35882/jeeemi.v8i1.297

vol. 14, no. 14, Jul. 2024, doi: 10.3390/app14146113.

[41] B. K. Schilling, M. J. Falvo, R. E. Karlage, L. W. Weiss, C. A. Lohnes, and L. Z. F. Chiu, “Effects of unstable surface training on measures of balance in older adults,” *J. Strength Cond. Res.*, vol. 23, no. 4, pp. 1211–1216, Jul. 2009, doi: 10.1519/JSC.0b013e3181918a83.

[42] N. Kim, J. Park, H. Shin, and Y. Bae, “Gastrocnemius Medial Head Stiffness Is Associated with Potential Fall Risk in Community-Dwelling Older Adults,” *Healthcare 2022, Vol. 10, Page 785*, vol. 10, no. 5, p. 785, Apr. 2022, doi: 10.3390/HEALTHCARE10050785.

[43] C. E. Craig, D. J. Goble, and M. Doumas, “Proprioceptive acuity predicts muscle co-contraction of the tibialis anterior and gastrocnemius medialis in older adults’ dynamic postural control,” *Neuroscience*, vol. 322, pp. 251–261, 2016, doi: 10.1016/j.neuroscience.2016.02.036.

[44] T. Deligiannis and M. Mangalam, “Geometric principles of wobble board design for balance training and rehabilitation,” *Scientific Reports 2025 15:1*, vol. 15, no. 1, pp. 28933-, Aug. 2025, doi: 10.1038/s41598-025-07290-1.

[45] P. X. Fuchs, A. Fusco, T. Y. Shiang, C. Cortis, and H. Wagner, “Wobble Board Performance: A Practical and Useful Quantification in Balance Assessment,” *Applied Sciences 2024, Vol. 14,* vol. 14, no. 14, Jul. 2024, doi: 10.3390/app14146113.

[46] U. Yalnaz, M. U. Sarwar, S. Qureshi, H. S. Saeed, I. Manzoor, and N. Rasheed, “Effectiveness of Wobble Board Exercises on Dynamic Balance among Undergraduate Students,” *Journal of University Medical & Dental College*, vol. 13, no. 2, pp. 391–395, May 2022, doi: 10.37723/jumdc.v13i2.737.

[47] H. T. P. Nguyen, Y. Woo, N. N. Huynh, and H. Jeong, “Scoring of Human Body-Balance Ability on Wobble Board Based on the Geometric Solution,” *Applied Sciences 2022, Vol. 12,* vol. 12, no. 12, Jun. 2022, doi: 10.3390/app12125967.

[48] J. G. Proakis and D. G. Manolakis, *Digital Signal Processing: Principles, Algorithms, and Applications*, 4th Editio. Pearson Education, 2007.

[49] A. Phinyomark, P. Phukpattaranont, and C. Limsakul, “Feature reduction and selection for EMG signal classification,” *Expert Syst. Appl.*, vol. 39, no. 8, pp. 7420–7431, Jun. 2012, doi: 10.1016/j.eswa.2012.01.102.

[50] C. J. De Luca and C. J. De Luca, “The Use of Surface Electromyography in Biomechanics,” *J. Appl. Biomech.*, vol. 13, no. 2, pp. 135–163, May 1997, doi: 10.1123/jab.13.2.135.

[51] R. V. . Hogg and Johannes. Ledolter, “Engineering statistics,” p. 420, 1989, Accessed: Feb. 16, 2026. [Online]. Available: https://books.google.com/books/about/Engineering_Statistics.html?id=RKxaxwEACAAJ

[52] D. C. . Howell, “Statistical methods for psychology,” p. 739, 2007, Accessed: Feb. 16, 2026. [Online]. Available: https://books.google.com/books/about/Statistical_Methods_for_Psychology.html?id=-bmMPwAACAAJ

[53] I. Ben Abdallah, Y. Bouteraa, and A. Alotaibi, “A hybrid EMG–EEG interface for robust intention detection and fatigue-adaptive control of an elbow rehabilitation robot,” *Scientific Reports 2025 15:1*, vol. 15, no. 1, pp. 40895-, Nov. 2025, doi: 10.1038/s41598-025-24831-w.

[54] A. Promsri, “Modulation of Lower-Limb Muscle Activity in Maintaining Unipedal Balance According to Surface Stability, Sway Direction, and Leg Dominance,” *Sports (Basel).*, vol. 10, no. 10, Oct. 2022, doi: 10.3390/SPORTS10100155.

[55] S. Sozzi, A. Nardone, and M. Schieppati, “Specific Posture-Stabilising Effects of Vision and Touch Are Revealed by Distinct Changes of Body Oscillation Frequencies,” *Front. Neurol.*, vol. 12, p. 756984, Nov. 2021, doi: 10.3389/FNEUR.2021.756984/FULL.

[56] L. Mademli, D. Mavridi, S. Bohm, D. A. Patikas, A. Santuz, and A. Arampatzis, “Standing on unstable surface challenges postural control of tracking tasks and modulates neuromuscular adjustments specific to task complexity,” *Scientific Reports* |, vol. 11, p. 6122, 123AD, doi: 10.1038/s41598-021-84899-y.

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