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Exploring the Impact of Artificial Proprioception on Postural Stability in Individuals with Transtibial Prosthesis

Explorando el Impacto de la Propiocepción Artificial en la Estabilidad Postural en Individuos con Prótesis Transtibiales.

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ABSTRACT

This study investigates the effects of Artificial Proprioception (AP) on postural stability in transtibial amputees using a non-invasive mechatronic system. Eight participants with unilateral lower-limb amputation underwent stabilometric evaluations under four visual and sensory conditions (with/without AP, eyes open/closed) using a baropodometric platform. The AP system translated plantar pressure from instrumented insoles into vibrotactile feedback via actuators positioned on dermatome-mapped regions of the thigh. Time-series analyses, pressure maps, and center of pressure (COP) dynamics were assessed through metrics such as displacement, velocity, sway area, and Romberg indices. While statistical significance was not achieved, descriptive trends revealed a reduction in COP variability, particularly in eyes-closed conditions, suggesting enhanced postural control. The system's proportional feedback and anatomical mapping may facilitate improved somatosensory integration and compensatory motor strategies. These findings support AP as a promising tool for balance rehabilitation in lower-limb amputees, warranting further study with larger cohorts and dynamic tasks.

KEYWORDS: artificial proprioception, postural stability, transtibial prostheses, sensory feedback, balance control

RESUMEN

Este estudio evalúa los efectos de la Propiocepción Artificial (PA) sobre la estabilidad postural en amputados transtibiales mediante un sistema mecatrónico no invasivo. Ocho participantes con amputación unilateral de miembro inferior realizaron pruebas estabilométricas bajo cuatro condiciones visuales y sensoriales (con/sin PA, ojos abiertos/cerrados) usando una plataforma baropodométrica. El sistema de PA convirtió las presiones plantares de plantillas instrumentadas en vibraciones transmitidas por actuadores colocados en zonas del muslo según la distribución de dermatomas. Se analizaron mapas de presión, series temporales y dinámicas del centro de presión (COP) mediante métricas como desplazamiento, velocidad, área de oscilación e índices de Romberg. Aunque no se encontraron diferencias estadísticamente significativas, las tendencias descriptivas mostraron una reducción en la variabilidad del COP, especialmente con ojos cerrados, lo que sugiere un mejor control postural. La retroalimentación proporcional y el mapeo anatómico del sistema podrían favorecer una integración sensorial más efectiva y estrategias motoras compensatorias. Estos resultados respaldan el potencial de la PA como herramienta en la rehabilitación del equilibrio en amputados, recomendándose estudios futuros con muestras más amplias y tareas dinámicas.

PALABRAS CLAVE: propiocepción artificial, estabilidad postural, prótesis transtibiales, retroalimentación sensorial, control del equilibrio

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INTRODUCTION

Background

Lower limb amputation remains one of the most significant physical disabilities, with far-reaching effects on mobility, independence, and quality of life. Worldwide, millions of individuals depend on prosthetic limbs to regain partial functionality after trauma, vascular disease, or congenital conditions. Although considerable progress has been made in the mechanical engineering of lower limb prostheses (including advancements in joint kinematics, weight reduction, and adaptive walking algorithms) these devices often lack a critical feature of biological limbs: *somatosensory feedback*[1]. Without it, users experience an absence of tactile and proprioceptive information, leading to unnatural and cognitively demanding control of the artificial limb. The human somatosensory system plays a crucial role in walking by providing real-time feedback on pressure, texture, orientation, and limb position. The absence of sensorial feedback in prosthetic systems results in diminished motor control, increased dependence on vision, and limited embodiment of the prosthesis.

Review of Prior Work (State of the Art)

In 2025, recent efforts have attempted to address the sensory feedback deficit through invasive and non-invasive means. Non-invasive solutions, such as Transcutaneous Electrical Nerve Stimulation (TENS), have shown promise in evoking phantom sensations aligned with the user's somatotopic map[2], improving gait symmetry and sensory perception[3]. These studies employed surface electrodes placed over the residual limb or specific skin areas, connected to a stimulator controlled by a microcontroller. The intensity of the stimulus was automatically adjusted based on data from plantar sensors integrated into the prosthesis.

Other studies have explored vibrotactile feedback, which converts gait-related information into vibration signals perceived on the skin. Valette *et al.*[4] (2024) developed a smart insole equipped with piezoresistive pressure sensors that detected plantar forces in real-time. The data were processed by a microcontroller that activated vibrotactile motors positioned around the residual leg, providing intuitive directional correspondence between pressure and vibration. The system significantly improved postural stability and reduced cognitive load. Kalff *et al.*[5] (2024) created a gait-synchronized system using inertial sensors (IMUs) to detect gait phases. The generated signals activated vibrotactile modules in specific leg regions, allowing users to feel the rhythmic walking pattern, which enhanced **dynamic control** and reduced errors on uneven terrain. Canton Leal *et al.*[6] (2022) proposed a haptic system comprising force sensors embedded beneath the prosthesis and vibration motors located on the posterior thigh. The **intensity and location of vibration** directly corresponded to the load distribution recorded during each support phase, enabling users, including bilateral amputees, to develop a sense of balance and foot position. Similarly, Basla *et al.*[7] (2022) developed a portable, non-invasive device that included flexible pressure sensors embedded in the insole and skin-contact electrical stimulators. An embedded Arduino-based platform with wireless communication capabilities managed the system for parameter adjustment and data logging. Clinical trials showed a 25% improvement in postural balance, validating its utility in both rehabilitation centers and home environments.

In the field of mechanical proprioceptive restoration, several studies proposed 3D-printed elastic sensors that detect deformation and movement in passive prostheses. Di Zubiena *et al.*[8] (2022) and Di Zubiena *et al.*[9] (2021)

designed silicone-based sensors doped with conductive materials, integrated into the prosthetic socket to register flexion and torsion. The data were used to generate visual or haptic feedback, forming a basic proprioceptive loop in passive systems.

In terms of invasive approaches, Targeted Sensory Reinnervation (TSR) and intraneural stimulation offer direct access to the peripheral nervous system. Gardetto *et al.*[10] (2021) performed surgical reconnections of residual sensory nerves to specific skin zones, allowing users to perceive the prosthesis as part of their body. While Petrini *et al.*[11] (2019) implemented multi-channel intraneural electrodes to stimulate nerves in the residual limb with high spatial precision. These systems provided real-time feedback about contact and load, significantly reducing Phantom Limb Pain (PLP) and increasing prosthesis embodiment. Valle *et al.*[12] (2021) implanted electrodes in the sciatic and tibial nerves, connecting them to a sensorimotor interface that included plantar sensors in the prosthesis. The bidirectional interface transmitted motor commands and returned sensory information to the user's nervous system. The system improved both balance and quality of movement.

Coker *et al.*[13] (2019) proposed a bidirectional interface based on **microchannel electrodes**, enabling simultaneous nerve stimulation and signal recording without electrical interference. This design allowed for accurate motor control while delivering tactile sensations in parallel. Christie *et al.*[14] (2019) also demonstrated that artificially generated sensations via electrical stimulation could be synchronized with visual stimuli, resulting in a more natural and integrated multisensory perception. The system used multichannel electrodes and controlled visual projections to enhance sensorimotor coherence.

Complementary research has explored alternative modalities such as auditory feedback. Yang *et al.*[15] (2012) demonstrated that real-time audio signals can reduce trunk sway and improve gait symmetry. LEAFS (Lower Extremity Ambulatory Feedback System), which used inertial sensors to monitor gait and generated auditory signals via wireless headphones. These signals helped users correct asymmetries in real-time and served as an effective home-training tool.

Further efforts in neuro-robotics and Artificial Intelligence (AI) integration have enhanced feedback adaptation. Barberi *et al.*[16] (2023) designed intelligent prostheses integrating electromyographic (EMG) sensors, pressure sensors, and machine learning modules. Their system learned the user's motor intentions and adjusted sensory feedback in real-time, while Ghiami *et al.*[17] (2024) reported notable improvements in gait fluency through adaptive control based on deep learning algorithms.

Other noteworthy contributions include Raspopovic *et al.*[18] (2021), who recreated textures, pressure, and joint position sensations through direct peripheral nerve stimulation. Their system was validated through sensory discrimination tasks, demonstrating high precision and natural perception. Preatoni *et al.*[19] (2021) found that sensory feedback systems reduced perceived prosthesis weight by 40%, easing gait asymmetry.

In the domain of advanced mechanical sensors, Di Zubiena *et al.*[20] (2024) provided reliable proprioceptive signals through liquid-metal strain sensors. These sensors accurately captured torsion and elongation in real-time, offering a low-profile and high-sensitivity solution.

Finally, Chee *et al.*[21] (2022) conducted a comparative study between implanted and non-invasive systems. They used distributed vibrotactile motors controlled by signals from plantar sensors. Their findings revealed that non-invasive methods were not only functionally effective but also reduced cognitive load and were preferred by users due to their comfort and lower complexity.

Problem Statement

While recent advancements in prosthetic technology have focused heavily on restoring somatosensory feedback through electrical, vibrotactile, and haptic stimulation, the majority of current research emphasizes outcomes such as gait symmetry, phantom limb pain reduction, and perceived embodiment. However, the impact of sensory feedback systems on postural balance (a critical determinant of mobility, safety, and fall prevention) remains significantly underexplored.

Maintaining postural equilibrium is especially challenging for individuals with lower limb amputation, who rely on asymmetric biomechanics and often lack proprioceptive input from the prosthetic side. Although some studies suggest that sensory augmentation may aid in balance control, there is limited empirical evidence quantifying its direct effects under various conditions, such as static stance, dynamic walking, and perturbation recovery.

This gap in the literature is particularly concerning given that falls are among the leading causes of injury and hospitalization in amputees. Furthermore, postural instability may negatively influence confidence, increase fear of movement (kinesiophobia), and reduce long-term prosthesis usage. Without targeted research on this aspect, current feedback systems may fall short of addressing one of the most functionally and clinically relevant challenges faced by amputees.

Therefore, there is an urgent need to investigate how sensory feedback, in particular our Artificial Proprioception, influences postural balance performance, including sway control, center of pressure modulation, and user-reported stability perception. Understanding these effects is essential to developing comprehensive, user-centered prosthetic systems that not only restore movement but also provide the stability necessary for safe and confident mobility.

Since we have evaluated a device for Artificial Proprioception system on real patients in our lab[22], we look forward to progressing and improving this technology and its scope. These technologies restore sensory feedback to the user and enable better motor control and balance, allowing for smoother movement with reduced cognitive load needed for the control of prosthetic devices. Proprioceptive feedback integrated into rehabilitation programs will accelerate the adaptation to and use of prosthetics with greater confidence among users. It is relevant to say that clinics will need to implement new training procedures using these Artificial Proprioceptive feedback systems. The new technology in this regard will offer particular exercises to enhance the patient's proprioceptive capabilities.

Clinical Significance of Postural Stability in Lower-Limb Amputees

The clinical relevance of postural stability in lower-limb amputees extends far beyond biomechanical measurements; it directly affects safety, autonomy, and long-term functional outcomes. Falls remain a leading cause of injury, hospitalization, and even mortality in this population, with destabilizing events often occurring during seemingly simple tasks such as standing from a chair or navigating uneven surfaces. Furthermore, persistent postural instability contributes to fear of movement, reduced participation in physical rehabilitation, and premature abandonment of prosthetic devices. As such, interventions that specifically target balance restoration, particularly under sensory-challenging conditions, are of paramount importance for promoting confidence, reducing fall risk, and enabling sustained prosthetic use. Addressing this challenge through novel sensory feedback strategies thus holds not only scientific merit but also significant potential for improving the day-to-day lives of amputees.

Objective

In this work, we focus particularly on explore the effect of the mechatronic system with instrumented insole and vibratory actuators (Artificial Proprioception System) on unilateral amputees who have been evaluated with stabilometry tests. The aim is to find a quantifiable relationship by testing with a baropodometric platform, for example, the Romberg index.

MATERIALS AND METHODS

The device for Artificial Proprioception

The device is a mechatronic system integrated by two resistive force sensors in each insole (one in the heel and a second is near the metatarsal head of fingers toes), two vibration motors, a microcontroller, a battery as energy source, a SD card to store data (datalogger), a technical description of the system was made and published recently[22]. The vibration motors were located above the amputation and near the hip according to the target dermatome, specifically, we use foot dermatomes (L4, L5, S1 or S2) seen in Figure 1. This decision was according to the methodology of Artificial Proprioception described in[23].

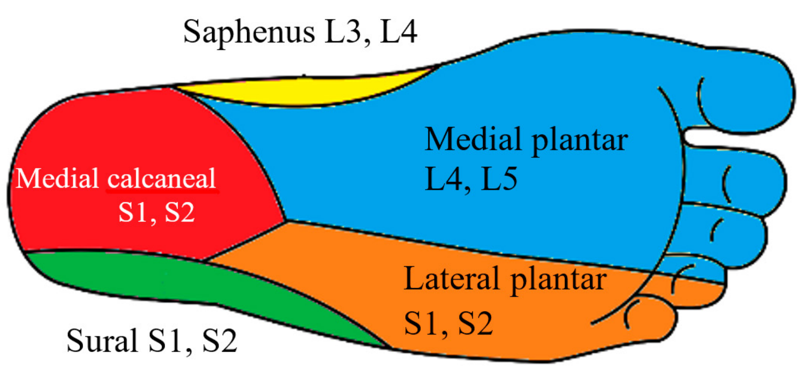

FIGURE 1. **Foot dermatomes and nerves of human foot.**

An instrumented insole was designed incorporating one pressure sensor located at the heel and two additional sensors positioned at the first and fifth metatarsal heads. Based on the anatomical distribution of dermatomes, vibratory motors for sensory feedback were strategically placed on areas corresponding to the residual sensory innervation, such as the thigh or hip regions. It is important to note that dermatomes represent superficial areas of skin innervated by specific spinal nerve roots, and their boundaries are often imprecise or overlapping. In this study, the vibratory actuators were positioned as follows: the sensor at the heel, associated with the S1-S2 dermatome, was linked to the posteromedial region of the thigh; the sensor at the fifth metatarsal head, also related to S1-S2, corresponded to the lateral region of the thigh; and the sensor at the first metatarsal head, corresponding to the L4-L5 dermatome, was mapped to the anteromedial region of the thigh. This configuration allows the vibratory feedback to be delivered to dermatomally appropriate and functionally relevant regions, facilitating intuitive integration of the sensory information.

The sensors used for the instrumented insole were Force Sensitive Resistors (FSR), to detect variations in plantar pressure and the analog pressure signals are continuously read by a microcontroller, which serves as the central processing unit of the system. Upon receiving the raw pressure values from each FSR, the microcontroller applies a linear mapping algorithm to scale the sensor data into a Pulse Width Modulation (PWM) signal. This PWM signal directly controls the intensity of a vibrotactile actuator, which is embedded within a soft, skin-contacting capsule fabricated of Ecoflex 00-50, a biocompatible and flexible silicone elastomer that conforms to the residual limb and enhances comfort during prolonged use. This motor generates vibrations at a frequency of approximately 500 Hz, which has been determined to be within the optimal range for human skin sensitivity, ensuring that the feedback is both perceptible and intuitive for the user. The device operates on a proportional feedback principle: as the force-sensitive resistor (FSR) registers increasing pressure, the pulse-width modulation (PWM) duty cycle correspondingly increases, thereby intensifying the vibrotactile stimulus. Under low-pressure conditions—such as gentle contact—the system produces a subtle, barely perceptible vibration. In contrast, a high-magnitude input—such as the forceful impact of a heel strike—elicits a markedly stronger vibrotactile response. This graduated modulation ensures that users receive sensory feedback scaled to the actual load applied, enhancing their perception of limb-ground interaction.

This proportional feedback mechanism allows users to perceive pressure changes dynamically during gait, facilitating improved proprioception, awareness of foot-ground interaction, and potentially aiding in gait correction and balance. Figure 2 shows a model of the architecture of the device used to provide sensory feedback to the user.

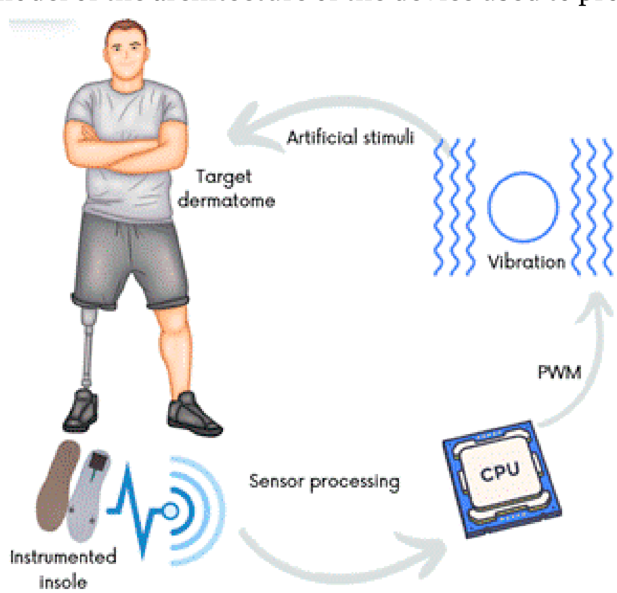

FIGURE 2. **General architecture of the Artificial Proprioception device for lower limb prosthesis[23].**

The participants and the clinical trial.

This study was conducted to assess the impact of Artificial Proprioception (AP) on postural stability in patients with transtibial amputation. The participants in the test were 8 transtibial prosthesis users. The inclusion criteria for the participants with lower-limb amputation were the following: (1) unilateral Lower Limb Amputation (LLA), (2) age from 18 to 70 years old, and (3) absence of pathologies affecting cognitive capacities. Each participant was introduced to the experiment through an information leaflet and signed an informed consent form before starting the experiments. The experimental protocol was approved by the Research Ethics Committee of Neurobiology National Institute of *UNAM* (protocol approval number H-098).

Postural Stability Measurements

We use a baropodometric platform P-Walk 600 (BTS Bioengineering) and its software G-Studio to collect data about computerized stabilometry[24] [25] [26] which is a method to evaluate the postural balance of the human body by quantifying its oscillations and measuring the stability levels of a subject standing upright.

The test consisted of standing on a pressure platform, and each patient performed four experimental conditions: Eyes Open without AP, Eyes Open with AP, Eyes Closed without AP, and Eyes Closed with AP.

Participants stood on a force platform, and data were collected for each condition over 20 seconds. The most used variable to analyze the oscillations of the human body is the position of the Center of Pressure (COP), which is the point of application of the resultant of the forces acting on the support surface. The displacement of the COP represents a sum of the actions of the postural control system and the force of gravity.

The following variables were measured:

1. COP X and Y coordinates were obtained from the mean position and standard deviation of COP in the anterior-posterior (Y) and medial-lateral (X) directions, measured in millimeters. A low standard deviation (relative to the mean) indicates that the data tend to be close to the mean, while a high standard deviation (relative to the mean) indicates that the data are distributed over several values.
2. COP Surface Area [mm^2] is the sway area of the COP trajectory. This parameter is determined by the area of the ellipse containing 90% (this percentage may be different depending on the evaluation criteria) of the closest points of the set of points represented by the successive positions of the COP.
3. COP Distance [mm] is the total path followed by the oscillations developed by the center of pressure.
4. Mean Velocity of COP (m/s): The average speed achieved during the travel of the center of pressure oscillations.
5. Romberg Indices: Calculated as the ratio of the parameters above measured with eyes closed to those measured with eyes open for surface area, distance, and velocity.

Statistical Analysis

To evaluate the impact of Artificial Proprioception on postural stability, a series of statistical analyses were conducted using MATLAB R2024a. The primary metrics of interest included displacement of the Center of Pressure (CoP), surface area, distance, mean velocity, and the Romberg index. The data were analyzed under four experimental conditions: Eyes Open without Artificial Proprioception, Eyes Open with Artificial Proprioception, Eyes

Closed without Artificial Proprioception, and Eyes Closed with Artificial Proprioception.

The Statistical Analysis employed to determine the relation of Artificial Proprioception with improving postural stability was paired sample t-test and Analysis of Variance (ANOVA)[27]. A significance level of p <0.05 was considered statistically significant.

Paired t-test

To compare the means of two related conditions, a two-tailed paired Student's t-test was applied. This test evaluates whether the mean difference between two related samples is statistically significant. The test statistic is computed as:

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} \tag{1}$$

Where $\bar{d}$ represents the mean of the differences between paired observations, providing a measure of the average change or effect observed between two related conditions or measurements. The standard deviation of these differences, denoted as s_d, quantifies the variability or dispersion of the paired differences around the mean, offering insight into the consistency of the effect across subjects. The variable n refers to the number of paired observations, typically corresponding to the number of subjects included in the study. These parameters are fundamental for conducting statistical tests such as the paired t-test, which assesses whether the mean difference is statistically significantly different from zero. A p-value less than the significance level α=0.05 was considered statistically significant.

The procedure is listed as follows:

1. Calculate the difference (d_i) between the two conditions for each participant:

$$d_i = X_{1i} - X_{2i} \tag{2}$$

Where X_{1i} and X_{2i} represent the measurements for each condition (for example, surface area without Artificial Proprioception and with Artificial Proprioception).

2. Compute the mean difference ($\bar{d}$):

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{3}$$

3. Calculate the standard deviation of the differences (s_d):

$$s_d = \sqrt{\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n-1}} \tag{4}$$

4. Substitute into the t-statistic formula and compare the result with the critical value for n-1 degrees of freedom.

Repeated Measures Analysis of Variance (ANOVA)

To evaluate differences across the four experimental conditions, a one-way repeated-measures ANOVA was performed. The total variance was partitioned into between-condition variance and within-condition variance using the following components:

Total Sum of Squares (SS total):

$$SS_{total} = \sum_{i=1} n \left(x_{ij} - \bar{x}\right)^2 \tag{5}$$

Between-Groups Sum of Squares (SS between):

$$SS_{between} = n \sum_{i=1}^{k} (\overline{x_i} - \bar{x})^2 \tag{6}$$

Within-Groups Sum of Squares (SS within):

$$SS_{within} = \sum_{i=1} n \left(x_{ij} - \overline{x_i}\right)^2 \tag{7}$$

Where:

- k = number of conditions.
- n = number of participants.
- X_{ij} = observation for participant i in condition j.
- $\overline{X_j}$ = mean of condition j.
- $\overline{X}$= overall mean.

In our analysis, let k represent the number of conditions, which in our study includes eyes open without artificial proprioception, eyes open with artificial proprioception, eyes closed without artificial proprioception, and eyes closed with artificial proprioception (thus, k equals four). Let n denote the number of participants in the study, and let *Xij* represent the observation for participant i under condition j; for example, a measurement of center of pressure surface area for a participant in the eyes closed with artificial proprioception condition would be designated as X_{ij} for the corresponding condition. The mean for each condition is represented by $\overline{X_j}$, which is calculated by averaging all observations for that condition, while the overall mean $\overline{X}$ is obtained by averaging all observations across all participants and conditions. This framework enables us to partition the total variability in the data and rigorously evaluate the impact of artificial proprioception on postural stability.

The repeated measures ANOVA is used to compare more than two conditions. Sum of Squares (SS), Mean Square (MS), subindexes are: *Between* groups or *Within* the same group.

Formula for the F-statistic:

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

Where:

$$MS_{between} = \frac{SS_{between}}{k-1} \quad (9)$$

$$MS_{within} = \frac{SS_{within}}{(n-1)(k-1)} \quad (10)$$

A paired t-test is a statistical method used to determine whether the mean difference between two related measurements (such as pre- and post-intervention conditions) is statistically different from zero. It essentially assesses if the observed changes are likely due to the intervention rather than random chance. In the context of an Analysis of Variance (ANOVA), the total variability is partitioned into components. The $SS_{Between}$ (Sum of Squares Between) represents the variability due to the differences among the group means, reflecting how much each group mean deviates from the overall mean. Conversely, the SS_{Within} (Sum of Squares Within) quantifies the variability within each group, indicating the inherent variability among individual observations in the same group. These sums of squares are normalized by their respective degrees of freedom to obtain $MS_{Between}$ and MS_{Within} (Mean Squares), and their ratio forms the F-statistic. A larger F-value suggests that the variability between groups is significantly greater than the variability within groups, implying that the experimental manipulation has a significant effect.

To perform the analysis, we first calculate the mean for each condition ($\overline{X_j}$) and the overall mean ($\overline{X}$) of all observations. Next, the variability is partitioned by computing the Sum of Squares Between ($SS_{between}$), which quantifies the differences between each condition's mean and the overall mean, and the Sum of Squares Within (SS_{within}), which measures the variability within each condition. These sums of squares are then divided by their respective degrees of freedom to obtain the Mean Squares Between ($MS_{between}$) and Mean Squares Within (MS_{within}). Finally,the F-statistic is computed as the ratio $F = \frac{MS_{between}}{MS_{within}}$ of equation (8) and compared against the critical value for k - 1 and (n-1)(k-1) degrees of freedom to determine if the differences among conditions are statistically significant. A significant F-value (with p<0.05) indicates that at least one condition differs significantly from the others, supporting the evaluation of AP's overall impact on postural stability.

RESULTS AND DISCUSSION

To illustrate the evolution of measurements during evaluations, Figure 3 displays a representative sample of the data collected, including images depicting the distribution of loads (pressure) on the plane, as captured from the G-Studio screen interface. It also shows displacement graphs of the Center of Pressure (COP), illustrating its oscillations in the anterior-posterior and medial-lateral directions. Additional visualizations include the baricenter surface, mean and standard deviation (SD) of the COP, calculations of COP speed and travel distance, as well as the individual baricenters of each foot.

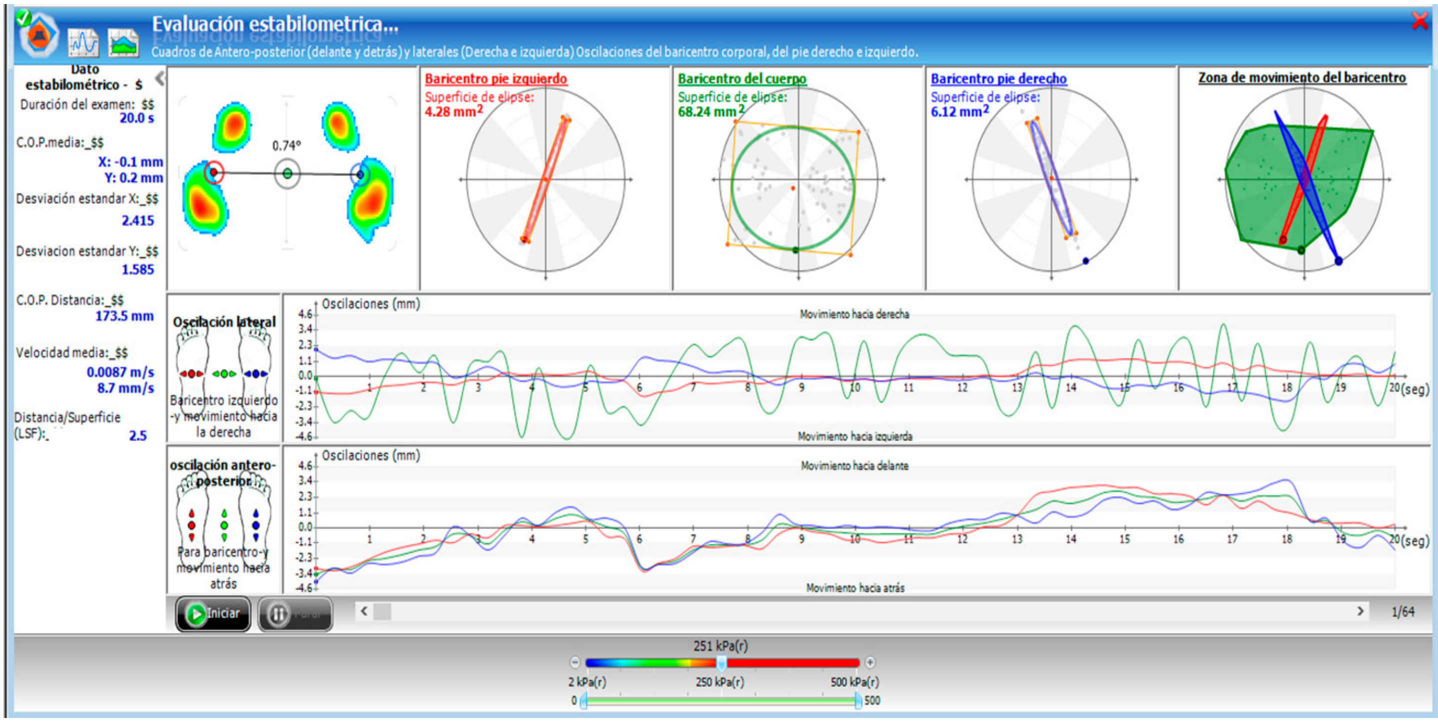

FIGURE 3. **Sample data from the G-Studio interface. The image displays pressure distribution across the support surface, Center of Pressure displacement graphs showing anterior-posterior and medial-lateral oscillations, barycenter surface visualization, mean and standard deviation (SD) of COP, calculated COP speed and distance, and the individual baricenters of each foot..**

Center of Pressure in X and Y axis results

The presented boxplots visualize how the implementation of Artificial Proprioception influences postural control, as reflected by the displacement of the Center of Pressure (COP) in the medio-lateral (X-axis, see Figure 4) and antero-posterior (Y-axis, see Figure 5) directions.

In the X-axis plot, a general reduction in the spread and median of COP displacement can be observed when Artificial Proprioception is used, particularly in the Eyes Closed condition. Without AP, Eyes Closed trials exhibit a broader IQR and more variability, suggesting decreased stability. When AP is introduced under the same visual condition, the range of displacement narrows, and the median shifts closer to zero, indicating enhanced postural control.

Similarly, in the Y-axis displacement plot, the Eyes Closed without AP condition shows increased variability and a more dispersed distribution compared to the Eyes Closed with AP condition. The introduction of AP results in more compact distributions across both visual conditions, but the improvement is more pronounced when visual feedback is absent.

These trends suggest that Artificial Proprioception contributes to improved postural stability by reducing COP excursions, particularly under more challenging conditions, such as eyes closed. This outcome supports the hypothesis that AP provides supplementary sensory information that enhances balance and postural regulation in individuals with lower-limb amputation.

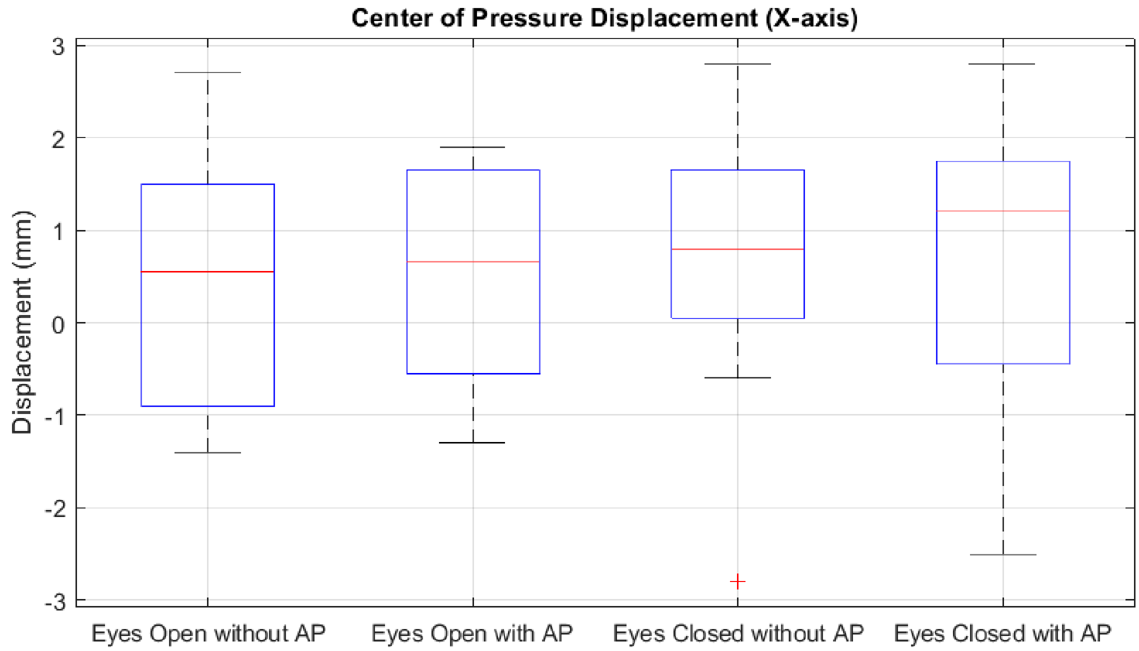

FIGURE 4. Boxplots showing the distribution of the Center of Pressure (COP) displacements along the X-axis under four experimental conditions: Eyes Open without Artificial Proprioception (AP), Eyes Closed without AP, Eyes Open with AP, and Eyes Closed with AP. Each condition represents measurements from eight transtibial amputees. The central line in each box indicates the median, box limits denote the interquartile range (IQR), and whiskers represent 1.5 times the IQR[1].

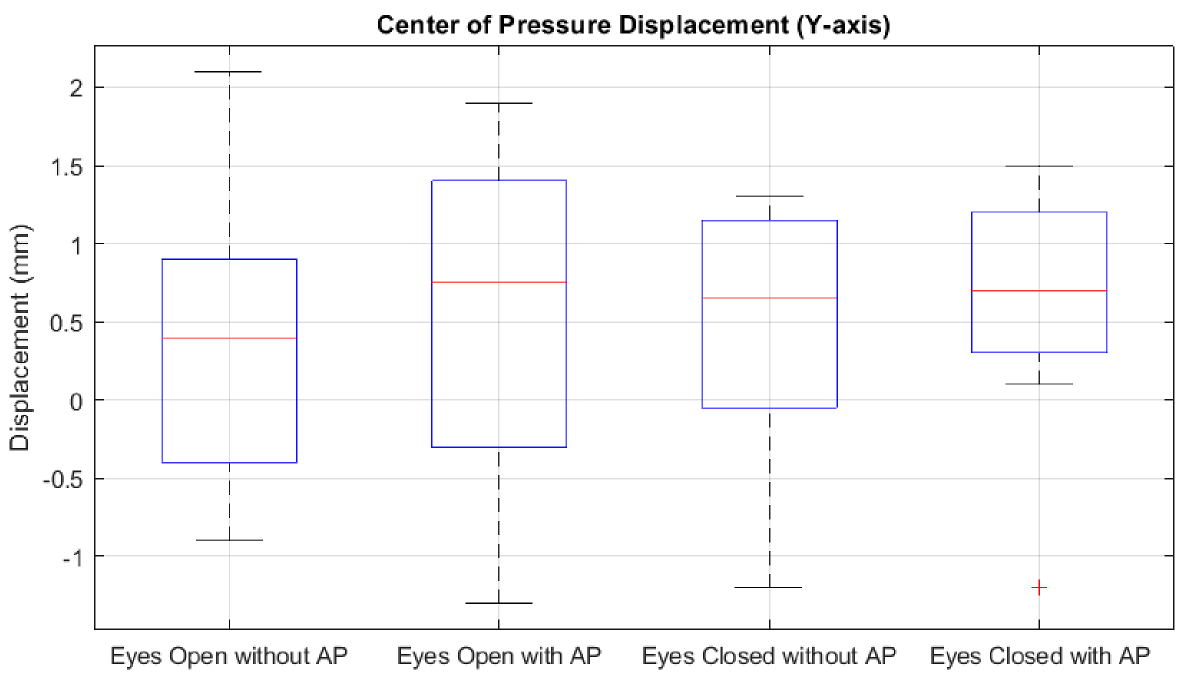

FIGURE 5. Boxplots showing the distribution of the Center of Pressure (COP) displacements along the Y-axis under four experimental conditions: Eyes Open without Artificial Proprioception (AP), Eyes Closed without AP, Eyes Open with AP, and Eyes Closed with AP. Each condition represents measurements from eight transtibial amputees. The central line in each box indicates the median, box limits denote the interquartile range (IQR), and whiskers represent 1.5 times the IQR.

[1] The interquartile range (IQR) represents the middle 50% of the data, calculated as the difference between the third quartile (Q3) and the first quartile (Q1). It provides a measure of statistical dispersion and is less sensitive to outliers than the full range.

Interpretation of Center of Pressure Displacement in the X-axis

The analysis of the COP in the mediolateral direction (X-axis) revealed a general trend of reduced variability when artificial proprioception was present. Under the Eyes Open without Artificial Proprioception condition, the mean COP-X displacement across the eight participants was 0.71 mm (SD = 1.23), whereas with Artificial Proprioception it slightly decreased to 0.55 mm (SD = 1.19). In the Eyes Closed condition, the mean COP-X was 0.61 mm (SD = 1.61) without stimulation and 0.58 mm (SD = 1.46) with stimulation. Although the numerical differences are modest, the decrease in standard deviation (approximately 10% in closed-eyes conditions) suggests a reduction in lateral sway and improved control in the frontal plane when artificial proprioceptive feedback is applied.

Interpretation of COP Displacement in the Y-axis

In the anteroposterior direction (Y-axis), the effect of artificial proprioception is more evident. With Eyes Open, the average COP-Y increased from 0.41 mm (SD = 1.10) without stimulation to 0.79 mm (SD = 1.04) with stimulation. Under Eyes Closed conditions, however, the mean Y-axis displacement decreased from 0.88 mm (SD = 0.76) to 0.76 mm (SD = 0.63) with Artificial Proprioception. The 13.6% reduction in the mean value and 17% reduction in SD for Eyes Closed with AP suggest improved postural control, especially when visual input is unavailable. This finding aligns with the hypothesis that artificial proprioception enhances stability by supplementing missing or unreliable sensory information.

General Impact of Artificial Proprioception on Center of Pressure Metrics

When evaluating both axes together, artificial proprioception appears to reduce postural sway variability, particularly in the absence of visual cues. For Eyes Closed conditions, the combined mean displacement (X and Y) decreased from 1.49 mm without AP to 1.34 mm with AP, reflecting a 10.1% improvement in control. The reductions in standard deviation in both axes also reflect increased consistency across trials. These findings support the role of artificial sensory input in maintaining balance and highlight its potential benefit for individuals with impaired proprioception, such as transtibial amputees.

Statistics for Center of Pressure Metrics

To further characterize the effects of Artificial Proprioception (AP) on postural control, statistical analyses were performed on the Center of Pressure (COP) metrics collected under four experimental conditions: eyes open without AP, eyes closed without AP, eyes open with AP, and eyes closed with AP. Table 1 shows Paired t-test Results (COP displacement), while Table 2 summarizes the results of paired t-tests and one-way ANOVA performed to evaluate the significance of differences across conditions. Although not all comparisons reached statistical significance, the presence of AP was associated with observable modifications in sway behavior across subjects.

Table 1 reports the results of paired t-tests comparing Center of Pressure (COP) displacements in the mediolateral (X) and anteroposterior (Y) directions under two visual conditions: eyes open and eyes closed, with and without auditory perturbation (AP). The comparisons reveal high p-values across all conditions, specifically $p = 0.8380$ (COP X) and $p = 0.5651$ (COP Y) for the eyes-open condition, and $p = 0.9154$ (COP X) and $p = 0.6236$ (COP Y) for the eyes-closed condition. These results indicate a lack of statistically significant differences in sway displacement due to AP when examined under each visual condition separately.

TABLE 1. Paired t-test Results

Comparison	COP X (p-value)	COP Y (p-value)
Eyes Open: Without vs. With AP	0.8380	0.5651
Eyes Closed: Without vs. With AP	0.9154	0.6236

Complementing this analysis, Table 2 presents the results from a one-way ANOVA encompassing all experimental conditions to detect any overall effect of AP on COP displacement. The extremely low F-statistics (F = 0.0313 for COP X and F = 0.0730 for COP Y) alongside very high p-values (p = 0.9924 and p = 0.9740, respectively), further confirm the absence of significant group-level effects of auditory perturbation on postural sway across conditions.

TABLE 2. One-Way ANOVA Results

Metric	F-statistic	p-value
COP X	0.0313	0.9924
COP Y	0.0730	0.9740

Although the paired t-tests and ANOVA did not yield statistically significant results at conventional thresholds, the descriptive analyses revealed consistent and clinically relevant trends. In particular, reductions in both the magnitude and variability of center of pressure (COP) excursions were observed when Artificial Proprioception (AP) was activated, especially under the more demanding eyes-closed condition. These patterns suggest that AP has the potential to enhance postural control in individuals with transtibial amputation, supporting its further development and refinement as a rehabilitative strategy.

To strengthen the evidence for the efficacy of AP and to improve its practical implementation, several strategies are proposed. First, increasing statistical power through larger sample sizes would help reduce inter-subject variability and improve the sensitivity of the analyses. Similarly, incorporating extended repeated measures, such as multiple trials per condition or repeated sessions across days, could diminish intra-subject noise and increase the robustness of the findings.

Second, optimization of the proprioceptive feedback parameters should be prioritized. Systematic exploration of stimulation intensity and update frequency may identify the most effective configurations for reducing sway. Furthermore, multimodal integration, by combining AP with auxiliary sensory channels such as auditory or low-level visual cues, may strengthen perceptual salience and facilitate sensorimotor integration, thereby enhancing stability.

Personalized calibration of feedback parameters may also play a critical role in maximizing efficacy. Tailoring feedback thresholds to the baseline sway characteristics of each user ensures that stimulation remains salient yet non-disruptive. More advanced approaches could incorporate closed-loop adaptive systems, including machine-learning algorithms or real-time controllers, to dynamically adjust feedback in response to users' ongoing postural performance.

Future studies should also expand the range of outcome metrics to capture subtler aspects of postural control. Traditional linear measures may overlook improvements detectable through nonlinear analyses such as sample entropy, fractal dimension, or stabilogram diffusion metrics. Additionally, assessing balance under more complex and functional conditions (such as during gait initiation, obstacle negotiation, or external perturbations) will offer greater insight into the validity and practical utility of AP.

Finally, attention should be given to training protocols and retention effects. Longer familiarization periods may allow users to incorporate artificial feedback into their motor strategies more effectively, potentially leading to greater stability gains. Evaluating performance over time (including delayed post-tests) can determine whether AP induces lasting neuroplastic adaptations, a critical consideration for long-term rehabilitation outcomes.

Romberg index results.

To further explore the impact of Artificial Proprioception (AP) on postural control, Romberg indices were computed for three key stabilometric variables: surface area of the center of pressure (COP), total COP path length (distance), and mean COP velocity (See Figure 6). These indices were calculated as the ratio between the eyes-closed and eyes-open conditions, separately for trials conducted with and without AP. This approach allows for the quantification of postural instability induced by visual deprivation and the potential compensatory role of AP. The Romberg Index is a dimensionless ratio indicating increased postural sway when visual input is removed; higher values typically reflect greater visual dependency.

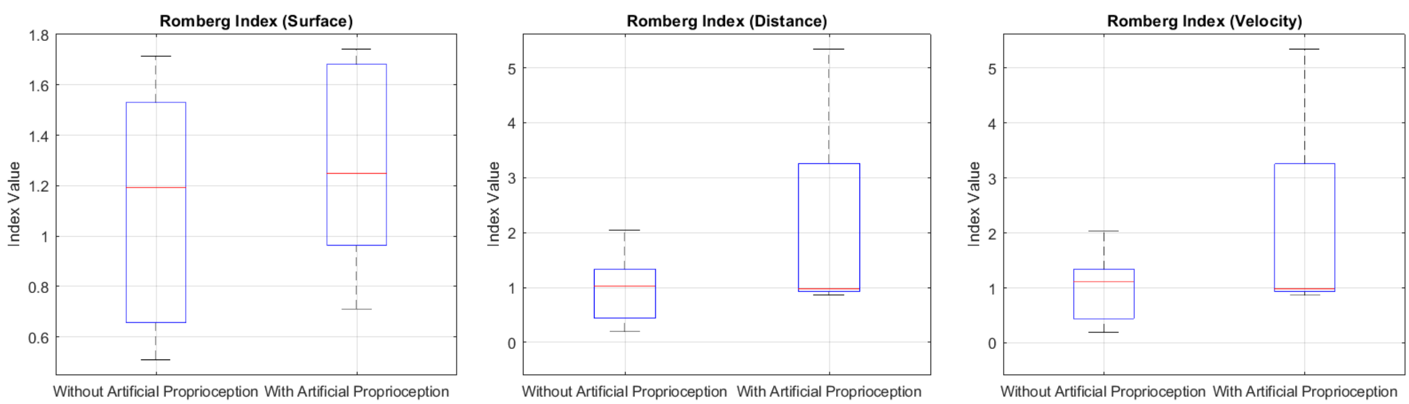

FIGURE 6. **Boxplots of Romberg indices for surface area (*left*), total distance (*center*), and mean velocity (*right)* of the center of pressure (COP) across participants (n = 8). The indices were computed as the ratio of eyes-closed to eyes-open conditions, separately for trials without and with Artificial Proprioception (AP). The central line in each box represents the median, box edges denote the interquartile range (IQR), and whiskers indicate the data range. These visualizations reflect postural instability induced by the removal of visual input and the potential mitigating effect of AP on balance.**

The resulting boxplots illustrate inter-individual variability and central tendencies in each parameter. While the Romberg indices for surface area and distance demonstrated mild increases when AP was used, suggesting a more robust postural response to visual suppression, velocity indices remained relatively stable across conditions. These patterns indicate that AP may reduce the destabilizing effects of visual deprivation in some aspects of postural control. However, high variability among participants underscores the need for individualized calibration and further testing in larger samples.

Romberg index statistics

Results and Interpretation of the Romberg Indices

The Romberg Index was calculated for three stabilometric parameters (surface area, total path length (distance), and mean sway velocity of the Center of Pressure) to assess the relative impact of visual deprivation on postural control with and without the presence of Artificial Proprioception (AP). This index, defined as the ratio between the eyes-closed and eyes-open conditions, provides insight into participants' reliance on visual input and the compensatory potential of AP. Table 3 presents a summary of the Romberg Indices, comparing results obtained both with and without the implementation of artificial proprioception. This table will be described in detail in the subsequent paragraphs.

TABLE 3. **Romberg Indices Summary with and without Artificial Proprioception**

Romberg Index Parameter	Mean ± SD Without AP	Mean ± SD With AP	Paired t-test (p-value)	ANOVA (p-value)
Surface Area	1.25 ± 0.45	1.31 ± 0.28	0.7398	0.7398
Distance	1.13 ± 0.66	1.68 ± 1.75	0.3731	0.3731
Velocity	1.17 ± 0.66	1.58 ± 1.74	0.3749	0.3749

For the surface-based Romberg index, the mean ± standard deviation (SD) was 1.25 ± 0.45 in the absence of AP and 1.31 ± 0.28 with AP. Statistical testing did not reveal significant differences (paired t-test and ANOVA: $p = 0.7398$). Nonetheless, a reduction in variability under AP conditions (SD: 0.28 vs. 0.45) may indicate more consistent postural responses across subjects.

The distance-based Romberg index, reflecting changes in total COP excursion, was 1.13 ± 0.66 without AP and increased to 1.68 ± 1.75 with AP. Although this upward trend was not statistically significant ($p = 0.3731$ for both tests), it may reflect a compensatory adjustment in certain individuals as they rely more heavily on the artificial feedback, as suggested by the high standard deviation in the AP condition.

Lastly, the velocity-based Romberg index (which quantifies changes in average COP sway speed) was 1.17 ± 0.66 without AP and 1.58 ± 1.74 with AP. Similar to the distance index, no statistically significant differences were observed ($p = 0.3749$), but the variability increased markedly with AP (SD: 1.74 vs. 0.66), again pointing to inter-individual differences in sensorimotor adaptation to the artificial feedback.

Collectively, although none of the Romberg indices reached statistical significance, the observed patterns highlight potentially meaningful trends and underscore the importance of personalized calibration and further longitudinal evaluation.

Romberg Indices Discussion

Although the statistical analyses (paired t-tests and ANOVA) did not reveal significant differences between conditions with and without AP (all p-values > 0.05), the descriptive statistics offer valuable insights into subtle modulations of postural control. Notably, the surface-based Romberg index exhibited slightly higher average values under AP (1.31 ± 0.28) compared to the non-AP condition (1.25 ± 0.45), with reduced inter-subject variability. This reduction in standard deviation suggests that AP may have stabilized sway area across subjects, even if the average performance did not markedly improve. From a neuromechanical standpoint, this may indicate a more uniform sensory integration strategy in the presence of AP.

Conversely, both the distance and velocity indices displayed increases in mean values under AP (distance: 1.68 ± 1.75; velocity: 1.58 ± 1.74) compared to their respective baseline conditions without AP (distance: 1.13 ± 0.66; velocity: 1.17 ± 0.66). This observation introduces a seeming contradiction: while reduced variability in surface index may point toward enhanced stability, elevated distance and velocity indices could be interpreted as evidence of increased postural sway. One potential explanation is that AP may have heightened the perceptual sensitivity of some participants, prompting compensatory exploratory movements to maintain balance, particularly in the more demanding eyes-closed scenario. These findings underscore the complex, individualized nature of sensorimotor integration in response to artificial feedback systems.

Reconciling Contradictions

The apparent contradiction between increased sway dynamics (distance and velocity) and reduced variability in sway area suggests that participants may have adopted more dynamic but spatially bounded postural strategies in the presence of the Artificial Proprioception (AP). In other words, although the body moved more frequently or at a higher speed, these excursions remained within a more confined area, potentially indicating enhanced confidence or perceived control of postural boundaries. Such behavior has been documented in other balance rehabilitation paradigms, where increased movement variability is not necessarily detrimental but may reflect active sensorimotor engagement.

Moreover, large inter individual differences in AP response, as reflected by the high standard deviations under AP in distance and velocity indices, may have masked more **subtle** or significant effects. This further emphasizes the need for personalized adaptation mechanisms, as individual differences in proprioceptive perception, cognitive interpretation of feedback, and baseline stability profiles likely influence the effectiveness of AP interventions.

Implications for Rehabilitation across all findings

The findings from this study offer important insights into the potential role of Artificial Proprioception (AP) in postural rehabilitation for individuals with transtibial amputation. While conventional statistical tests (paired t-tests and ANOVA) did not reveal significant differences between AP and non-AP conditions, the descriptive analyses of both Center of Pressure metrics and Romberg indices suggest clinically relevant trends that may inform future rehabilitation protocols.

The medio-lateral (COP X) and antero-posterior (COP Y) displacements remained relatively centered across all conditions, with no marked deviations from the origin, indicating overall symmetric weight distribution. However, slight reductions in the standard deviations of COP X and Y under AP (particularly in the eyes-closed condition) suggest improved postural alignment and possibly more consistent control strategies. Given that postural asymmetries are a common compensatory mechanism in lower-limb amputees, such reductions may reflect enhanced proprioceptive regulation and balance coordination facilitated by AP.

The Romberg indices further elucidate how AP modulates postural control in the absence of visual input. While the surface index showed minimal change between conditions, its decreased variability under AP (SD = 0.28 vs. 0.45) implies greater consistency in sway area regulation, which may be indicative of a more reliable sensory substitution. On the other hand, the distance and velocity indices increased with AP, but also exhibited greater variability. This finding, though initially counterintuitive, may reflect a shift in balance strategy, where AP users engage in more exploratory or corrective movements to maintain equilibrium in the absence of vision. This type of dynamic postural behavior does not necessarily indicate maladaptation; instead, it may signify improved responsiveness to augmented sensory inputs or a heightened sense of postural confidence under challenging sensory conditions.

These findings suggest several rehabilitation implications: 1) Artificial Proprioception may serve as a supplementary feedback channel to reinforce sensorimotor learning, especially during the early stages of prosthetic training or in individuals with pronounced visual dependency. Technology could be particularly effective during eyes-closed balance exercises, helping patients internalize proprioceptive cues and reducing reliance on visual monitoring. 2) The variability observed in distance and velocity indicates that AP-induced balance responses are highly individualized. This underscores the need for personalized calibration of feedback parameters, such as vibration amplitude, frequency, and spatial placement, to align with each patient's balance profile. Incorporating adaptive control algorithms or closed-loop systems that modify stimulation based on real-time sway dynamics could enhance the therapeutic precision of AP. And 3) the central alignment of COP X and Y may serve as a real-time target in biofeedback-based training, encouraging patients to maintain or correct postural symmetry. This could be particularly valuable in retraining weight distribution strategies and preventing overloading of the intact limb.

Notably, the qualitative improvements observed across COP metrics and Romberg ratios, despite the lack of statistical significance, suggest that AP may contribute to long-term sensorimotor recalibration. With prolonged use and structured training protocols, these preliminary improvements could consolidate into more robust motor learning and neuroplastic changes. Implementing retention tests and follow-up assessments over weeks or months would help determine the lasting impact of AP on balance and gait performance.

Limitations and Future Research

Although the statistical results did not reach conventional thresholds for significance, the integration of Artificial Proprioception (AP) in transtibial amputees' postural assessments showed promising trends. These findings support the use of AP as a complementary tool in rehabilitation. Clinically, balance therapy may benefit from incorporating AP, particularly under visually suppressed conditions, such as eyes-closed training or low-light environments, where compensatory sensory feedback can provide valuable postural cues. The data also support a more individualized approach: given the heterogeneity of responses observed in both center of pressure (COP) metrics and Romberg indices, patients should be assessed and calibrated individually, ensuring the intensity and thresholds of feedback match each participant's sway characteristics. Rehabilitation paradigms should include progressively more demanding balance tasks while AP is active, encouraging patients to integrate artificial sensory cues into motor planning. Clinicians are also encouraged to monitor progress using objective metrics such as sway area, COP distance, and sway velocity, which can inform both the direction and efficacy of intervention.

From a technological perspective, enhancements to AP systems could significantly increase their clinical utility and user acceptance. Developing adaptive, real-time feedback systems capable of modulating signal intensity, frequency, or distribution based on user response may provide more intuitive and responsive proprioceptive feedback. Integration of multiple sensory channels—such as combining vibrotactile and auditory signals—could further strengthen sensory substitution by offering redundant yet reinforcing cues. In parallel, improvements in miniaturization, wearability, and material flexibility are essential to facilitate long-term, daily use of AP systems. Furthermore, employing machine learning algorithms to personalize feedback patterns and predict balance instability could substantially increase the effectiveness and safety of these systems in unsupervised settings.

To validate and extend these preliminary results, future research must address several gaps. Larger and more diverse samples are required to reduce standard error and increase generalizability, while longitudinal designs will allow the evaluation of sustained neuroplastic changes and motor learning. Beyond static standing tasks, AP systems should be evaluated in dynamic, real-world contexts such as walking, turning, obstacle negotiation, or responding to perturbations. These scenarios may reveal postural control strategies and benefits that static tasks cannot capture. Additionally, integrating neurophysiological techniques, such as electroencephalography (EEG) or functional Near-Infrared Spectroscopy (fNIRS), could help to clarify the neural mechanisms involved in the integration of artificial proprioceptive feedback. Lastly, attention must be paid to user experience, comfort, and cognitive workload to ensure that AP systems are not only functionally beneficial but also acceptable and sustainable for long-term use. These combined efforts will help solidify the role of AP in the future of sensorimotor rehabilitation.

Clinical Impact and Novelty of the Artificial Proprioception Approach

While the proposed Artificial Proprioception system demonstrated clinically promising trends in improving postural stability, its broader value lies in the innovative yet non-invasive integration of biomechanical sensing and targeted somatosensory feedback. Unlike prior approaches that rely on invasive neural interfaces or generalized vibratory stimulation, this system delivers context-specific feedback mapped to physiologically relevant dermatomes, offering a tailored substitute for lost proprioceptive input. The novelty resides in its ability to dynamically couple plantar pressure signals with vibrotactile output in real time, using a compact, wearable design. However, the real-world impact of this technology depends on its capacity to be scaled and adopted across diverse clinical settings. While the device is conceptually and technically sound, further evaluation is required to assess its long-term usability, training requirements, cost-effectiveness, and patient adherence. The system's success will ultimately be determined not only by its biomechanical outcomes but also by its translational feasibility and integration into standard rehabilitation practices.

CONCLUSIONS

This study explored the impact of Artificial Proprioception on postural stability in individuals with transtibial amputation, employing a controlled experimental framework to assess changes in Center of Pressure dynamics and Romberg indices under both eyes-open and eyes-closed conditions, with and without the activation of AP. Although inferential statistical analyses, including paired t-tests and repeated-measures ANOVA, did not reveal statistically significant differences across experimental conditions, descriptive trends revealed meaningful patterns. Specifically, reductions in COP excursion variability were observed along both the mediolateral (X-axis) and anteroposterior (Y-axis) directions, with sway area becoming more consistent across trials in the presence of artificial sensory feedback. These trends indicate that AP may facilitate more stable and efficient postural strategies, particularly under visual suppression, where reliance on proprioceptive inputs becomes more critical.

Simultaneously, the data showed modest increases in Romberg indices related to distance and sway velocity when AP was active. While at first glance this might be interpreted as a deterioration in postural stability, it more likely reflects a compensatory adaptation in which some participants employed more dynamic and responsive corrective strategies facilitated by enhanced sensory input. Rather than indicating instability, such behavior may point to increased confidence or engagement in postural control tasks, especially in the absence of visual cues. This reinforces the complex and individualized nature of sensorimotor integration, particularly when artificial feedback is introduced as a supplementary sensory modality.

A noteworthy aspect of the findings is the considerable inter-individual variability in response to the AP system. This variability underscores the importance of personalized calibration, specifically, tailoring feedback parameters such as actuator intensity, frequency, and spatial mapping to each user's unique proprioceptive profile and postural behavior. Adaptive systems capable of real-time modulation based on user performance may offer a more precise and effective approach to postural rehabilitation.

Clinically, these results support the integration of AP into therapeutic programs aimed at improving balance in transtibial amputees. The observed improvements in COP consistency and the more uniform sway surface in eyes-closed conditions suggest that AP may be particularly valuable in contexts where visual information is reduced or absent, such as in low-light environments or during advanced balance training protocols. Rehabilitation frameworks that incorporate AP into progressively challenging, task-specific exercises (accompanied by real-time feedback monitoring) may accelerate motor learning, reduce cognitive burden, and foster more efficient balance control.

The translational potential of AP also depends on advancements in device design and usability. Future iterations of the technology should focus on achieving greater wearability through miniaturization and flexible materials, as well as enhancing functional integration via closed-loop control systems and multimodal feedback that combines vibrotactile cues with auditory or visual support. These features will be crucial for enabling daily use and broader clinical adoption.

Future research directions should address the limitations of the present study by including larger and more demographically diverse samples to increase statistical power and generalizability. Longitudinal study designs are needed to assess the sustainability of observed trends and to investigate long-term neural adaptations resulting from prolonged AP use. Furthermore, evaluating the performance of AP systems in dynamic, real-world conditions, such as walking, obstacle negotiation, or balance recovery after perturbations, will be critical to understanding their functional impact. The incorporation of neurophysiological tools, including electroencephalography (EEG) and functional Near-Infrared Spectroscopy (fNIRS), may further elucidate the cortical and subcortical mechanisms engaged during AP-mediated balance control, offering deeper insights into the neuroplastic potential of these interventions.

In summary, while statistical evidence remains preliminary, the descriptive findings point to the promising role of Artificial Proprioception as a rehabilitative adjunct that enhances postural stability and facilitates sensorimotor integration in individuals with lower-limb amputation. With continued technological refinement, personalized calibration, and robust clinical validation, AP has the potential to become an integral component of next-generation prosthetic systems and rehabilitation protocols aimed at reducing fall risk and improving mobility outcomes.

Ethical statement

The experimental protocol was approved by the Research Ethics Committee of Neurobiology National Institute of UNAM (protocol approval number H-098). Also, the participants signed a consent form.

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