UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura

https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1275
DOI: https://doi.org/10.14483/22487638.21406

RESEARCH

Analysis in the Time Domain of Static Stability in Individuals with Unilateral Transtibial Amputation

Análisis en el dominio del tiempo de la estabilidad estática en individuos con amputación unilateral transtibial

Lely A. Luengas-C.[1], Omar Pérez Ducón[2] y Agustin Liz Lis[3]

Fecha de Recepción: 11 de octubre de 2023 **Fecha de Aceptación**: 21 de noviembre de 2024

Cómo citar: Luengas-C. L. A., Pérez Ducón O., Liz Lis A. Analysis in the Time Domain of Static Stability in Individuals with Unilateral Transtibial Amputation, *Tecnura*, 29(84), 54-66. https://doi.org/10.14483/22487638.21406

Abstract

Objective: To evaluate static postural behavior in the time domain in individuals with unilateral transtibial amputation compared to non-amputated subjects.
Methodology: Static postural behavior in the time domain was assessed in 10 individuals with transtibial amputation (SAT) and 10 non-amputated individuals (SNA) using piezoelectric instrumented insoles to measure the center of pressure (CP). Parameters analyzed included CP trajectory excursion, CP velocity, range, RMS value, average amplitude, and maximum and minimum amplitude calculated in both anteroposterior and mediolateral directions.
Results: Significant differences were found between the SAT and SNA groups in all parameters and in both directions ($p<0.05$). Both groups showed a preference for variation in the anteroposterior direction; however, the TAA group exhibited high variability in measurements in this direction.
Conclusions: These findings may provide valuable insights into how amputation and prosthetics can influence the stability and balance of individuals, which could be useful in rehabilitation processes and the design of prosthetics aimed at improving the quality of life of this population.
Financing: This scientific research article derives from the research project ”Application of clustering as a method for discriminating plantar pressure distribution in individuals with transtibial amputation,” funded by Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.

Keywords: linear analysis, transtibial amputees, postural control, static stability, posturography.

[1]PhD, Electronic Engineer, Professor at Universidad Distrital Francisco José de Caldas, Bogotá, Colombia. Correo electrónico: laluengasc@udistrital.edu.co
[2]Electronics Technologist, currently pursuing a degree in Control Engineering at the Francisco José de Caldas District University, Bogotá, Colombia. Correo electrónico: operezd@udistrital.edu.co
[3]Control Engineering student at the Francisco José de Caldas District University, Bogotá, Colombia.. Correo electrónico: alizl@udistrital.edu.co

Resumen

Objetivo: Evaluar el comportamiento postural estático en el dominio del tiempo en individuos con amputación unilateral transtibial en comparación con sujetos no amputados.
Metodología: Se evaluó el comportamiento postural estático en el dominio del tiempo en 10 individuos con amputación transtibial (SAT) y 10 individuos no amputados (SNA) utilizando plantillas instrumentadas piezoeléctricas para medir el centro de presión (CP). Los parámetros analizados incluyeron la excursión de la trayectoria del CP, la velocidad del CP, el rango, el valor RMS, la amplitud media y las amplitudes máxima y mínima, calculadas tanto en la dirección anteroposterior como en la mediolateral.
Resultados: Se encontraron diferencias significativas entre los grupos SAT y SNA en todos los parámetros y en ambas direcciones (p<0,05). Ambos grupos mostraron una preferencia por la variación en la dirección anteroposterior; sin embargo, el grupo SAT exhibió una alta variabilidad en las mediciones en esta dirección.
Conclusiones: Estos hallazgos pueden proporcionar información valiosa sobre cómo la amputación y las prótesis pueden influir en la estabilidad y el equilibrio de los individuos, lo que podría ser útil en los procesos de rehabilitación y en el diseño de prótesis destinadas a mejorar la calidad de vida de esta población.

Financiación: Este artículo de investigación científica deriva del proyecto de investigación .Aplicación de la agrupación (clustering) como método de discriminación de la distribución de la presión plantar en individuos con amputación transtibial", financiado por la Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.

Palabras clave: análisis lineal, amputados transtibiales, control postural, estabilidad estática, posturografía.

Introduction

Amputation is the procedure in which a part of the body is removed due to reasons such as traumatic injury, disease, or surgical intervention. According to Iglesias Triviño (1), the most common causes of amputation include vascular, traumatic, and oncological pathologies. Lower limb amputation accounts for 85 % of all amputations, with transtibial amputation being a recurrent procedure. It is worth noting that regardless of the level of amputation, the loss of a lower body segment has a significant impact due to alterations in the sensory and musculoskeletal systems, modifications in the functioning of directly and indirectly involved segments, and the effects on functions such as body support, gravity force control, bipedal stance, and ambulation. Consequently, individuals with this condition may experience difficulty maintaining stability (1,2).

Stability is defined as the ability of individuals to maintain an upright and balanced posture while standing, preserving postural control to keep the center of body mass within the limits of the support hexagon. This applies to both static and dynamic conditions, ensuring balance during functional movements (3, 4). In individuals with transtibial amputation who use prosthetics, some factors influence static stability, including: 1) Prosthetic Design: The design and components of the prosthesis play a crucial role in maintaining stability. Recent developments have led to prosthetic feet and ankles designed to mimic the biomechanics of a biological foot, offering improved shock absorption, energy return, and standing stability. 2) Socket Fit and Alignment: The socket is the part of the prosthesis that connects with the residual limb or stump. Proper socket fit and alignment are essential for stability. A poorly fitting or misaligned socket can cause discomfort, uneven weight distribution, and reduced stability.

3) Muscle Strength and Control: Balance maintenance also relies on the strength and control of the remaining muscles in the residual limb and the intact limb. 4) Posture and Weight Distribution: Amputees may need to learn how to distribute their weight evenly and adjust their posture to prevent leaning or falling. 5) Sensory Feedback: Prosthetics do not provide the same level of sensory feedback as biological limbs (2, 5, 6).

Postural stability is characterized by quantifying the displacement of the center of pressure (COP) over time. The COP represents the vertical ground reaction force that reflects the forces and torques at the ankle. It is recorded using devices that sense the force between the foot and the support surface, providing a time series of COP position in both the anterior-posterior (AP) and medial-lateral (ML) directions. These AP and ML time series reveal patterns of postural behavior and are analyzed independently using various techniques in both the time and frequency domains (7, 8). Among the linear measures of COP in the time domain are: Range: Quantifies the specific maximum body oscillation. Excursion: Measures the total COP path length, calculated by summing the distances between adjacent points in the time sequence. RMS (Root Mean Square): Represents the standard variation of COP displacement, average amplitude, as well as minimum and maximum amplitudes. Velocity: Represents displacement of COP over a measured time period (9).

Studies analyzing COP behavior in individuals with transtibial amputation provide insights into their adaptation to amputation and the impact of different prosthetic interventions on their balance control (6, 10–12). By comparing COP data between non-amputated subjects and those with amputations, researchers and medical professionals can obtain information about the effectiveness of prosthetic interventions and rehabilitation strategies. Therefore, the objective of the study is to compile data on linear COP variables in the time domain for individuals with unilateral transtibial amputation and compare it with non-amputated individuals.

Methodology

Participants (10 non-amputated (SNA) and 10 with unilateral transtibial amputation (SAT)) stood on instrumented insoles to measure plantar pressure and were instructed to stand still. The experiment consisted of three static tests, each lasting 30 seconds, with a five-minute rest interval between them. Time-domain stability characteristics were calculated based on the registration of the plantar pressure center under the feet. Non-amputated subjects and transtibial amputees were compared.

Participants

The sample of statically registered postural stability data consisted of ten non-amputated subjects (age=37.4±9.03 years, height=168.4±7.106 cm, weight=67.4±14.955 kg) and ten men with unilateral transtibial amputation (age= 31.1±3,213 years, height=171.8±0.067 cm, weight=78.1±7.824 kg). Exclusion criteria included lower-limb injuries in the last six months and any musculoskeletal condition that could interfere with postural stability, such as lower limb pain or a neurological disorder. Ethical approval for this study was obtained from the Bioethics Committee of Universidad Distrital Francisco José de Caldas.

Experimental Procedures

Static postural stability was tested using the Romberg test under the first condition: standing with eyes open on firm ground. This task was chosen because it reflects natural posture. Subjects were asked to stand upright on instrumented insoles with 99 piezoelectric sensors each (Novel, Pedar, USA), with their arms at their sides, wearing their normal footwear, remaining as stable as possible, and looking straight ahead at a white wall 1.5 meters away from the wall.

Data Processing

All data from the instrumented insoles were processed offline using MATLAB software (R2023, MathWorks, USA) and filtered using low-pass Butterworth filters with a cutoff frequency of 10 Hz (12). Considering the researcher's oral instructions at the beginning and end of the static postural bipedal test (PS), the first and last 5 seconds of unprocessed data were discarded. Excursion of the CP trajectory, CP velocity, range, RMS value, average amplitude, and maximum and minimum amplitudes were calculated in both anteroposterior and mediolateral directions.

Statistical Analysis

Processed data were statistically analyzed using MATLAB software (R2023, MathWorks, USA). The normality of data distribution was examined using the Shapiro-Wilk test (<50 samples). For comparisons of SAT data against SNA, the Mann-Whitney U test was used for non-normal variables, and the Levene test for equality of variance for normal variables. An independent T-test was used for equal variances, and Welch's T-test was employed for unequal variances. Significance was tested at $p < 0.05$.

Normality in Data Distribution: The normal distribution, or Gaussian distribution, represents how various numerical values of continuous variables are distributed in nature; in this case, CP oscillation and CP velocity for both SAT and SNA groups.

Shapiro-Wilk Test: This test evaluates whether a population sample is normally distributed. We used it to test for normality. The higher this statistical value, the more variance there is from the normality line. Therefore, the null hypothesis will be rejected. It is recommended for small samples, numbering fewer than 50 observations.

T-Test and Non-Parametric Alternatives: Non-parametric tests do not assume a probability distribution for the data.

Distribution-free: The data is not normally distributed and does not have a particular distribution.

Statistical Significance Level: Also denoted as Alpha or α; it is the probability value of rejecting the null hypothesis when it is true. For example, a significance level of 0.05 indicates a 5 % risk of assuming there is a difference when, in reality, there is none.

Results

Ten male SAT subjects and ten SNA subjects (four women and six men) performed the static postural assessment test. Data related to static postural stability parameters concerning CP oscillation and CP velocity are presented in Table 1. The values of these data differed between the examined groups. All parameters are higher in the transtibial amputee group, as shown in Figure **1**.

Tabla 1. Results of the static postural assessment test

PARAMETER	ADDRESS	SAT	SNA	P
EXCURSION	Mediolateral	141,919	36,984	0,002
(mm)	Anteroposterior	785,290	199,330	0,001
VELOCITY	Mediolateral	1,151	0,183	0,000
(mm/s)	Anteroposterior	3,791	0,873	0,000
RANGE	Mediolateral	1,520	0,367	0,001
(mm)	Anteroposterior	8,124	2,113	0,000
RMS	Mediolateral	0,379	0,096	0,001
(mm)	Anteroposterior	2,088	0,541	0,002

MEAN	Mediolateral	0,313	0,081	0,001
(mm)	Anteroposterior	1,730	0,439	0,001
MAXIMUM	Mediolateral	0,737	0,184	0,001
AMPLITUDE (mm)	Anteroposterior	4,203	0,945	0,001
MINIMUM	Mediolateral	-0,783	-0,183	0,001
AMPLITUDE (mm)	Anteroposterior	-3,921	-1,168	0,002

Note. This table displays the data of the postural stability parameters related to the CP oscillation and CP velocity of the twenty subjects. Own elaboration.

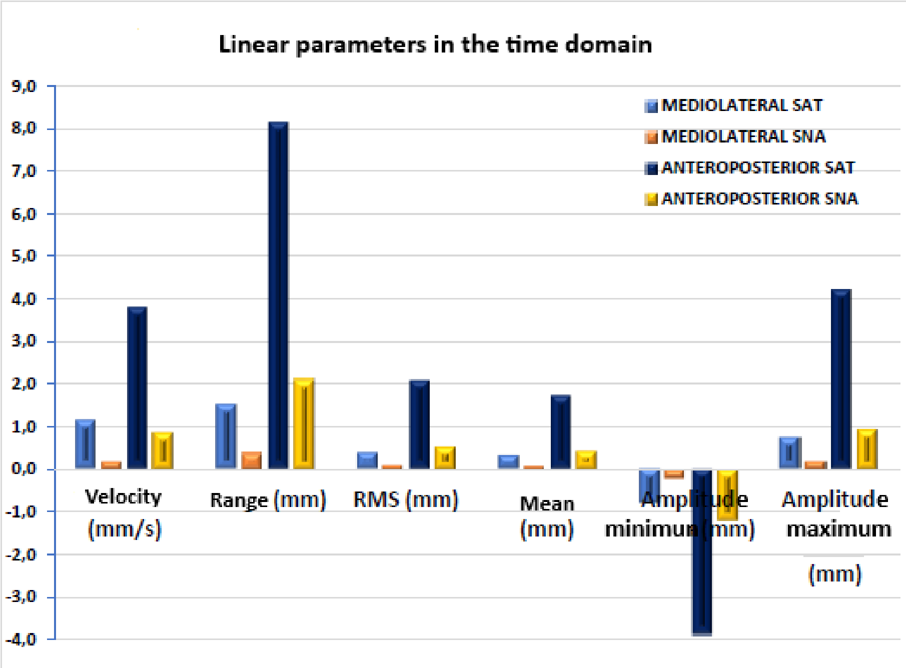

Figura 1. Behavior of linear parameters of the center of pressure in the time domain for subjects with SAT and SNA, shown in the anteroposterior and mediolateral directions

Note. Own elaboration

In the static bipedal position, all CP parameters in the time domain show higher values in the anteroposterior direction than in the mediolateral direction in both groups. The excursion of the CP is greater in amputated individuals compared to non-amputated ones, with higher movement observed in the anteroposterior axis than in the medial-lateral axis. Regarding the RMS value, there are significant differences in the amplitude of CP oscillations between amputees and non-amputees; amputated individuals experience wider CP oscillations during static tests compared to non-amputated individuals. The displacement shows that amputees exhibit marked variability in the anteroposterior direction, as shown in Figure **2**. CP velocity is higher in the group of individuals with amputation compared to the group of non-amputated individuals in both directions; however, when comparing both directions, oscillation velocity increases in the anteroposterior direction for both groups.

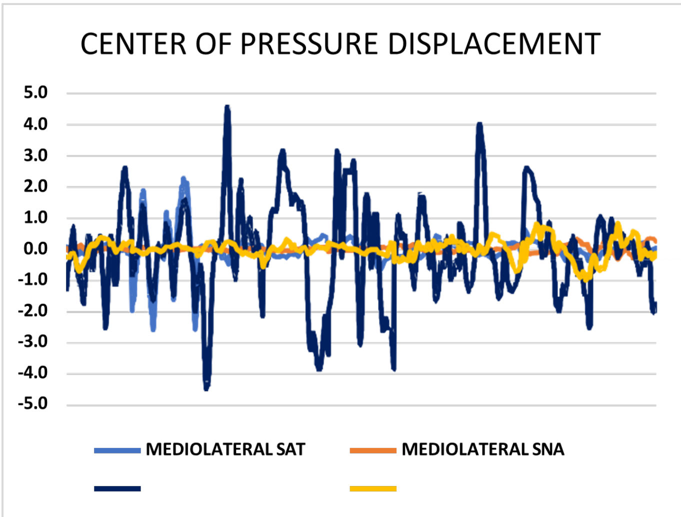

Figura 2. Center of pressure displacement in SAT and SNA, shown in the anteroposterior and mediolateral directions during the test recording time

Note. Own elaboration

One way to visually assess the displacement behavior of the CP is through a statokinesiogram. In this graph, mediolateral data is taken as the X-axis, and anteroposterior data as the Y-axis. Figure **3** shows the statokinesiogram of the examined groups.

Additionally, a software tool was developed in Python that allows for the visualization of linear parameters in both graphical and numerical formats, facilitating the examination of the linear behavior of the CP for medical personnel or researchers. Another advantage of the software is that it can read data from a flat file, enabling it to process CP data from any sensor device.

The software incorporates a 95 % confidence ellipse graph. This method allows for the exploration of the area covered by the CoP displacement. It involves fitting a prediction ellipse to cover the anteroposterior CoP against mediolateral CoP data. This procedure is accomplished using principal component analysis to achieve a 95 % probability that a new observation falls within the ellipse. It calculates the covariance matrix of the data, performs singular value de-

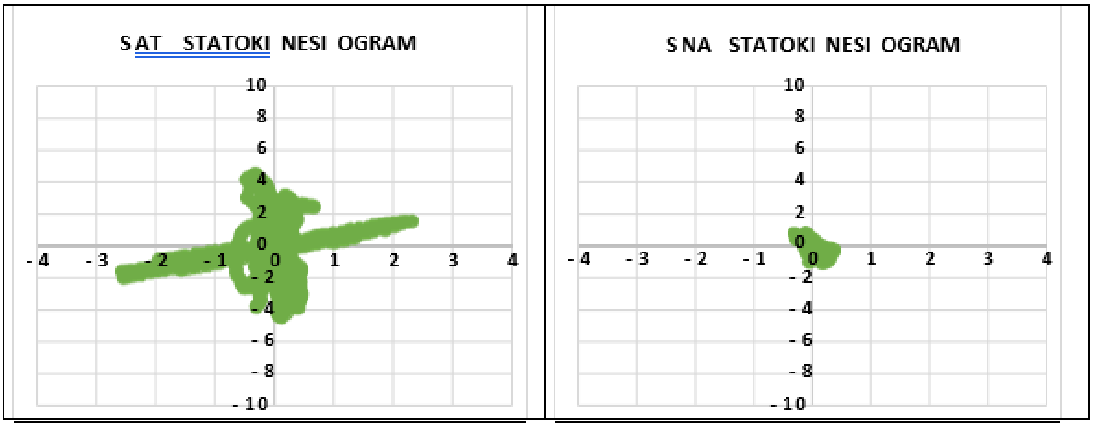

Figura 3. Statokinesiogram of the two examined groups

Note. The SNA group shows less displacement in both directions compared to SAT. Own elaboration.

composition, obtains the 95th percentile function, and calculates the ellipse's area. Figure **4** shows the graphical interface of the software.

The analysis of the SNA group using the software is shown in Figure **5**. When comparing the confidence ellipse of the two groups, it can be observed that the area of the ellipse is larger in SAT.

Discussion

The center of pressure (CP) refers to the point on the ground where the resultant force of all ground reaction forces acting on a body is concentrated. It is often used as an indicator of how a person distributes their weight and maintains balance during activities that require standing on two feet, which is why its study allows for the detection of behavior specific to a population group (8). Therefore, it was used in this study in an attempt to obtain conclusive data from individuals with transtibial amputation.

In the present study, it was evident that the excursion of the CP is greater in amputated individuals compared to non-amputated ones, which could be due to the influence of the prosthesis, changes in biomechanics, or neuromuscular factors related to amputation. The excursion values in the anteroposterior direction are higher than in the mediolateral axis, a situation that could be related to weight distribution and postural changes during balance tests, indicating the use of ankle strategies to maintain balance, which is consistent with the results of studies using a similar testing protocol (5,13).

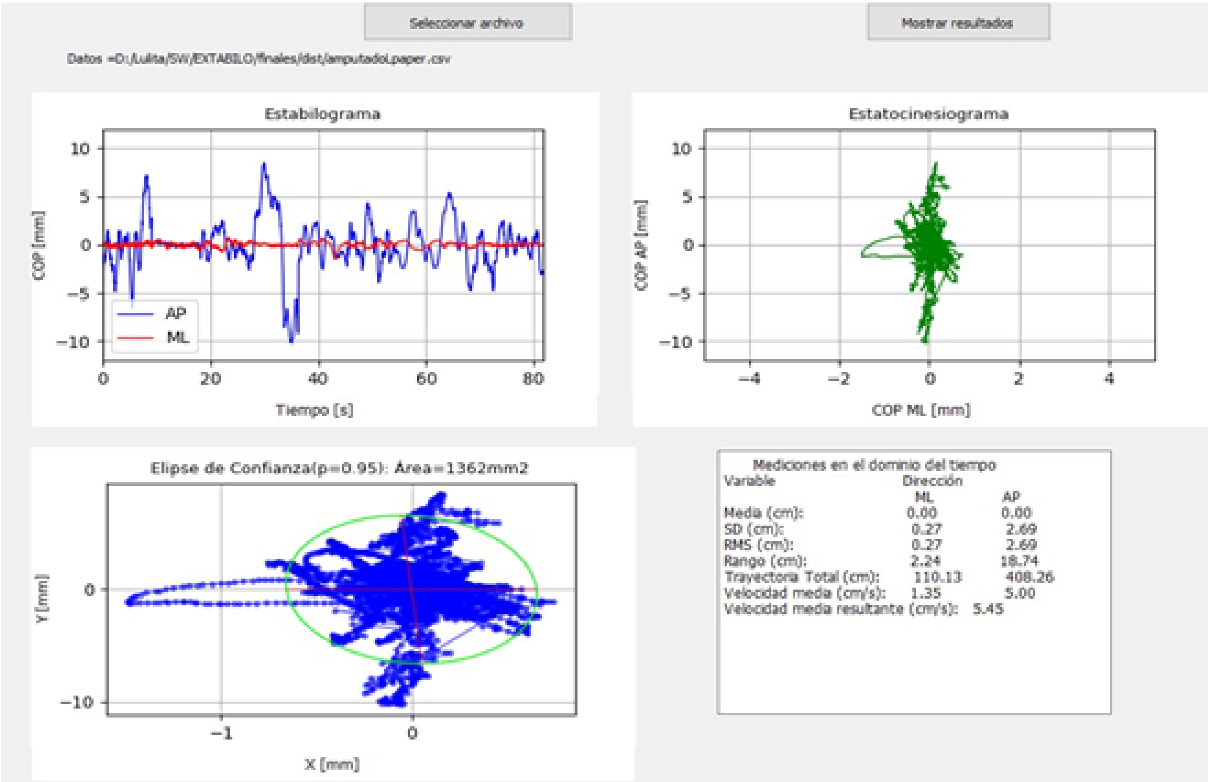

Figura 4. Software environment developed for visualizing linear parameters in the time domain of the CP, data analysis is performed for the SAT group

Note. Own elaboration.

The variation in RMS suggests that the significant differences present between the groups may be a consequence of the biomechanical conditions and balance control experienced by individuals in each group. Furthermore, in the SAT group, it is related to biomechanical and neuromuscular adaptation following amputation (7).

The significant difference between CP displacement values between the groups (as shown in Figure **3**), especially in the anteroposterior direction (as seen in Figure **2**), allows us to assert that amputees have reduced capacity in maintaining stability, a situation that may be related to the loss of anatomical structures and changes in neuromuscular function due to amputation (6,13,14).

Individuals with transtibial amputation experience higher velocity in CP displacement during static standing compared to individuals without amputation, and these data are similar to those of other studies (5,6). Considering the parameter of velocity in either the mediolateral

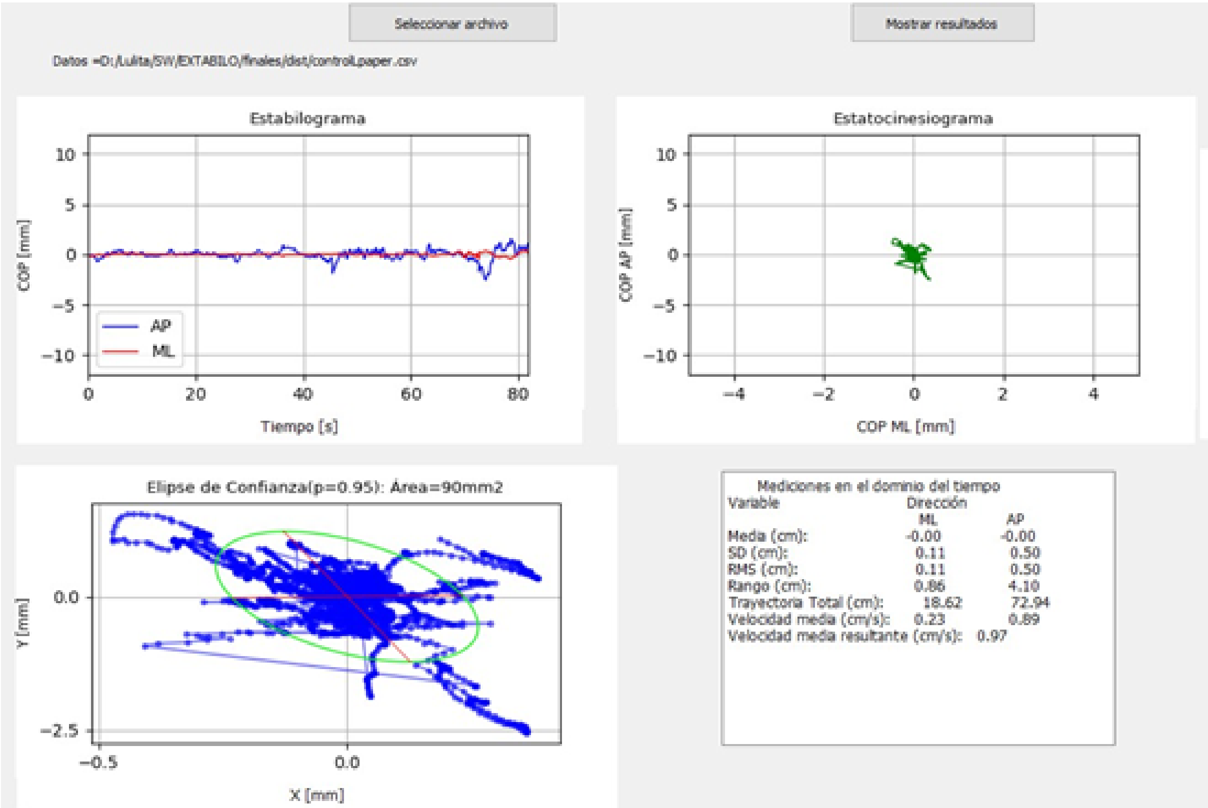

Figura 5. Analysis of the SNA group using the developed software

Note. Own elaboration.

or anteroposterior direction, the SAT group shows less stability (higher mean levels) than the SNA group. In static balance, the ankle strategy is responsible for controlling movements in the anteroposterior axis, involving torque generated by the plantar and dorsal flexors of the ankle. In individuals with transtibial amputation, the ability to use an ankle strategy is impaired, which would explain the greater instability in this direction compared to the lateral one. Research shows that individuals with transtibial amputation have difficulty bearing load on the lower limb due to existing joint instability in the sagittal and frontal planes, primarily at the knee joint. The larger area of the ellipse in SAT indicates that this group has greater oscillation than SNA. The ellipses also reveal a preference for displacement in the Y-axis, meaning in the anteroposterior direction. Despite technological advances in prosthetics, the asymmetry in load between the two lower limbs of amputees persists, leading to an overload of mechanical stresses on the biological lower limb, which can cause pain or joint cartilage degeneration (2,15,16).

Conclusions

The study of the analysis related to transtibial amputation and its impact on static bipedal stability revealed that individuals with unilateral transtibial amputation exhibit greater oscillations in both the mediolateral and anteroposterior directions compared to the non-amputated group. These oscillations could result from several factors:

- Loss of anatomical structures: Transtibial amputation entails the loss of part of the leg, which can affect the structure and biomechanical function of the lower limb. The absence of a portion of the limb can make it more challenging to maintain balance and stability.
- Altered sensorimotor system: Amputation can disrupt the sensorimotor system, which includes sensory feedback (from receptors in the skin, muscles, and joints) and motor response (muscle control). This can lead to reduced perception and control of one's own body in space, affecting balance.
- Reduced neuromuscular response: The description mentions a reduced neuromuscular effector response. This could refer to the ability of the remaining muscles to respond efficiently and cohesively to nerve signals, which can hinder body stabilization during balance.
- Poor sensorimotor integration: The mentioned poor sensorimotor integration may indicate issues with how the central nervous system processes and uses sensory information to control movements and maintain stability. The lack of adequate sensory feedback can make real-time adaptation to maintain balance challenging.

In summary, individuals with transtibial amputation may face significant challenges in maintaining balance due to the loss of anatomical structures, changes in the sensorimotor system, and potential issues with the integration of sensory information and motor response. The behavior of the center of pressure in transtibial amputees is a complex and diverse subject that involves an interplay of anatomical, biomechanical, and individual adaptation factors.

The results of this research can be valuable in rehabilitation and the design of specific interventions to improve the stability and quality of life of amputated individuals. The utility lies in understanding how amputations and factors inherited from this condition affect stability and balance. As such, the importance of rehabilitation and the development of specific strategies to support the integration processes and functionality of amputated individuals is emphasized.

Funding

This scientific research article derives from the research project .Application of clustering as a method for discriminating plantar pressure distribution in individuals with transtibial amputation,"funded by Universidad Distrital Francisco José de Caldas, Bogota, Colombia.

References

[1] A. R. Iglesias Triviño, R. E. Soria Ayuda, A. Blas Martínez, A. J. Sánchez, and E. Villarroya Bielsa, "Artículo monográfico: fisioterapia en la amputación de la extremidad inferior.," *RSI - Revista Sanitaria de Investigación*, Sept. 04, 2021. Accessed: Sept. 29, 2025. [Online]. Available: https://revistasanitariadeinvestigacion.com/articulo-monografico-fisioterapia-en-la-amputacion-de-la-extremidad-inferior/

[2] S. S. Mahulkar, P. A. Telang, and S. P. Arora, "Rehabilitation of a Patient after a Transtibial Amputation: A Case Report," *Cureus*, vol. 14, no. 10, p. e30773, Oct. 2022, doi: 10.7759/cureus.30773.

[3] C. L. Ávila Rendón, L. D. Gallo Cardona, and J. Castellanos Ruiz, "Estabilidad en amputación transtibial unilateral. Serie de casos," *Fisioterapia*, vol. 42, no. 4, pp. 218–223, July 2020, doi: 10.1016/j.ft.2020.02.001.

[4] L. D. Gallo Cardona, J. Castellanos Ruiz, and C. L. Ávila Rendón, "Fuerzas de reacción desde el piso durante la marcha en personas con amputación transtibial unilateral, serie de casos," *Rehabilitación*, vol. 56, no. 3, pp. 237–242, July 2022, doi: 10.1016/j.rh.2021.02.001.

[5] B. Kolářová, M. Janura, Z. Svoboda, P. Kolář, D. Tečová, and M. Elfmark, "Postural Control Strategies and Balance-Related Factors in Individuals with Traumatic Transtibial Amputations," *Sensors*, vol. 21, no. 21, 2021, doi: 10.3390/s21217284.

[6] N. Sarroca *et al.*, "Influence of insole material density in the stability of patients with prosthetic unilateral transtibial amputation," *Sci. Rep.*, vol. 12, no. 1, p. 7854, May 2022, doi: 10.1038/s41598-022-11564-3.

[7] L. A. Luengas and L. F. Wanumen Silva, "Modelos computacionales en la posturografía," *Tecnura*, vol. 26, no. 73, pp. 30–48, July 2022, doi: 10.14483/22487638.18060.

[8] T. Wafa, C. Zalewski, C. Tamaki, D. Barac-Cikoja, M. Bakke, and C. Brewer, "A new paradigm for assessing postural stability," *Gait Posture*, vol. 100, pp. 188–192, Feb. 2023, doi: 10.1016/j.gaitpost.2022.12.010.

[9] L. A. Luengas Contreras and D. C. Toloza Cano, *Estabilidad en amputados transtibiales unilaterales*. in Espacios (Universidad Distrital "Francisco José de Caldas"). Universidad Distrital Francisco Jose de Caldas, 2019. [Online]. Available: https://books.google.com.co/books?id=DL3vEAAAQBAJ

[10] S. Das, D. Nandi, and B. Neogi, "Design Analysis of Prosthetic Unilateral Transtibial Lower Limb with Gait Coordination," *Prosthesis*, vol. 5, no. 2, pp. 575–586, 2023, doi: 10.3390/prosthesis5020040.

[11] G. Moisan, L. Miramand, H. Younesian, and K. Turcot, "Balance control deficits in individuals with a transtibial amputation with and without visual input," *Prosthet. Orthot. Int.*, vol. 46, no. 2, 2022, [Online]. Available: https://journals.lww.com/poijournal/fulltext/2022/04000/balance_control_deficits_in_individuals_with_a.4.aspx

[12] L. A. Luengas C. and D. C. Toloza, "Análisis frecuencial y de la densidad espectral de potencia de la estabilidad de sujetos amputados," *TecnoLógicas*, vol. 23, no. 48, pp. 1–16, May 2020, doi: 10.22430/22565337.1453.

[13] L. Chen, Y. Feng, B. Chen, Q. Wang, and K. Wei, "Improving postural stability among people with lower-limb amputations by tactile sensory substitution," *J. NeuroEngineering Rehabil.*, vol. 18, no. 1, p. 159, Nov. 2021, doi: 10.1186/s12984-021-00952-x.

[14] D. F. Rusaw, R. Alinder, S. Edholm, K. L. L. Hallstedt, J. Runesson, and C. T. Barnett, "Development of a theoretical model for upright postural control in lower limb prosthesis users," *Sci. Rep.*, vol. 11, no. 1, p. 8263, Apr. 2021, doi: 10.1038/s41598-021-87657-2.

[15] A. Alhossary *et al.*, "Identification of Secondary Biomechanical Abnormalities in the Lower Limb Joints after Chronic Transtibial Amputation: A Proof-of-Concept Study Using SPM1D Analysis," *Bioengineering*, vol. 9, no. 7, 2022, doi: 10.3390/bioengineering9070293.

[16] BA. Petersen, PJ. Sparto, and LE. Fisher, "Clinical measures of balance and gait cannot differentiate somatosensory impairments in people with lower-limb amputation," *Gait Posture*, vol. 99, pp. 104–110, Jan. 2023, doi: 10.1016/j.gaitpost.2022.10.018.