Contribution of each leg in the static postural stability of unilateral transtibial amputees, a study with Information Theory

Aporte de cada pierna en la estabilidad estática postural de amputados transtibiales unilaterales, estudio con teoría de la información

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Lely Adriana Luengas Contreras
Universidad Distrital Francisco José de Caldas. Bogotá, D.C. (Colombia)
laluengasc@udistrital.edu.co

Daissy Carola Toloza Cano
Universidad Manuela Beltrán. Bucaramanga, D.C. (Colombia)
daissy.toloza@docentes.umb.edu.co

Luis Felipe Wanumen Silva
Universidad Distrital Francisco José de Caldas. Bogotá, D.C. (Colombia)
lwanumen@udistrital.edu.co

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Abstract

Introduction— Transtibial amputees tend to isolate themselves because they lack confidence in performing daily tasks; rehabilitation processes such as the use of prostheses are carried out for their social reintegration, where postural stability must be ensured, and activities allowed in diverse contexts.

Objective— Verify the contribution of each leg and direction (anterior/posterior and medial/lateral) of the Center of Pressure (CoP) in the static postural stability of unilateral transtibial amputees due to landmines using information theory.

Methodology— A quantitative experimental design was applied to examine the displacement and velocity of the CoP using infometric measurements in nine transtibial amputees, and the non-parametric U Mann-Whitney test was applied to recognize statistically notable differences ($p < 0.05$) between each leg.

Results— There are statistically notable differences between the legs in the variables of displacement and velocity. Each leg contributes differently to the control of the static bipedal posture, and their behavior in the directions of movement of the CoP differs from each other, but they work together to generate compensation strategies that allow maintaining stability.

Conclusions— The use of Information Theory made it possible to evaluate stability objectively, without specifying the kind of relationship between this and the input variables, which favored the recognition of the CoP shift as its best discriminant in comparison with velocity. Transtibial amputees control static bipedal posture with the non-amputated leg to compensate for the loss of lower leg afferents and efferents due to the amputation. The results demonstrate the suitability of using information theory in the evaluation of lateralized postural control in pathological conditions.

Keywords— Transtibial amputees; information theory; static stability; bioengineering; physical rehabilitation

Resumen

Introducción— Los amputados transtibiales tienden a aislarse porque carecen de confianza al ejecutar tareas cotidianas, para su reintegración social se efectúan procesos de rehabilitación como el uso de prótesis, donde se asegura estabilidad postural para realizar diversas actividades.

Objetivo— Verificar la contribución de cada pierna y cada dirección (antero-posterior, medio-lateral) del Centro de Presión (CoP) en la estabilidad estática postural de amputados transtibiales.

Metodología— Se realizó un estudio observacional en nueve amputados transtibiales unilaterales para examinar el desplazamiento y la velocidad del CoP usando medidas infométricas, y se utilizó el test de U Mann-Whitney ($p < 0.05$) para identificar diferencias entre cada pierna.

Resultados— Cada pierna contribuye de diferente manera en el control de la postura bípeda estática y su comportamiento en las direcciones de movimiento del CoP difieren entre sí; pero trabajan en conjunto para generar estrategias de compensación para mantener la estabilidad.

Conclusiones— La Teoría de la Información (TI) de Shannon permitió evaluar de forma objetiva la estabilidad, sin precisar la clase de relación existente entre las variables, lo que favoreció el reconocimiento del desplazamiento del CoP como discriminante de la estabilidad. Los amputados transtibiales controlan la postura bípeda estática con la pierna no amputada para compensar la pérdida de los aferentes y eferentes debido a la amputación. Los resultados demuestran la idoneidad de utilizar TI en la evaluación del control postural lateralizado en condiciones patológicas. La investigación presente aporta en la comprensión de la actividad postural para contribuir en el proceso de rehabilitación física de los amputados.

Palabras clave— Amputados transtibiales; teoría de la información; estabilidad estática; bioingeniería; rehabilitación física

I. Introduction

Colombia suffers from more than 11 thousand victims per land mine, this number will continue to grow since the demining process entails a high investment of time and human resources, and the location of these artifacts is unknown [1]. Between January and June 2020, 100 mine events occurred, affecting 126 civilians, including 17 minors, and 56 combatants, about 80% are injured and amputated, being the amputation below the knee or transtibial the one with the highest recurrence [1]. The transtibial prosthesis is used as a physical rehabilitation mechanism to provide part of the functions of the lost limb.

The adaptation of subjects with the loss of a limb not only depends on the level of amputation but also the prosthesis applied and the way to maintain postural control. The adaptation of the subjects refers to joining daily life and performing various tasks, including walking independently with low energy consumption at a comfortable velocity, but all this can be done if there is stability during the bipedal posture static [2].

Due to the loss of musculoskeletal structures, the amputee's center of mass shifts to the non-amputee side, altering the location of the center of gravity and thus stability [2]. It leads amputees to frequently experience falls [3]. Falls are associated with functional limitations and are indicators of impaired independence, mobility, and activity [3]-[4].

Studies have shown that more than 50% of lower body segment amputees experienced falls within a year and have a higher risk of falling compared to non-amputees [4]-[5].

Stability in standing is described as the ability to maintain the body's center of gravity within its base of support. It is achieved through the complex and synchronized functioning of several systems, including the musculoskeletal and neurological systems [6]. Biomechanical limitations impact static postural stability; for instance, the reaction forces distributed over the two legs must counteract the acceleration of vertical gravity to stabilize the position of the Center of Gravity (CG) along the vertical axis. Furthermore, the lack of vertical alignment of the human skeleton means that muscular activities are always present to immobilize the joints [6]-[7].

The body is incapable of generating constant tension and immobilizing the whole body. Instead, it acts on each body segment, one at a time. With the center of gravity's movement control through the modification of the pressure distribution under feet, the relative displacement of the CoP for the vertical projection of the center of gravity is acted upon, in such a way that stability is achieved [6]-[7].

Instability can occur by reducing proprioception information caused by loss of feedback from the foot. In non-amputees, the maintenance of stability in the static standing position is achieved by employing hip and ankle stability strategies. In transtibial amputees, as they do not have an anatomical ankle, the ankle strategy is compensated by increasing the hip strategy. This mechanism increases the use of the non-amputee side [8]-[9].

Exploratory studies of the behavior of the CoP center of pressure in terms of time and frequency have been carried out to provide information on the mechanisms committed to controlling the static posture. Concluding that the more irregular or unpredictable the series, the stability decreases and suggests that the homogeneity of the CoP oscillation is an indicator of the control of bipedal posture. The displacement and velocity of the CoP are among the most studied measures, Additionally, it was found that the relationship between stability and CoP is non-linear [6], [10]-[13].

Information contained in the variables can be measured with the mathematical information theory developed by Shannon and Warren (mathematical theory of communication), who established that every communication system has a set of messages (information sent H (X)) that can be selected and sent through a channel communication delivering information to the receiver (H(Y)). Information can be corrupted by noise or by equivocation, which are factors that influence its quality. There, the noise is the conditional entropy of the output when the input is known, as well as the equivocation is the entropy of the input when the output is known [14].

Every system can be estimated as a communication system, considering that the different combinations of the input variables represent the messages to be transmitted and carry information from the output. The amount of information transmitted symbolizes the relationship between inputs and outputs, it also contributes to the prediction of the output variable as long as this ratio is greater than 0, the greater the information transmitted, the better the predictive model will act. Information Theory (IT) detects a relationship, whether linear or not, based on mutual information or joint entropy between X and Y [15].

To make use of IT, the variables must be categorical. One way to transform numerical variables into categorical is by using the "less information loss" (LIL) IT-based-algorithm. The information contained in the variables is optimally preserved by creating clusters, according to the variables' goodness indices. The clustering limits are set; so that the total amount of information about the output variable in the different clusters is the maximum that any other arrangement of clustering limits provides. In this way, the amount of data gets reduced, and representative groupings of the system characteristics remain [14]-[15].

The present study was designed to verify the contribution of each leg according to the bilateral CoP displacements, which makes it possible to analyze lateralized postural control in individuals suffering from lateralized postural impairment due to unilateral transtibial amputation. Static postural stability in lower limb amputees has not been investigated through information theory analysis, previous studies have performed postural analysis using techniques that linearly relate the displacement and velocity with stability, but it has been proven that the relationship is not linear [10]-[13]. TI analyzes relationship between variables, independent of type of relationship, therefore it was proposed to use this theory to evaluate the relative contribution of each leg to static bipedal posture in unilateral transtibial amputees, by using spatio-temporal posturographic measures such as the displacement and the velocity of CoP presented by each leg. This article presents the research carried out to measure CoP in study group, the analysis of the CoP using TI and the indicators of biomechanical parameters to understand the postural activity, so they will allow improving the adaptation of the prostheses in the future.

II. Methodology

A. *Experimental Design*

In the Prosthetic and Amputee Service of the Hospital Militar Central (Bogotá, Colombia), a cross-sectional descriptive study was carried out with an observational component to measure the location of the CoP, the plantar force was measured with the Pedar® system [16]. The system consists of insoles that allow obtaining information on force that interacts between the foot and the sole of the shoe, as well as the measurement of the distribution of the contact force and the location of the CoP.

B. *Subjects*

Nine unilateral transtibial amputees participated in the study, average age 32 years, 35 years (SD: 3, 2, range 29 years-46 years), average body mass 78,25 kg (SD: 6,5, range 66 kg-89 kg), average height 176 cm (SD: 2, 7, range 160 cm-180 cm), cause of amputation trauma by land mine; type of prosthesis by liner, pin and carbon foot with high activity (Fig. 1). The study was approved by the Bioethics Committee of the UDFJC. Participants gave their written informed consent for the experimental procedure. The inclusion criteria were age between 20 years and 40 years, unilateral transtibial amputation after one-year, daily use of the prosthesis for more than one year, ability to stand in a bipedal position with the prosthesis without walking aids. Participants were excluded if they had any medical conditions that could affect their mobility or balance, such as neurological, orthopedic or rheumatic disorders, use of antipsychotic, antidepressant or tranquilizing drugs, otitis media, reduced somatosensory sensitivity of the non-amputated leg, ulceration or pain in the stump or prosthesis fit problems.

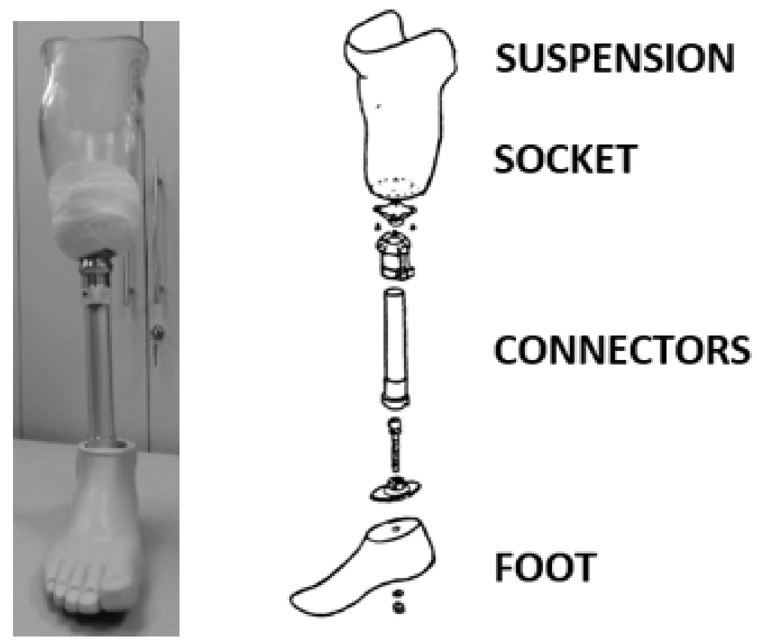

Fig. 1. Prosthesis used by amputees, suspension by liner and pin, and carbon foot of high activity.
Source: Own elaboration.

C. *Protocol*

Participants were placed on the Pedar® brand instrumented insole [16], wearing the usual footwear and clothing. Each Pedar template has 99 capacitive sensors, a thickness of 1.9 mm, pressure measurement range between 30 and 1 200 (kPa), and a resolution of 5 (kPa). Plantar pressure data were collected at 50 Hz using the Pedar® system during the static bipedal position scenario. The subject is in an anatomical standing position looking at a white wall for 10 s. Three trials were recorded for the scenario, with an interval of 5 minutes between each one (Fig. 2).

Fig. 2. Pedar System.
Source: [16].

D. *Analysis*

The data were stored and organized in Matlab®. It was established that the right side was amputated, and the left one was not. Then the displacement and velocity calculation of each foot and each direction were performed, obtaining the variables in Table 1. To compare the displacement and velocity measurements between the two legs and find statistically significant differences, the Mann-Whitney U test was used, with a significance level of 0.05.

Table 1. Variables used in the research.

Variable	Units	Conceptual definition
MLNA	mm	Displacement of the CoP in medial/lateral direction of the non-amputated foot.
APNA	mm	Displacement of the CoP in anterior/posterior direction of the non-amputated foot.
MLA	mm	Displacement of the CoP in medial/lateral direction of the amputated foot.
APA	mm	Displacement of the CoP in anterior/posterior direction of the non-amputated foot.
VMLNA	mm/s	CoP velocity in medial/lateral direction of the non-amputated foot.
VAPNA	mm/s	CoP velocity in anterior/posterior direction of the non-amputated foot.
VMLA	mm/s	CoP velocity in the medial/lateral direction of the amputated foot.
VAPA	mm/s	CoP velocity in anterior/posterior direction of the amputated foot.

Source: Own elaboration.

For the calculation of the mean CoP velocity in the two axes, medial-lateral and antero-posterior, (1) was used, which corresponds to the cumulative sum of the CoP displacement over the total time.

$$Velocity = \frac{1}{N-1}\sum_{i=1}^{N-1} v(i) \tag{1}$$

The displacement corresponds to the average distance between the maximum and minimum CoP displacement for each axis evaluated, (2).

$$Displacement = \frac{1}{N}\sum |CoP| \tag{2}$$

These data were included in the PowerHouse® software to perform the transformation of numerical data to categorical data using the Least Loss of Information algorithm (LIL).

The entropy (in bits) was calculated for each variable. The entropy *Yx* was to know the noise of each of the variables without considering the other variables. The entropy *YX* was to know the noise of a variable considering it as part of the selected group of variables, and the confidence (percentage) that the information transmitted by each variable is representative of the data set from which the sample was obtained. The entropy is calculated with (3), where *X* is the input variable, *Y* the output variable, *p* the probability [15].

$$H(X \vee Y = y) = -\sum_{x} p(x \vee y) log_2 p(x \vee y) \tag{3}$$

With the data obtained, the variables that contribute to the system were selected, in such a way that they transmit the greatest amount of information (gain). These become as representative of the output variable as possible. The selection was made in descending order of the gain, that each one of them contains about the output variable, a variable was added if the balance increases. Balance is understood as the symmetry between the information incorporated with the inclusion of that variable, and the lost confidence in the information accumulated by all variables [17].

Once the selection of variables was obtained, the infometric measurements of the system, input, output, noise, equivocation, and mutual information were established, to know the behavior of the final variables in the system.

III. Results

The statistical values of the average and standard deviation of the displacement and velocity that occur under each foot, and in both directions studied —medial/lateral and anterior/posterior— are observed in Table 2 and Fig. 3. In all variables with the U Mann-Whitney test, statistically significant differences were obtained between both analysis groups ($p < 0.05$).

Table 2. Mean values of displacement, velocity and LIL value.

Variables	Average		Amount of different data		Maximum	
	Initial ± SD	LIL	Initial	LIL	Initial ± SD	LIL
MLNA (mm)	0.152 ± 0.08	0.143	948	10	0.408	0.407
APNA (mm)	2.498 ± 1.59	2.380	2706	10	6.286	6.257
MLA (mm)	0.473 ± 0.58	0.460	1255	10	1.066	1.533
APA (mm)	0.961 ± 0.35	0.960	2871	10	2.120	2.227
VMLNA (mm/s)	0.909 ± 0.44	0.964	1790	10	13.220	13.220
VAPNA (mm/s)	5.378 ± 0.44	5.866	3092	10	35.977	35.977
VMLA (mm/s)	1.393 ± 1.93	1.128	1857	10	20.025	20.253
VAPA (mm/s)	2.204 ± 0.63	2.808	3100	10	29.040	29.564

ML: medial/lateral. AP: antero/posterior. A: amputated. NA: non-amputated. V: velocity. SD: standard deviaton.

Source: Own elaboration.

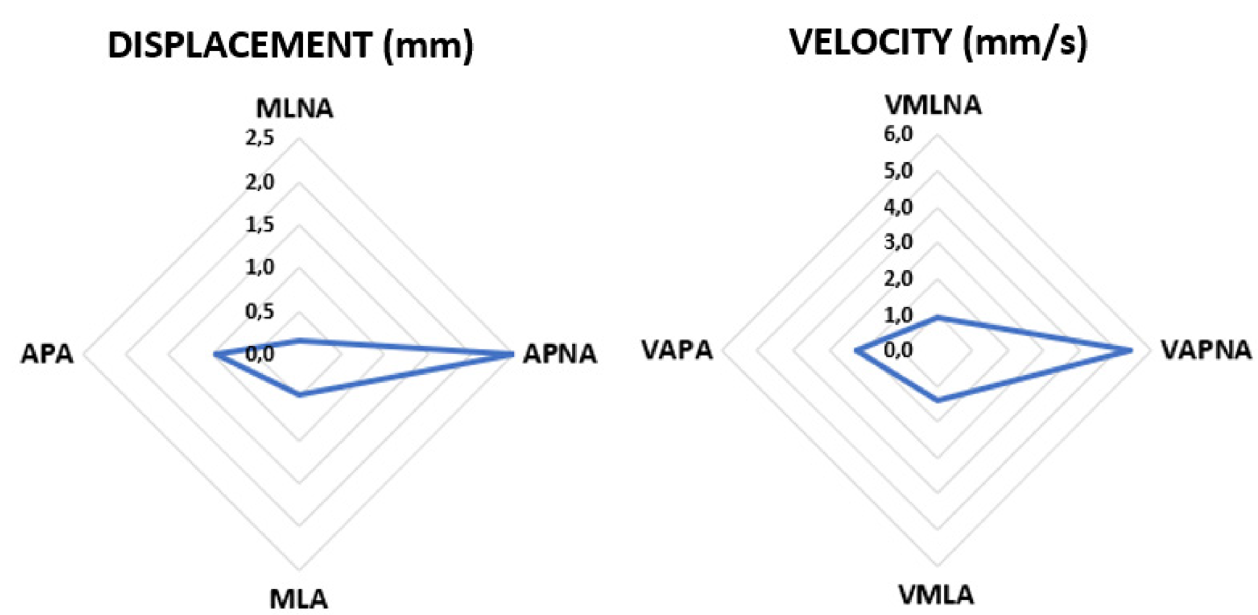

Fig. 3. Displacement and Velocity in medial/lateral anterior/posterior axes.
Source: Own elaboration.

When transforming numerical variables to categorical, the average values get altered, but the amount of different data decreases considerably in all variables (Table 3). With the categorical data, the entropy (3) and noise values of each independent variable were calculated in the system (*Yx*), the noise of the variable in the set of variables (*YX*), confidence, balance, and gain of each variable (Table 3).

Table 3. Entropy, confidence, and balance values for each variable.

Variable	Entropy (bits)	Noise Yx (bits)	Noise YX (bits)	Confidence (%)	Balance (%)	Gain (%)
MLNA	2.723	0.772	0.234	85	65	9.01
APNA	1.782	0.671	0.671	96	32	32.88
MLA	2.379	0.789	0.49	95	49	18.07
APA	2.204	0.826	0.324	94	64	16.63
VMLNA	2.953	0.610	0.610	96	38	38.99
VAPNA	1.998	0.636	0.416	95	56	19.4
VMLA	2.643	0.651	0.268	90	66	14.78
VAPA	2.656	0.746	0.246	45	10	0

ML: medial/lateral. AP: antero/posterior. A: amputated. NA: non-amputated. V: velocity.

Source: Own elaboration.

The selection of variables to identify the variables of impact on the system was made, taking into account the value of system confidence, balance, and confidence that each variable presents both displacement and velocity (Table 3). Contribution of variables were observed graphically, Fig. 4. It was identified that in displacement all the variables have a significant percentage of contribution, which does not occur in velocity.

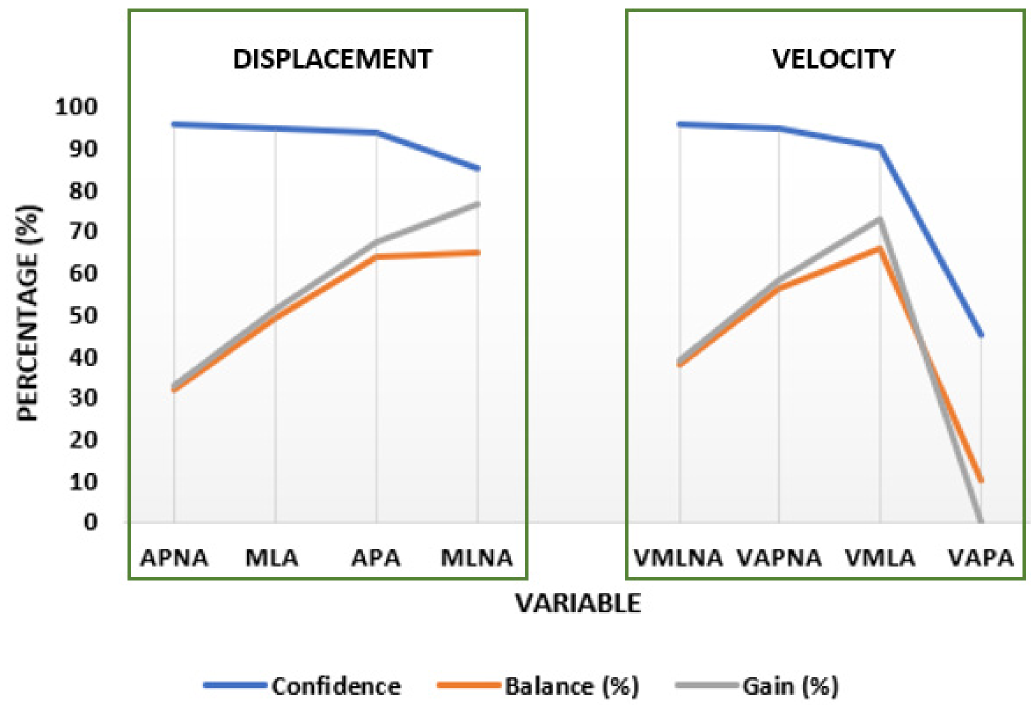

Fig. 4. Contribution from each variable to the system, in terms of confidence, balance, and gain. ML: medial/lateral. AP: anterior/posterior. A: amputated. NA: non-amputated.
Source: Own elaboration.

In displacement, all variables present a gain greater than 9%, according to the amount of information transmitted that can be calculated through entropy (3). Hence all are included in the final system model. Thus, the representative info metric measurements of the stability system are shown in Fig. 5.

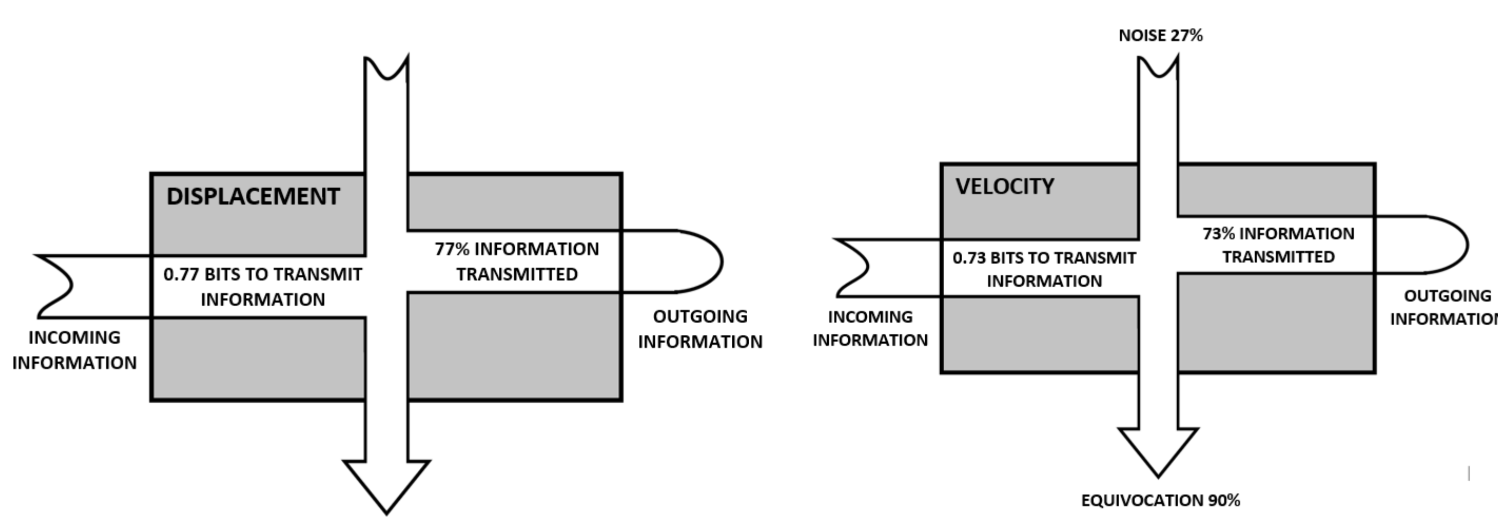

Fig. 5. Infometric measures of the stability system, considering displacement and velocity of the CoP.
Source: Own elaboration.

Three velocity variables contribute to stability. These are the non-amputated side in both directions, and the amputated side in the medial/lateral direction. The anterior/posterior direction of the amputated side has a gain of 0%; therefore, it is ruled out in the selection. With the selected variables VMLNA, VAPNA, and VMLA, the information map is obtained (Fig. 5).

IV. Discussion

When separately evaluating the postural control measures of each foot, the research showed that the non-amputated leg and the amputated leg do not contribute equally to the control of standing up static in transtibial amputees, as reported by Rougier and Bergeau [8].

Two types of irregularity were revealed. The first one implies the CoP displacement used to stabilize the static bipedal posture. Higher values were observed in the displacement of the non-amputated side, compared to the amputated side. This agrees with previous studies [18]-[20]. The second asymmetry refers to the velocity of the CoP, which differs between the two legs, with the antero-posterior direction of the non-amputated side being the greatest. The same results were obtained by Hendershot and Nussbaum [21].

These findings suggest high motor activity on the non-amputated side to regulate stability. The high value of displacement in the antero-posterior direction advises the use of the ankle for maintaining the posture. The high ML displacement value on the amputated side proposes increased use of the hip musculature as a strategy to receive more somatosensory stimuli and compensate for the lack of sensory input due to amputation. The use of the abductors and adductors of the hip possibly promotes efficient weight transfer between the legs, preventing the use of unnecessary compensation strategies such as lateral trunk flexion [22]-[24].

High CoP displacement and velocity values under the non-amputee side may reflect that amputees continuously explore the supporting floor with the somatosensory inputs of the anatomical foot, thus facilitating postural control and compensating for the loss of the ankle on the side amputee. This assertion goes supported by the study of french studies [25].

In researching the contribution of the variables using information theory, it was found that the amputated side exhibits high entropy values. This may be since this side is not capable of exercising adequate control over the location of the CoP. Reduced entropy values of the non-amputated side suggest the use of this side for stability control. The contribution of both legs to achieve static stability gets affected by events that alter joint lateralization, such as amputation. Eventually, amputees modify their contribution strategies; hence the high values of CoP displacement and velocity, to finally achieve control over postural static stability. Similar results were found in other research using other analysis techniques [6]-[7], [23].

The selection of variables shows that displacement is a better discriminant of stability than velocity since its input variables have a higher relationship with stability. Then, the control of the static bipedal posture is influenced by the CoP displacement of the two legs in both directions, with APNA being the largest contributor in the system. The velocity of the amputated side in the antero-posterior direction has a low attribution to stability since, as mentioned, there is no anatomical ankle that allows for postural control strategies.

IT allowed detecting the exact representation information of the input set, reducing the amount of data, which makes the processing gets done more simply since a large amount of data is hard to process [17].

V. Conclusions

The contribution of this research has been to detail both the relationship between the stability and the displacement of the CoP, as well as its stability and velocity by using analysis techniques based on information theory. This allowed knowing the contribution of each leg and CoP direction for postural control.

The use of information theory in the study of posture was verified. It allows the establishment of characteristics of the system from the behavior of the inputs and outputs, without resorting to linear methods for analysis. In the same way, it was verified that the use of CoP measures analyzed with Information Theory allows understanding the postural control mechanisms, in addition they can demonstrate the relative contribution of each leg to the control of the static bipedal posture.

Displacement better represents stability compared to velocity, since the four displacement variables MLNA, APNA, MLA, and APA allow the response of amputees to be detected to maintain stability; being the APNA parameter the one that generates the most contribution to postural control. Then the use of the ankle strategy on the non-amputated side is validated in the control.

The asymmetric load on each of the amputees' legs causes the CoP regulation to be modified in its displacement and velocity parameters. Each side performs different actions to have postural stability; therefore, it is observed that the non-amputated side has a high antero-posterior incidence. It allows asserting the use of ankle control postural strategy, while on the amputated side, there is a higher contribution in medial-lateral direction by indicating the use of hip strategy.

The unevenness shown in the CoP displacement patterns in both legs is an adaptive change induced by amputation in response to the unilateral alteration of the neuromuscular system in the anatomical joint of the excised ankle. The postural stability system increases the use of the non-amputated leg to control the posture of both legs.

Since the study of amputees with laterality alteration was approached, findings of this research may contribute to the investigation of stability in groups of subjects who also present laterality alteration, such as hemiparetic patients. They also carry out processes adaptive for the recovery of postural control.

In the future, it is intended to explore postural stability in amputees due to causes other than antipersonnel mine trauma to compare the findings. The goal is also to study dynamic stability in amputees. The results of the research are expected to contribute to the understanding of postural activity and contribute to the physical rehabilitation process.

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Lely Adriana Luengas Contreras. Universidad Distrital Francisco José de Caldas (Bogotá, D.C., Colombia). https://orcid.org/0000-0002-3600-4666

Daissy Carola Toloza Cano. Universidad Manuela Beltrán (Bucaramanga, D.C., Colombia). https://orcid.org/0000-0002-2199-6797

Luis Felipe Wanumen Silva. Universidad Distrital Francisco José de Caldas (Bogotá, D.C., Colombia). https://orcid.org/0000-0002-8877-5681