ISSN: 1692-7257 - Volume 2 – Number 46 - 2025

RCTA
Revista Colombiana de Tecnologías de Avanzada
UNIPAMPLONA

Digital Object Identifier: 10.24054/rcta.v2i46.4006

Evaluation of the transtibial amputee gait using inertial sensors and cyclograms: impact of prosthetic misalignment

Evaluación de la marcha del amputado transtibial mediante sensores inerciales y ciclogramas: impacto de la desalineación protésica

PhD. Esperanza Camargo Casallas[1], PhD. Lely Adriana Luengas Contreras[1], MSc. Enrique Yamid Garzón González[1]

[1] ***Universidad Distrital Francisco José de Caldas,*** *Grupo de Investigación DIGITI, Bogotá, Colombia.*

Correspondence: *{ecamargoc, laluengasc}@udistrital.edu.co*

Received: *january 29, 2025.* ***Accepted:*** *june 03, 2025.* ***Published:*** *july 06, 2025.*

How to cite: *E. Camargo Casallas, L. A. Luengas Contreras, and E. Y. Garzón González, "Evaluation of the transtibial amputee gait using inertial sensors and cyclograms: impact of prosthetic misalignment", RCTA, vol. 2, no. 46, pp. 123–131, Jul. 2025..*
Recovered from https://ojs.unipamplona.edu.co/index.php/rcta/article/view/4006

Abstract: Gait in transtibial amputees involves significant biomechanical adaptations due to the absence of the distal segment of the lower limb, leading to alterations in movement patterns. Dynamic alignment of the prosthesis is essential for efficient locomotion but is often adjusted subjectively through clinical observation. This study analyzed the gait of three transtibial amputees using inertial sensors and cyclograms. The TECH-NAID® system, which employs inertial measurement units (IMUs), was used for motion capture, while cyclograms enabled a detailed and objective assessment of joint kinematics. Gait was evaluated under standard alignment and controlled misalignment conditions at the socket (abduction/adduction, flexion/extension) and the prosthetic foot (dorsiflexion/plantarflexion, inversion/eversion), with angular variations of 2°, 6°, and 10°. The results revealed significant alterations in the kinematics of the hip, knee, and ankle joints, as well as compensatory mechanisms between limbs. Cyclograms proved to be effective clinical tools for assessing gait deviations in prosthetic rehabilitation.

Keywords: Transtibial Alignment, Cyclograms, Inercial sensors, Kinematics, Prosthetic gait.

Resumen: La marcha del amputado transtibial usuario de prótesis implica adaptaciones biomecánicas relevantes debido a la ausencia del segmento distal de la extremidad inferior, lo que modifica los patrones de movimiento. La alineación dinámica de la prótesis es crucial para una locomoción eficiente, pero suele ajustarse subjetivamente mediante observación clínica. Este estudio analizó la marcha de tres sujetos con amputación transtibial utilizando sensores inerciales y ciclogramas con el fin de caracterizarla. Se utilizó el sistema TECH-NAID® para la captura del movimiento haciendo uso de sensores inerciales, y los ciclogramas facilitaron una evaluación detallada y objetiva de la cinemática articular. Se comparó la marcha en condiciones de alineación estándar y bajo desalineaciones controladas en el socket (abducción/aducción, flexión/extensión) y en el pie protésico (dorsiflexión/plantiflexión, inversión/eversión) con variaciones angulares de 2°, 6° y 10°. Los resultados revelaron alteraciones significativas en las articulaciones de cadera, rodilla y tobillo, así como mecanismos compensatorios entre miembros inferiores. Los ciclogramas demostraron ser herramientas útiles para la evaluación clínica de la marcha en rehabilitación protésica. La disposición de herramientas tecnológicas en el apoyo del área de salud permite análisis objetivos; en concreto, en la presente investigación, se puedo identificar asimetría biomecánica en el patrón de marcha de personas con amputación.

Palabras clave: alineación transtibial, ciclogramas, cinemática, marcha prostética, sensores inerciales.

1. INTRODUCTION

Gait in transtibial amputees (below-knee) presents significant biomechanical alterations due to the loss of bone, ligaments, and muscles from the distal segment of the lower limb, resulting in changes in gait patterns. Therefore, proper prosthetic alignment is a key factor for achieving functional, comfortable, and energy-efficient ambulation. Accurate alignment improves symmetry, stability, and reduces load on the residual limb and contralateral side [1]-[3].

Transtibial prosthetic alignment, also known as femorotibial alignment, refers to the spatial relationship between prosthetic components and the residual limb. This process involves bench, static, and dynamic alignment phases [4]-[6].

Dynamic alignment, performed during ambulation, aims to optimize functional performance and minimize energy expenditure. However, in many medical centers this adjustment is still based on visual assessment and clinical experience—methods that, although widespread, entail high inter-technician variability and may compromise consistency [2], [4], [7]-[13]. Despite research linking misalignment to altered gait patterns, gait evaluation remains largely subjective, as many deviations cannot be detected without specialized tools such as gait analysis laboratories [2], [5], [9]-[17].

Some studies have introduced controlled misalignments to assess biomechanical impacts [18], showing that even small angular or linear changes can affect user stability and comfort [2], [8], [19], [20]. Thus, gait analysis is positioned as a key tool for evaluating locomotor kinematics and kinetics, providing objective insights into musculoskeletal function. Among the most precise methods are 3D optical systems, which model motion with high fidelity but require controlled environments.

As an alternative, inertial sensors (accelerometers, gyroscopes, magnetometers) offer more accessible and portable solutions, capable of recording acceleration, angular velocity, and spatial orientation in real-time—even outside the laboratory setting [21].

Additionally, force platforms can measure ground reaction forces and plantar pressures, complementing kinematic analyses with dynamic data [22]. Recent advances propose wearable systems with AI algorithms for optimizing dynamic alignment, and approaches integrating inertial sensors into mobile devices for analyzing gait parameters with high correlation to optical systems [23]. Machine learning models are also being explored to predict misalignments in real-time [24], as well as computational methods based on postural stability for static alignment [25].

This study focuses on analyzing transtibial amputee gait using inertial sensors, applying cyclograms to objectively visualize joint kinematics. A cyclic approach is proposed to relate mechanical and voluntary joint variables in both limbs, aiming to identify critical parameters during the gait cycle and contribute to the development of more accurate clinical prosthetic alignment strategies.

2. METHODOLOGY

2.1 Experimental Design

This study evaluated the sensitivity of sagittal-plane gait kinematics in transtibial amputees under systematic variations of dynamic prosthetic alignment. From a biomedical engineering perspective, a protocol was designed to modify specific prosthetic alignment parameters and quantify their impact on gait patterns.

The manipulated variables included:

- *Socket flexion/extension (FLEX/EXT)*
- *Socket abduction/adduction (ABD/ADD)*
- *Prosthetic foot dorsiflexion/plantarflexion*
- *Prosthetic foot inversion/eversion*

Each parameter was individually adjusted at angles of 2°, 6°, and 10°, ensuring patient safety was not compromised.

2.2. Study Population

Three male subjects with unilateral transtibial amputation caused by trauma (antipersonnel mines) participated in the study. All were treated at the Central Military Hospital in Bogotá.

Demographic range: Age: 30–48 years, Weight: 72–82 kg, Height: 1.76–1.85 m.

2.3. Equipment and Motion Capture System

The TECH-NAID® system was used for motion capture. This system integrates inertial sensors—including accelerometers, gyroscopes, and magnetometers—to measure acceleration, angular velocity, and orientation. Sensors were strategically positioned on the thighs, shanks, feet, and lumbar region (serving as a global reference), and connected via USB or Bluetooth.

2.4. Data Acquisition Procedure

Each participant walked a straight 7-meter path across 12 trials. Between 280 and 310 samples per gait cycle were captured at a sampling frequency of 50 Hz using the TECH-MCS® software. Figure 1 illustrates the sensor configuration used for each subject.

Fig. 1. *Sensor placement diagram.* ***Source:*** *Authors' elaboration.*

2.5. Data Processing

Data were processed using MATLAB® with custom-developed scripts. A structured matrix was built, enabling the generation of 2D/3D animations and computation of joint vectors. Cyclograms were derived for each participant. Virtual markers were implemented to enhance the accuracy of segmental analysis, evaluating the biomechanical effects of each misalignment condition.

3. RESULTS

3.1 Gait Analysis in Transtibial Amputees Using Angle-Angle Cyclograms

Human gait is a cyclic phenomenon that can be analyzed using angle-angle cyclograms, which graphically represent the relationship between joints throughout the gait cycle. In this study, cyclograms were used to evaluate the effect of different socket and prosthetic foot adjustments on the gait mechanics of transtibial (TT) amputees. One gait cycle per participant was analyzed, focusing on the hip and knee flexion-extension of the prosthetic limb and comparing it with the sound limb (Fig. 2).

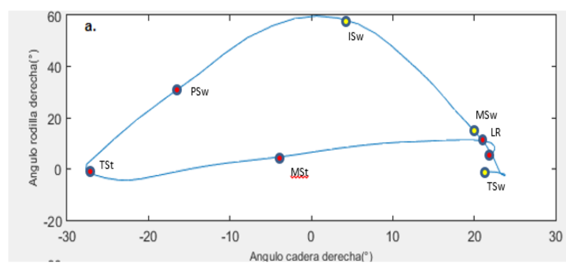

Figure 2. Cyclogram of the amputated side: Right hip vs. right knee.
Source: Authors' elaboration.

3.1.1. Ipsilateral (Amputated) Limb – Dynamic Alignment

The right hip vs. right knee cyclogram (Fig. 2), corresponding to the ipsilateral (amputated) side, allows identification of the gait cycle phases: Load Response (LR), Mid Stance (MSt), Terminal Stance (TSt), Pre-Swing (PSw), Initial Swing (ISw), Mid Swing (MSw), and Terminal Swing (TSw).

During LR, the hip is near full extension and the knee is flexed (~12°). In MSt, the hip extends (~5°) and the knee shows minimal flexion (~8°). In TSt, the hip reaches maximum extension, and the knee becomes neutral. In PSw, the knee flexes (~40°) and the hip remains extended (~15°). During ISw and MSw, hip flexion increases while the knee reaches peak flexion. Finally, in TSw, the hip flexes (~20°) and the knee extends (~5°).

3.1.2. Contralateral (Sound) Limb

The contralateral analysis (Fig. 3) shows: In LR, hip and knee are flexed (~20° and ~8°, respectively). In MSt, the knee extends slightly (~5°), and the hip maintains mild flexion (~3°). In TSt, the hip reaches ~27° of extension. During PSw, the knee flexes (~30°), and the hip maintains ~17° of extension. In ISw, the knee reaches maximum flexion (~63°) and the hip flexes (~8°). In MSw, the hip reaches peak flexion (~23°) while the knee extends. In TSw, the hip remains at ~20° flexion and the knee at ~10°.

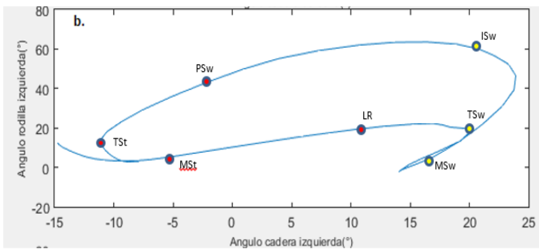

Fig. 3. *Cyclogram of the sound limb: Left knee vs. left ankle.*
Source: *Authors' elaboration.*

3.1.3. Knee-Ankle Relationship of the Contralateral Limb.

The Figure 4 illustrates the knee vs. ankle relationship on the sound side: During LR, the knee begins in ~20° flexion and the ankle in ~5° plantarflexion, transitioning into dorsiflexion (~5°). In MSt, the knee extends and the ankle reaches ~12° dorsiflexion. In TSt, ankle dorsiflexion peaks (~14°) and the knee flexes (~13°). During PSw, the knee flexes (~43°) and the ankle moves into ~10° plantarflexion. In ISw, the ankle reaches maximum plantarflexion (~12°), returning to neutral as the knee reaches peak flexion. In MSw, the knee extends and the ankle remains near neutral. In TSw, the knee stays extended and the ankle in a neutral position, with a sudden flexion-extension shift in the knee and a slight plantarflexion (~5°).

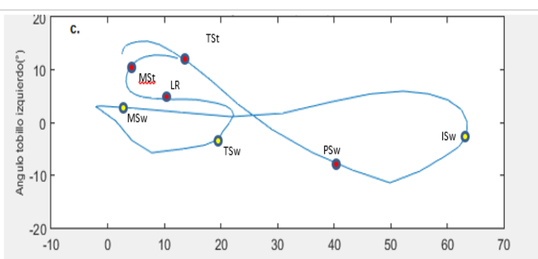

Fig. 4. *Cyclogram of the sound limb: Left knee vs. left ankle.*
Source: *Authors' elaboration.*

3.2 Socket Misalignments: Abduction (ABD) vs. Adduction (ADD)

3.2.1 Socket Abduction (ABD)

In the contralateral limb, Figure 5 shows reduced hip and knee flexion during Load Response (LR). In Mid Stance (MSt), hip extension increases and becomes more pronounced with higher abduction angles, whereas in Terminal Stance (TSt), hip extension decreases as abduction increases. In Terminal Swing (TSw), knee flexion is reduced. During Pre-Swing (PSw), both hip extension and knee flexion decrease symmetrically. In Initial Swing (ISw), knee extension peaks at ~40°, representing a ~20° reduction compared to the aligned condition. During Mid Swing (MSw), hip and knee tend to align, and in TSw, knee extension increases while hip flexion decreases. The anatomical ankle shows increased knee flexion and dorsiflexion during the transition from TSt to ISw, and increased plantarflexion from ISw to PSw.

In the ipsilateral limb, a reduction in hip and knee flexion is observed from ISw to MSw. Hip extension significantly decreases in TSt when abduction exceeds 6°.

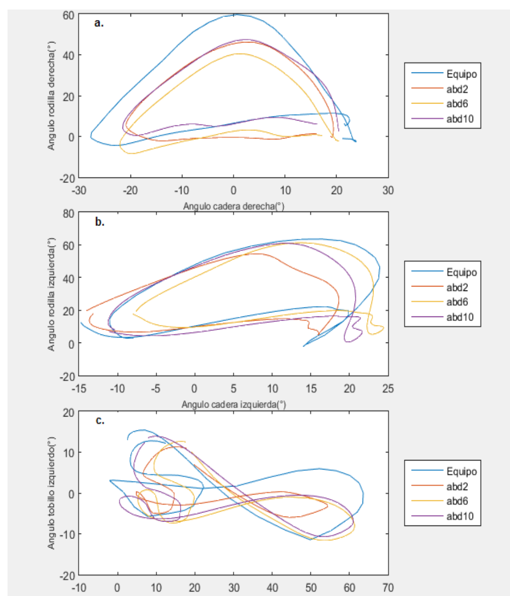

Fig. 5. *Cyclograms for different abduction levels of the socket. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

3.2.2 Socket Adduction (ADD)

In the contralateral limb, hip extension during LR is comparable to normal gait. Hip flexion decreases slightly in LR but not significantly. In MSw, the expected peak hip flexion seen in normal gait is diminished (Figure 6).

The knee-ankle cyclogram shows that swing-phase loops become smaller with 2° and 6° of adduction. At 10°, the pattern shifts toward increased plantarflexion. In MSt, ankle dorsiflexion increases.

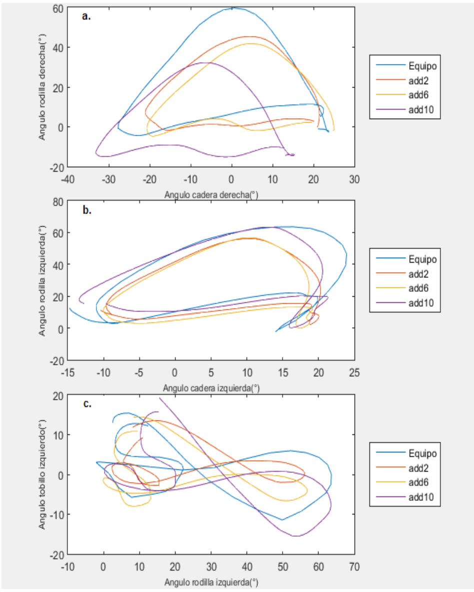

Figura 6*. Cyclograms for different adduction levels of the socket. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

In the ipsilateral limb, 10° of adduction causes both hip and knee hyperextension. With 2° and 6°, hip extension and knee flexion are reduced.

The correlation between ABD and ADD lies in their impact on frontal and sagittal plane movement patterns, often in opposite or phase-specific ways. ABD appears to limit flexion-extension ranges in the sound limb during swing, whereas ADD (especially at 10°) may induce marked hyperextension in the amputated limb. Both misalignments force compensatory strategies in the sound limb, as seen in altered hip and knee flexion-extension.

3.3 Socket Misalignments: Flexion (Flex) vs. Extension (Ext)

Las desalineaciones del socket en el plano sagital Sagittal plane misalignments of the socket (flexion and extension) also result in compensatory responses in joint kinematics (Figure 7).

3.3.1 Socket Flexion (Flex)

In the contralateral limb, most joint movements are similar to those in the properly aligned condition, except during Initial Swing (ISw) and Mid Swing (MSw), where the hip fails to reach the necessary flexion, thereby limiting swing amplitude.

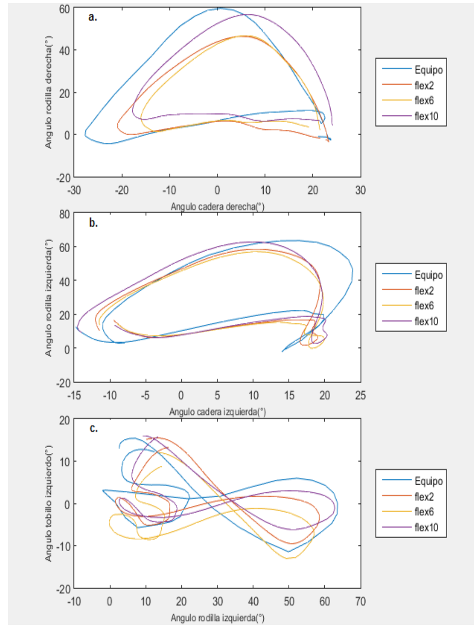

Fig. 7*. Cyclograms for different levels of socket flexion. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

In the ipsilateral limb, knee flexion decreases during Load Response (LR), approaching hyperextension. In Terminal Stance (TSt), hip hyperextension is reduced. During the swing phase, knee flexion increases.

3.3.2 Socket Extension (Ext)

In the contralateral limb, knee flexion decreases in LR. In TSt, hip hyperextension is reduced. During PSw, the hip is in a neutral position, and knee flexion decreases in proportion to the degree of socket extension. In MSw, hip flexion is absent and knee flexion is reduced.

In the ipsilateral limb, a 2° extension misalignment increases hip hyperextension. However, at 6° and 10°, hip kinematics begin to resemble normal alignment. In PSw, the hip remains neutral and the knee is flexed approximately ±40°. During swing, both hip and knee flexion decrease in inverse proportion to socket extension. The knee-ankle cyclogram shows reduced loop size and greater plantarflexion in TSw (Fig 8).

Socket flexion limits hip flexion in the sound limb during swing, while socket extension may eliminate hip flexion in MSw and increase hip hyperextension in the amputated limb, even with minor

RCTA
Revista Colombiana de Tecnologías de Avanzada
UNIPAMPLONA

misalignments. Both sagittal-plane misalignments affect knee flexion during loading on the amputated side, with socket flexion driving the knee closer to hyperextension.

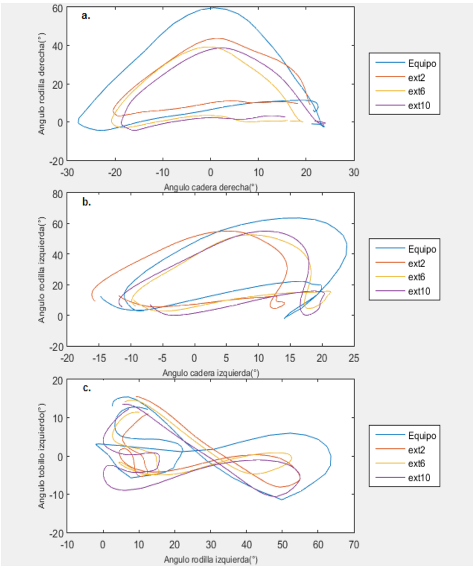

Fig. 8. *Cyclograms for different levels of socket extension. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

3.4 Prosthetic Foot Misalignments: Plantarflexion vs. Dorsiflexion

3.4.1 Prosthetic Foot Plantarflexion

In the ipsilateral limb, a significant reduction in hip and knee range of motion is observed from Mid Stance (MSt) to Mid Swing (MSw). The contralateral limb compensates by increasing hip extension and decreasing knee flexion. Hip flexion during swing remains close to normal ranges. The anatomical ankle shows a greater range of both plantarflexion and dorsiflexion during the swing phase (Fig 9).

3.4.2 Prosthetic Foot Dorsiflexion

Increased dorsiflexion of the prosthetic foot severely limits mobility in the amputated limb (Figure 10). In contrast, the contralateral limb demonstrates improved mobility, achieving hip flexion close to that of normal gait. The sound foot behaves very similarly to standard gait conditions.

In comparison, plantarflexion restricts movement in the ipsilateral limb and induces broad compensatory strategies in the contralateral limb. Conversely, while dorsiflexion severely limits the amputated limb, it appears to facilitate near-normal kinematics in the contralateral limb. These findings underscore the intersegmental desynchronization caused by prosthetic foot misalignments.

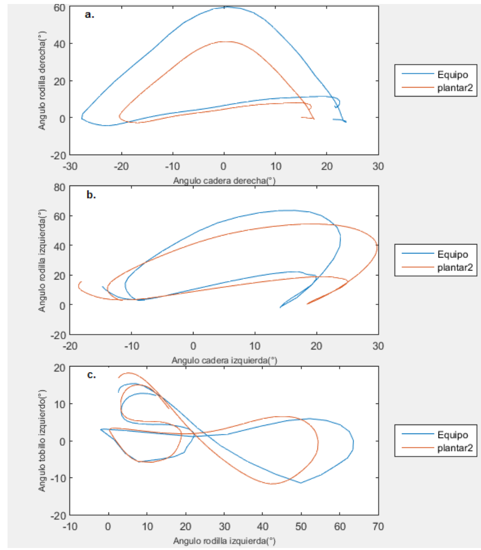

Fig. 9. *Cyclograms for different levels of plantarflexion.a) a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

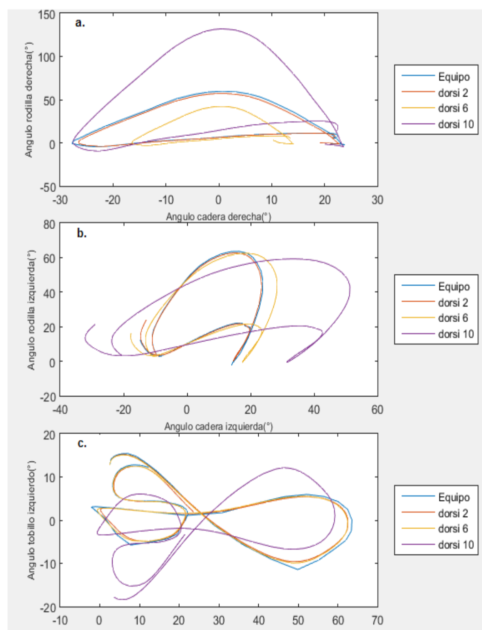

Fig. 10. *Cyclograms for different levels of dorsiflexion. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle.* ***Source:*** *Authors' elaboration.*

3.2.7. Inversion and Eversion of the Prosthetic Foot

In the ipsilateral limb, during Terminal Stance (TSt), the hip remains in hyperextension, although less than in the standard alignment condition. With the foot in eversion, knee flexion in Pre-Swing

RCTA
Revista Colombiana de Tecnologías de Avanzada
UNIPAMPLONA

(PSw) decreases by approximately 50%; with inversion, it decreases by around 25%.

In the contralateral limb, significant changes are observed with the foot in eversion, while modifications with inversion are less pronounced. Similar trends are observed in the sound foot (Figure 11).

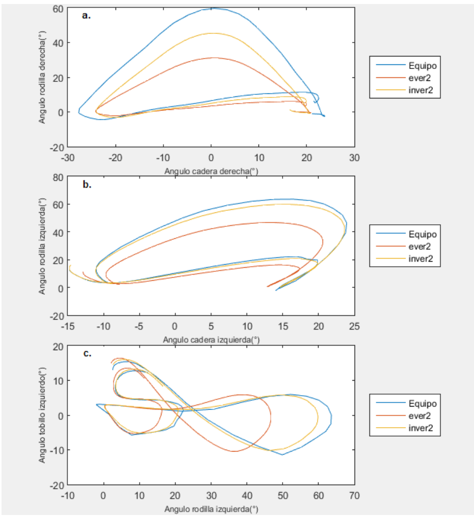

Fig. 11*. Cyclograms for different levels of prosthetic foot inversion and eversion. a) Right hip – right knee b) Left hip – left knee c) Left knee – left ankle*
Source: *Authors' elaboration.*

4. CONCLUSIONS

The results confirm that prosthetic alignment has a significant impact on gait kinematics in transtibial amputees, where even minimal angular deviations produce notable changes in joint ranges and interjoint coordination. Cyclograms enable precise visualization of these effects, revealing dysfunctions that may go unnoticed in conventional clinical evaluations.

The implementation of inertial sensors proved effective for capturing kinematic data in uncontrolled environments, allowing real-time monitoring of prosthetic behavior outside the laboratory. Combined with cyclogram analysis, this approach enhances clinical gait evaluation by providing objective information for personalized adjustment of prosthetic alignment and functionality.

The integration of inertial sensors, cyclograms, and MATLAB®-based data processing lays the groundwork for the development of intelligent prosthetic realignment systems supported by artificial intelligence, aimed at optimizing real-time adjustment.

Cyclograms are a fundamental tool for accurately evaluating interjoint coordination during gait in transtibial amputees, enabling the detection of subtle deviations caused by prosthetic misalignment. By facilitating more objective and detailed diagnostics, their integration into clinical practice is key to improving long-term quality of life for users, promoting effective rehabilitation and safe functional mobility.

Engineering contributes to the analysis of gait patterns in transtibial amputees through technological tools designed to identify biomechanical asymmetries that affect locomotion efficiency and safety. This analysis helps optimize prosthetic design and alignment, improve load transfer, and reduce compensations that may lead to secondary conditions—ultimately contributing to the development of functional and personalized technological solutions.

ACKNOWLEDGMENTS

We extend our gratitude to the victims of the armed conflict and to the Central Military Hospital for their support in this research. We also thank the Research Office (ODI) of Universidad Distrital Francisco José de Caldas for its institutional backing.

REFERENCES

[1] L. Baron, "Evaluación de la funcionalidad en pacientes con amputación transtibial unilateral basada en el Cuestionario de Evaluación de Prótesis (PEQ)," Universidad El Bosque, Bogotá, Colombia, 2020. [En línea]. Disponible en: Repositorio Un Bosque
[2] M. P. Chagas, F. R. Castro, M. A. A. Sanches, J. H. Agostinho, C. A. Alves y A. A. Carvalho, "Plataforma instrumental para la alineación estática de prótesis de extremidades inferiores," Instrumentation Science & Technology, vol. 48, no. 3, pp. 231–241, mayo 2020, doi: 10.1080/10739149.2019.1691586.
[3] E. Vázquez, Amputados y su rehabilitación, México, DF: CONACYT, 2016. [En línea]. Disponible en: https://www.anmm.org.mx/publicaciones/ultimas_publicaciones/Rehabilitacion.pdf
[4] E. Camargo, L. A. Luengas-C. y E. Y. Garzón, "Efectos de la alineación dinámica en la marcha protésica transtibial en el plano sagital de un modelo cinemático utilizando

OpenSim," International Review on Modelling and Simulations, vol. 15, no. 6, pp. 374–380, 2022. [En línea]. Disponible en: Premio Digno

[5] L. Montesinos, R. Castaldo y L. Pecchia, "Sobre el uso de la entropía aproximada y la entropía muestral con series temporales del centro de presión," Journal of NeuroEngineering and Rehabilitation, vol. 15, no. 1, art. 116, 2018, doi: 10.1186/s12984-018-0465-9. [En línea]. Disponible en: BioMed Central

[6] A. Khajuria y D. Joshi, "Correlatos corticales explicados por EEG en amputados transfemorales durante el equilibrio con retroalimentación vibrotáctil: un estudio piloto," Medical Engineering & Physics, vol. 101, art. 103772, 2022, doi: 10.1016/j.medengphy.2022.103772. [En línea]. Disponible en: PubMed

[7] S. Baig, R. M. Dansereau, A. D. C. Chan, A. Remaud y M. Bilodeau, "Análisis de conglomerados de medidas del centro de presión," International Journal of Electrical and Computer Systems, vol. 1, no. 1, 2012, doi: 10.11159/ijecs.2012.002. [En línea]. Disponible en: IJECS

[8] D. C. Toloza, L. A. Luengas-C. y Y. Pérez, Herramientas de análisis para la estabilidad postural estática. Caso de aplicación: individuos con amputación transtibial, Bogotá: UD Editorial, 2022. [En línea]. Disponible en: Premio Digno

[9] G. Sarailidis, T. Wagener y F. Pianosi, "Integración del conocimiento científico en el aprendizaje automático utilizando árboles de decisión interactivos," Computers & Geosciences, vol. 170, art. 105248, 2023, doi: 10.1016/j.cageo.2022.105248.

[10] C. B. Tan, M. H. A. Hijazi y P. N. E. Nohuddin, "Comparación de diferentes núcleos de máquinas de vectores de soporte para la detección de voz artificial," Telkomnika (Telecommunication Computing Electronics and Control), vol. 21, no. 1, 2023, doi: 10.12928/TELKOMNIKA.v21i1.24259.

[11] M. Al-Tarawneh, M. Muheilan y Z. Al-Tarawneh, "Detección de diabetes basada en el movimiento de la mano utilizando técnicas de aprendizaje automático," International Journal of Engineering Applications, vol. 9, no. 4, 2021, doi: 10.15866/irea.v9i4.20616.

[12] E. Matel, F. Vahdatikhaki, S. Hosseinyalamdary, T. Evers y H. Voordijk, "Un enfoque de red neuronal artificial para la estimación de costos de servicios de ingeniería," International Journal of Construction Management, vol. 22, no. 7, 2022, doi: 10.1080/15623599.2019.1692400.

[13] Y. Du et al., "Modelo de clasificación para la detección de carcinoma ductal in situ mediante espectroscopía infrarroja por transformada de Fourier basado en un modelo semántico estructurado profundo," Analytica Chimica Acta, vol. 1251, art. 340991, 2023, doi: 10.1016/j.aca.2023.340991.

[14] L. A. Luengas-C., D. C. Toloza y L. F. Wanumen, "Contribución de cada pierna en la estabilidad postural estática de amputados transtibiales unilaterales, un estudio con teoría de la información," Inge Cuc, vol. 17, no. 2, pp. 211–220, 2021.

[15] N. Tafti, M. Karimlou, M. A. Mardani, A. S. Jafarpisheh, G. R. Aminian y R. Safari, "Desarrollo y evaluación preliminar de un nuevo método de alineación protésica basado en la anatomía para prótesis transtibial," Assistive Technology, vol. 32, no. 1, pp. 38–46, enero 2020, doi: 10.1080/10400435.2018.1467513.

[16] R. T. Disler et al., "Factores que afectan el equilibrio postural en pacientes con EPOC y su influencia en las actividades de la vida diaria," European Respiratory Journal, vol. 15, no. 1, 2019.

[17] H. Hashimoto, T. Kobayashi, F. Gao, M. Kataoka, M. S. Orendurff y K. Okuda, "Efecto de los cambios de alineación protésica transversal en los momentos de reacción del encaje durante la marcha en individuos con amputación transtibial," Gait & Posture, vol. 65, pp. 8–14, junio 2018, doi: 10.1016/j.gaitpost.2018.06.119.

[18] G. Pirouzi, N. A. Abu Osman, S. Ali y M. Davoodi Makinejad, "Un nuevo dispositivo de alineación protésica para leer y registrar datos de alineación de prótesis," Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, vol. 231, no. 12, pp. 1127–1132, diciembre 2017, doi: 10.1177/0954411917735082.

[19] T. Nomura, K. Watanabe, T. Nosaka, H. Matsubara, M. Akiyama y K. Inui, "Relación entre la alineación de la prótesis transfemoral y la trayectoria del centro de presión plantar en el plano frontal," Journal of Physical Therapy Science, vol. 28, no. 2, 2016, doi: 10.1589/jpts.28.576.

[20] K. Taneda et al., "Efectos de la pérdida simulada del campo visual periférico en el control postural estático en adultos jóvenes sanos," Gait & Posture, vol. 86, pp. 233–239,

diciembre 2019, doi: 10.1016/j.gaitpost.2021.03.011.

[21] A. A. Ramli et al., "Caracterización de la marcha en la distrofia muscular de Duchenne utilizando un acelerómetro de un solo sensor: enfoques de aprendizaje automático clásico y profundo," Elsevier, 2021.

[22] X. Zhang, Z. Liu y G. Qiu, "Medición de las habilidades de equilibrio de amputados transtibiales utilizando la teoría de utilidad multiatributo," Biomedical Research International, vol. 2021, art. 8340367, 2021, doi: 10.1155/2021/8340367.

[23] J. A. Martínez, P. Gutiérrez y C. Delgado, "Evaluación de la marcha basada en sensores inerciales para la alineación de prótesis transtibial utilizando dispositivos móviles," IEEE Journal of Biomedical and Health Informatics, vol. 28, no. 1, pp. 34–42, enero 2024.

[24] S. Kim, H. J. Lee y D. Park, "Predicción en tiempo real de la alineación en prótesis transtibiales utilizando aprendizaje automático y datos de IMU," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 33, pp. 112–120, febrero 2025.

[25] L. A. Luengas Contreras, E. Camargo Casallas y L. F. Wanumen Silva, Modelos Computacionales y Biomecánica Humana. Caso Práctico de Alineación Estática de Prótesis Transtibial Fundamentada en la Estabilidad Postural, Bogotá, Colombia: Ediciones Universidad Cooperativa de Colombia, 2024.