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Mustafa Sharaf Jaian

Mahmud Rasheed Ismail

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ORIGINAL STUDY

Experimental Evaluation of Walking Stability of Bilateral Transtibial Prosthetic User: A Case Study

Mustafa Sharaf Jaian *, **Mahmud Rasheed Ismail**

Department of Prosthetics and Orthotics, College of Engineering, Al-Nahrain University, Baghdad, Iraq

ABSTRACT

Bilateral transtibial amputation presents a complex biomechanical condition in which the loss of biological ankle function and reduced sensory feedback can compromise walking stability. This case study aimed to experimentally evaluate gait stability in a bilateral transtibial prosthesis user under controlled sensory and mechanical walking conditions using a portable G-Walk inertial measurement system. The novelty of this study lies in the use of a structured three-factor experimental protocol that systematically combined visual input, arm posture, and surface type across twelve walking conditions to assess walk quality, propulsion, propulsion symmetry, and pelvic symmetry indices. The participant was a 31-year-old bilateral transtibial prosthesis user with a K3 mobility level using bilateral EchelonVAC multi-axis carbon feet. The results showed clear variations in stability-related gait parameters across the tested conditions. The most favorable gait pattern was observed during walking on a solid surface with eyes open and natural arm swing, whereas the least favorable pattern occurred during walking on a foam surface with eyes closed and hands on hips. Overall, visual deprivation and compliant surface walking appeared to have the strongest destabilizing influence on gait stability. These findings provide useful biomechanical insight into gait stability challenges in bilateral transtibial prosthesis use and may support future rehabilitation planning, prosthetic evaluation, and stability assessment under sensory-challenging walking conditions.

Keywords: Bilateral transtibial amputation (BTTA), Dynamic gait stability, Pelvic symmetry indices, IMU based G-WALK system, Sensory and mechanical conditions

1. Introduction

Bilateral transtibial amputation (BTTA) involves the loss of both lower limbs below the knee joint. This condition eliminates the biological function of the ankle and significantly reduces sensory feedback from the lower extremities, which are necessary to maintain balance during walking. As a result, maintaining gait stability becomes one of the most critical challenges for people with bilateral transtibial prostheses [1–4]. A prosthesis is a mechanical device that replaces a missing limb or limb segment and restores the basic functions, such as standing and walking. It is composed of constructive elements and linkage mechanisms that connect to the residual limb for load transmission and motion generation. Prosthesis design is adapted from human biomechanics and materials science in order to optimize gait efficiency, balance control, and user comfort [5–9]. In this context, stability is clinically critical because lower-limb prosthesis users often face higher balance demands and instability under sensory-challenged conditions (e.g., reduced vision) and on compliant surfaces, which are well known to increase sway, instability, and fall-risk indicators in amputees [10–14]. Therefore, an experimental study of stability in BTTA is important for objectively quantifying how controllable gait becomes as sensory reliability and mechanical support change, and for guiding rehabilitation strategies that target real-world fall-risk scenarios [15–19]. According to recent biomechanical evidence, prosthetic foot type significantly affects gait

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* Corresponding author.
E-mail addresses: Mustafa.Sharaf.PRO24@ced.nahrainuniv.edu.iq (M. S. Jaian), muhmood.rashid@nahrainuniv.edu.iq (M. R. Ismail).

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stability, as reflected in a more symmetrical plantar pressure distribution, decreased center-of-pressure angular deviation, and ground reaction force alignment, indicating improved dynamic balance during walking [20–23]. In this experiment, we test factors directly linked to balance control, including arm position (free/hands on hips/extended), visual condition (eyes open/closed), and surface type (solid/foam), because each factor can systematically alter stabilizing moments, sensory weighting, and base-of-support control during walking [10, 11]. Previous studies have provided important evidence regarding gait characteristics and stability-related behavior in bilateral transtibial amputees, Fiedler et al., (2013) measured gait in two of bilateral transtibial amputees, in which prosthesis-integrated load cells permitted the quantification of limb-loading imbalance. They used continuous kinetic/temporal data from walking tasks and determined that quantifiable limb asymmetries persist, which can affect stability-related loading patterns [24]. Su et al. (2007) investigated the gait of 19 bilateral transtibial amputees using standardized prosthetic feet through quantitative gait analysis. They analyzed spatiotemporal, kinematic, and kinetic features of walking; the authors concluded that bilateral transtibial gait differs from normative gait and indicates stabilizing, protective adjustments, such as modified speed/cadence, as well as deliberate patterns [25]. Su et al., (2008) used lab-based gait analysis to compare gait parameters between different subgroups of bilateral transtibial amputees (e.g., by etiology). They investigated spatiotemporal and other gait outcomes associated with stability control. They found that bilateral transtibial gait performance varies across clinical profiles, providing evidence to justify assessments focused on stability profile factors of the individuals [26]. Further evidence has also shown that prosthetic configuration and device-related factors can influence stability-relevant gait behavior in bilateral transtibial amputees, Su et al., (2010) examined the effect of increased prosthetic ankle range on gait in individuals with bilateral transtibial amputees. They tested gait outcomes with modified ankle motion provision and found that providing ankle motion can change gait behavior pertinent to stability and functional walking control [27]. Major et al., (2013) investigated walking speed and ankle prosthetic adaptors during bilateral transtibial amputees stepping, specifically targeting stability-related factors and the dynamic control requirements. They employed experimental gait tests among conditions and found significant device setup- and speed-related effects on stability-relevant factors in bilateral transtibial gait [28]. Jeon et al., (2022) reported a bilateral transtibial case comparing microprocessor-controlled vs conventional ankle/foot solutions with follow-up gait analysis. They used 3D gait analysis and patient-reported evaluation over time and concluded that advanced prosthetic control can improve gait characteristics associated with stability and functional performance [29]. Mohanty et al., (2020) presented a detailed bilateral transtibial gait case study compared with able-bodied gait. They used instrumented gait analysis to document deviations relevant to balance control and concluded that bilateral transtibial gait shows compensations that justify focused experimental stability evaluation [30]. Despite these contributions, several gaps remain in the existing literature, many bilateral transtibial investigations rely on laboratory gait characteristics or small-sample or case-based designs, limiting generalizability and condition stability mapping (e.g., case reports and pilot samples) [24, 29, 30]; several works examine device configuration (ankle motion/adapters) or speed effects but do not systematically combine (surface type, visual input, and arm posture) as controlled, factorial stability stressors in one protocol [27, 28]; and there remains a need for portable, clinically deployable experimental assessment that quantifies stability under tightly controlled walking conditions that mimic real-world sensory and mechanical challenges [16]. Although several studies have investigated gait characteristics in bilateral transtibial prostheses users, most have focused on spatiotemporal parameters, configuration of prosthetic devices, or walking speed. Only a limited number of experimental studies have systematically evaluated dynamic stability under combined sensory and mechanical conditions in this population. Bilateral transtibial prostheses users represent a unique biomechanical situation due to the absence of biological ankle control in both limbs, resulting in increased reliance on visual input, trunk strategies, and prosthetic propulsion symmetry. Therefore, controlled experimental multi-factor stability assessment in this population remains clinically relevant and scientifically underexplored. Based on this gaps, the contributions of this study are as follows:

(1) Development of a controlled three-factor experimental protocol to assess gait stability in bilateral transtibial prosthesis user.
(2) Quantitative assessment of propulsion and pelvic symmetry responses under combined sensory and mechanical gait conditions.
(3) Identification of the most stable and least stable walking conditions that can inform rehabilitation planning and fall risk management.

Aim of the study: Accordingly, the aim of this study was to experimentally evaluate walking stability in

Nomenclature & Symbols

BTTA	Bilateral Transtibial Amputation
IMU	Inertial Measurement Unit
G-WALK	Portable IMU-based Gait Analysis System
PTB	Patellar Tendon Bearing
PRF	Propulsion of the Right Foot
SI-PAT	Symmetry Index of Pelvic Angle Tilt
SI-PAR	Symmetry Index of Pelvic Angle Rotation
L5	Fifth Lumbar Vertebra
kg	Kilogram
VAC	Active Vacuum Suspension System
K3	Functional Mobility Level
LWQI	Left Walk Quality Index
RWQI	Right Walk Quality Index
PLF	Propulsion of the Left Foot
PSI	Propulsion Symmetry Index
SI-PAO	Symmetry Index of Pelvic Angle Obliquity
COM	Center of Mass
m	Meter

bilateral transtibial prosthesis user using the portable G-WALK IMU system [31–33], under controlled walking conditions, including variations in visual input (eyes open/closed), arm posture (free/hands on hips/extended), and surface type (solid/foam).

2. Biomechanical basis of gait stability

Gait stability in people with bilateral transtibial prostheses depends on the interaction between center of mass, base of support and sensory integration. Due to biological ankle function and the absence of proprioceptive feedback, balance control primarily relies on visual and somatosensory input as well as hip and trunk strategies [34]. Dynamic stability during walking can be explained through propulsion and symmetry parameters. Propulsion reflects the forward driving contribution of each limb, and balanced propulsion supports controlled progression [35]. Symmetry indices of pelvic tilt, obliquity, and rotation quantify coordination between body segments; Low symmetry may indicate compensatory trunk or pelvic motion associated with instability [36]. Visual input and surface compliance directly affect balance regulation. Removing visual feedback or walking on a compliance surface increases reliance on remaining sensory systems, which can alter propulsion patterns and pelvic symmetry [37]. Therefore, gait stability in bilateral transtibial prosthesis users can theoretically be understood as a function of sensory control, propulsion balance, and kinematic pelvic symmetry under varying environmental conditions [30].

3. Materials and methods

3.1. Participant and prosthetic configuration

The participant was a 31-year-old man, 169 cm tall and weighing 64 kg. He was classified as a K3 ambulatory user and had been using bilateral prostheses for

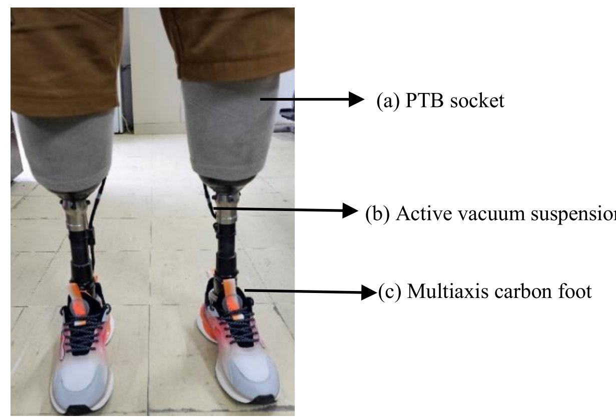

Fig. 1. Prosthetic components.

approximately 5 years before testing. No major health problems were reported at the time of testing. He was fitted with EchelonVAC multi-axis carbon feet on both prosthetic limbs (Fig. 1c). The participant used a PTB socket (Fig. 1a) with active vacuum suspension (Fig. 1b), a gel liner, and a sleeve. The prosthetic components and settings were identical on both sides.

3.2. Measurement system (G-WALK IMU)

Gait data were recorded using a G-Walk IMU (Fig. 2). The device was attached to the participant's waist, close to the L5 vertebra (Fig. 3), and secured with an elastic belt to prevent movement artefacts during walking. Data were acquired using G-Studio software. The G-WALK system is widely used in prosthetic gait assessment to objectively evaluate gait and movement patterns. In this study, the system was used for data acquisition and analysis, and the device was calibrated before each session (Fig. 4).

3.3. Experimental protocol

The participant walked 6 m forward and 6 m back in each trial (Fig. 5). All conditions were performed

Fig. 2. G-WALK IMU device.

Fig. 3. G-WALK IMU position.

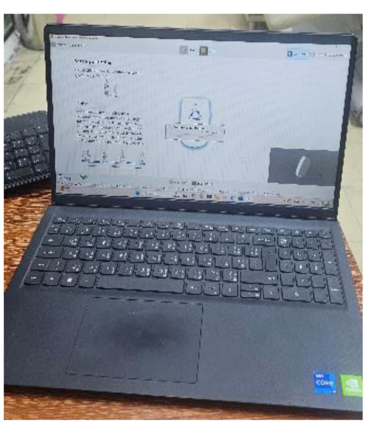

Fig. 4. G-WALK IMU calibration.

Fig. 5. Experimental walking path.

over the same distance, and a rest period of approximately 15 minutes was provided between attempts. The participant was asked to walk at a comfortable, self-selected pace in all trials. The protocol started with eyes-open walking on a solid surface using three arm positions: natural arm swing, hands on hips, and arms extended laterally. The same arm-position sequence was then repeated on the foam surface. After completing the eyes-open trials, the participant performed the same walking conditions with eyes closed on both surface types and using the same three arm positions. Each condition was repeated three times. For each condition, the trial with the clearest recording and no interruption was selected for descriptive analysis because it provided the most reliable gait signal and avoided the influence of interrupted or unclear recordings. The participant was instructed to maintain a straight walking path during each trial; however, minor directional deviations were unavoidable during some eyes-closed conditions. The experimental workflow is illustrated in Fig. 6.

3.4. Data processing and descriptive analysis

Gait outcomes from the 12 experimental walking conditions were organized in Microsoft Excel and summarized descriptively using percentage values and comparative bar charts. Because this study involved a single participant, the analysis was limited to descriptive comparison across conditions rather than inferential statistical testing.

4. Results and discussion

Output measurements obtained using the G-Walk device included left foot propulsion (PLF), right foot propulsion (PRF), propulsion symmetry index (PSI), left walk quality index (LWQI), and right walk quality index (RWQI). Additional parameters included the symmetry index of pelvic tilt (SI-PAT), the symmetry

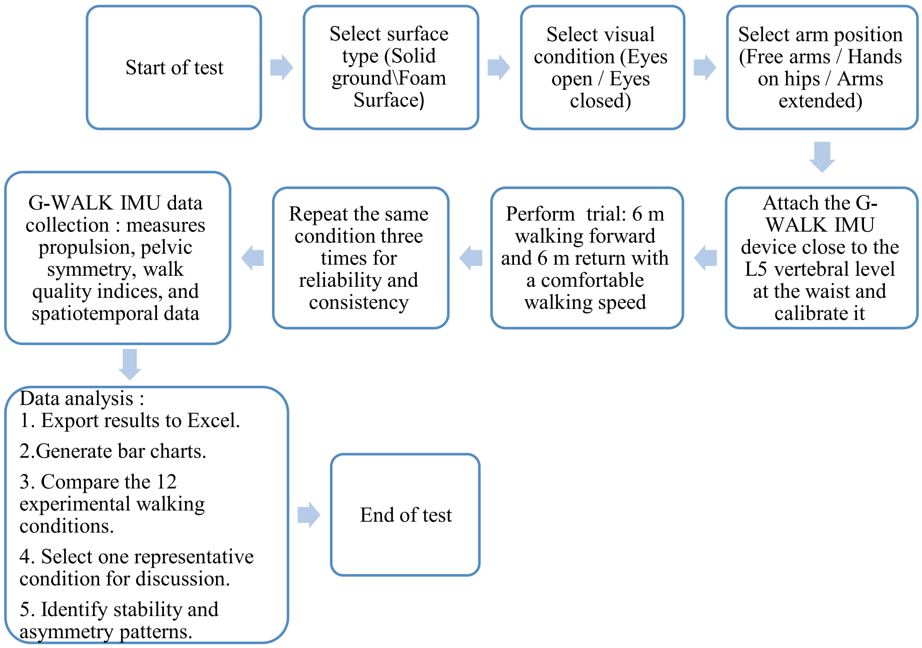

Fig. 6. Experimental workflow of the gait assessment protocol under different surface, visual input, and arm position conditions.

index of pelvic obliquity (SI-PAO) and the symmetry index of pelvic rotation (SI-PAR). Across twelve walking conditions, the gait data showed noticeable variations in walk quality, propulsion performance and pelvic symmetry in response to different combinations of arm posture, visual status and surface type. Walk quality indices were generally higher and propulsion values showed more consistent symmetry under solid-surface conditions (conditions 1-6) compared to foam surface conditions (conditions 7–12), which showed greater variability in propulsion magnitudes and symmetry indices. Eyes-open walking generally showed more favorable stability-related responses than eyes-closed walking, whereas several eyes-closed conditions showed lower propulsion values and reduced pelvic symmetry, particularly when combined with foam-surface walking. Pelvic rotation symmetry varied considerably across the conditions tested, with relatively high values in trials performed with natural arm swing on a solid surface, and lower values on foam surfaces and under conditions with less visual input. The numerical values of gait parameters measured across twelve experimental walking conditions are summarized in Table 1, while a graphical comparison of these parameters is presented in the bar chart in Fig. 7.

To demonstrate the analytical procedure used in this study, Condition 1 is presented as a representative example of gait parameter evaluation, and the same procedure was applied consistently to the remaining walking conditions. Condition 1 represented walking on a solid surface with eyes closed and hands on hips. As shown in Table 1 and Fig. 8, this condition showed relatively high walk quality, moderate propulsion values, and balanced propulsion symmetry. However, pelvic symmetry responses were not uniform across the three planes of pelvic motion, with pelvic rotation symmetry showing the lowest response. This finding suggests that reduced visual input combined with restricted arm posture may increase compensatory pelvic motion and slightly reduce dynamic stability.

The relative stability of each walking condition was interpreted based on the combined behavior of walk quality indices, propulsion magnitude, propulsion symmetry, and pelvic symmetry parameters, as summarized in Table 1 and Fig. 7.

Based on the overall pattern of measured stability-related parameters, Condition 4 represented the most favorable walking condition. This condition was performed on a solid surface with eyes open and natural arm swing. As summarized in Table 1 and Fig. 7, it showed the strongest combined pattern of walk quality, propulsion performance, propulsion symmetry, and pelvic symmetry among the tested conditions. Collectively, these responses indicate a relatively stable gait pattern characterized by high walk quality, effective propulsion performance, relatively favorable propulsion symmetry, and coordinated pelvic movement.

In contrast, Condition 11 represented the least favorable walking condition. This condition was

Table 1. Summary of gait parameters across the 12 experimental walking conditions measured using G-WALK IMU system.

Conditions	Position	Hands	Eyes	Surface	LWQI %	RWQI %	PLF%	PRF%	PSI%	SI-PAT %	SI-PAO %	SI-PAR %
1	Walking on Straight Line	On Hips	Closed	Solid	98.6	95.2	46.4	47.2	95.1	89.7	68.2	27.4
2	Walking on Straight Line	Arms extended	Closed	Solid	95.8	91.4	34.4	38.4	98.5	81.9	52.2	56.8
3	Walking on Straight Line	Natural	Closed	Solid	98.3	98.2	45.6	44.8	95.6	42.5	94.3	95.7
4	Walking on Straight Line	Natural	Open	Solid	99	99.4	69.6	72	91.5	83.3	85.8	95.1
5	Walking on Straight Line	On Hips	Open	Solid	98.7	98.9	62.4	71.2	90.1	58	85.7	96.2
6	Walking on Straight Line	Arms extended	Open	Solid	96.7	91.7	72.8	72	96.3	58.6	84.3	78.5
7	Walking on Straight Line	Arms extended	Open	Foam	99.7	93	52.8	65.6	91.2	50.5	83.1	75.1
8	Walking on Straight Line	On Hips	Open	Foam	99.3	95	72	55.2	88.4	46.8	64.7	77.4
9	Walking on Straight Line	Natural	Open	Foam	99.2	95.5	69.6	70.4	89.5	50.1	90	96.5
10	Walking on Straight Line	Natural	Closed	Foam	99.4	98.3	56.8	52.8	94.6	49.4	95.9	85.3
11	Walking on Straight Line	On Hips	Closed	Foam	96.1	96.4	42.4	37.6	93.3	9.7	89.5	94.2
12	Walking on Straight Line	Arms extended	Closed	Foam	97.6	96.2	35.2	36.8	91.6	13.4	94.9	75.6

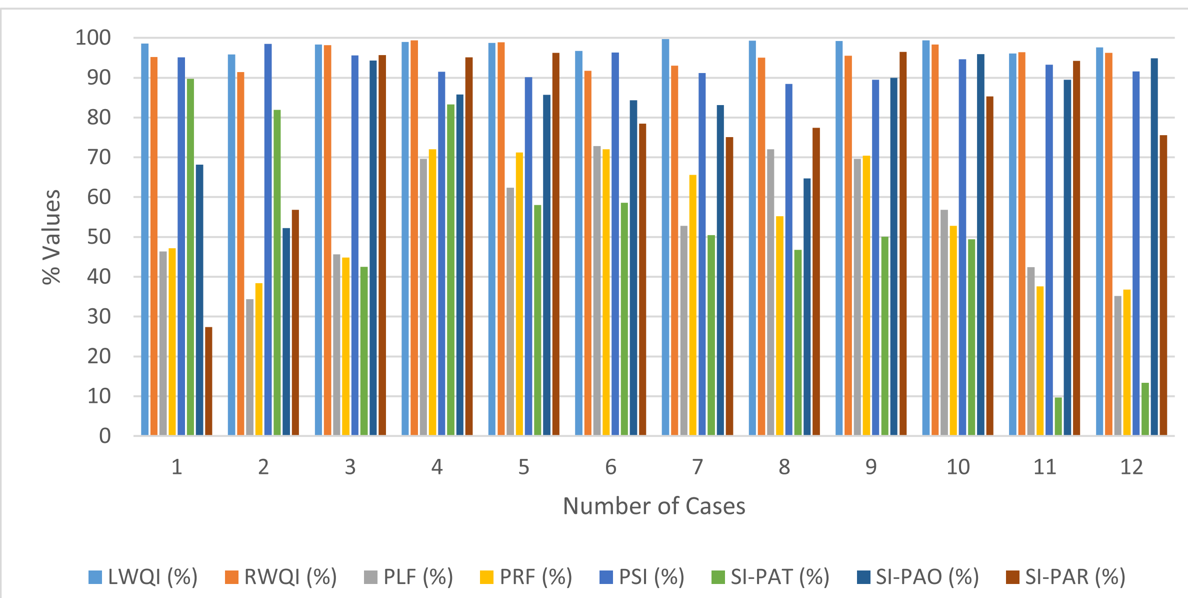

Fig. 7. Bar chart comparison of gait stability parameters across the twelve experimental walking conditions.

performed on a foam surface with eyes closed and hands on hips, combining reduced visual input, compliant surface support, and restricted upper-limb contribution. As shown in Table 1 and Fig. 7, this condition showed lower propulsion values and a marked reduction in pelvic tilt symmetry, despite relatively preserved propulsion symmetry. This suggests that the instability observed in Condition 11 was not mainly related to side-to-side propulsion imbalance, but rather to reduced pelvic control under combined sensory and mechanical challenge. The foam surface may have reduced mechanical stability during foot contact, while eye closure limited visual feedback and the hands-on-hips posture restricted natural arm contribution to balance control. Together, these factors likely increased the participant's reliance on compensatory pelvic control, resulting in a less stable gait pattern.

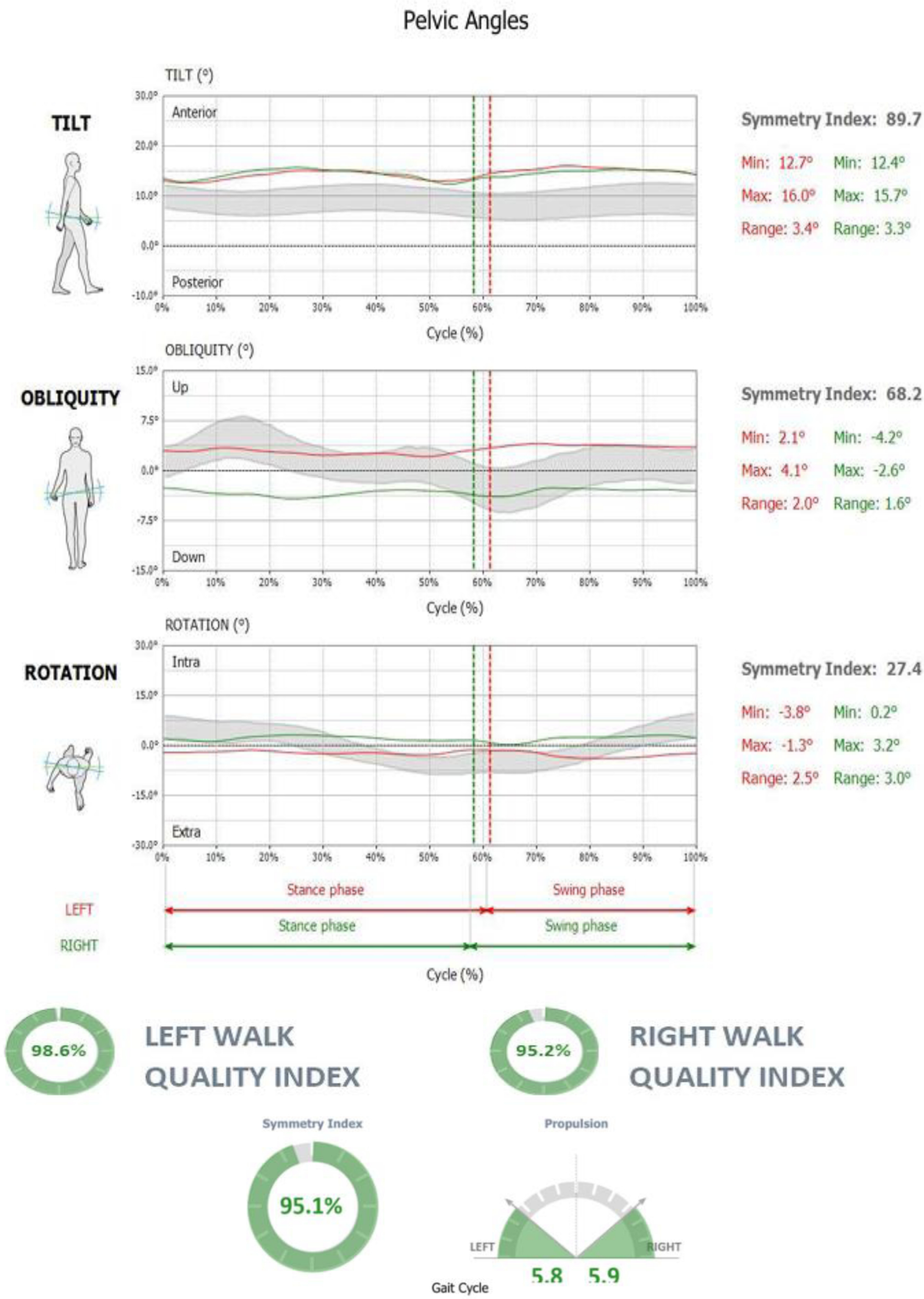

Fig. 8. Example of G-WALK gait analysis output for condition 1.

A direct comparison between Conditions 4 and 11 further highlights the difference between the most favorable and least favorable stability patterns. As shown in Table 1 and Fig. 7, Condition 4 showed a stronger overall stability profile, with higher walk quality, greater propulsion values, and more coordinated pelvic symmetry. In contrast, Condition 11 showed lower propulsion performance and a marked reduction in pelvic tilt symmetry, although propulsion symmetry remained relatively preserved. Therefore, the difference between these two conditions indicates that combined visual deprivation, compliant surface walking, and restricted hand position produced a less stable gait pattern than the more favorable sensory and mechanical environment observed in Condition 4. Across the tested walking conditions, visual input appeared to have a strong influence on gait stability. Conditions performed with eyes closed were generally associated with lower propulsion values and greater alteration in pelvic motion, particularly when combined with foam-surface walking. Surface compliance also affected gait control, while restriction of arm movement reduced the participant's ability to maintain a balanced gait pattern in challenging situations. These findings highlight the importance of sensory feedback, environmental stability, and upper-body coordination in maintaining gait control in individuals using bilateral transtibial prostheses.

These observations are consistent with previous biomechanical studies examining gait characteristics and stability in individuals with transtibial amputation. Previous research has reported that prosthetic gait often involves compensatory adjustments in propulsion and pelvic motion due to the absence of biological ankle function, which can affect gait symmetry and overall walking stability [25]. Similarly, biomechanical analyses of transtibial amputees have shown that individuals often rely on adaptive pelvic and trunk strategies to maintain balance during prosthetic walking [38]. In addition, studies examining the impact of sensory conditions on balance have demonstrated that reduced visual input and unstable walking surfaces can negatively affect postural stability in people with lower-limb amputations [10]. The current findings are in general agreement with these observations; however, they further show that instability may become more evident when multiple challenges are combined within the same walking condition. In particular, Condition 11 showed that visual deprivation, compliant surface walking, and restricted arm posture together produced a less favorable stability pattern, mainly through reduced propulsion performance and altered pelvic control. This provides a broader interpretation of the findings by showing that gait instability in bilateral transtibial prosthesis use may depend on the combined effect of sensory input, surface stability, and upper-body contribution rather than on a single factor alone.

These findings may contribute to improving clinical understanding of gait stability challenges in bilateral transtibial prosthesis users and may assist clinicians and researchers in evaluating prosthetic performance under sensory-challenging walking conditions.

5. Conclusion

This study experimentally investigated gait stability in a bilateral transtibial prosthesis user under twelve walking conditions involving different combinations of visual input, arm posture, and surface type. The analysis of gait parameters obtained using the G-Walk system showed noticeable variations in walk quality, propulsion magnitude, propulsion symmetry and pelvic motion symmetry across the conditions tested. Among the scenarios evaluated, walking on a solid surface with eyes open and natural arm swing (condition 4) showed the most stable gait pattern, with more favorable walk quality, propulsion, and pelvic symmetry responses. In contrast, walking on the foam surface with eyes closed and hands placed on hips (condition 11) represented the most challenging condition, with reduced propulsion and altered pelvic control indicating reduced gait stability. These findings highlight the combined influence of sensory input, environmental conditions, and upper-body contribution on maintaining stable gait patterns in individuals using bilateral transtibial prostheses. Despite the single-participant design, the results provide case-specific biomechanical insight into how different sensory and mechanical limitations can affect gait stability during bilateral prosthetic walking. The findings can support clinicians and researchers in evaluating prosthetic performance and understanding stability challenges in bilateral transtibial prosthesis users. Future studies could extend this work by including larger participant groups, comparing different prosthetic foot designs, and integrating advanced biomechanical measurement systems to further investigate gait stability mechanisms under complex walking conditions.

6. Limitations

There are several limitations to this study that should be considered when interpreting the results. The experimental analysis was performed on a single bilateral transtibial prosthesis user; therefore, the findings should be interpreted as case-specific observations and cannot be generalized to all individuals with bilateral lower-limb amputation or all bilateral transtibial prosthesis users. Furthermore, the analysis relied on wearable inertial sensor measurements obtained from the G-Walk system without additional motion capture or force plate data. Future studies involving larger participant groups and more comprehensive biomechanical measurement systems may provide deeper insight into gait stability mechanisms in bilateral transtibial prosthesis users. Nevertheless, the controlled experimental protocol and detailed gait parameter analysis provide valuable biomechanical insight into stability behavior under different sensory and environmental walking conditions.

7. Clinical implications

The findings in this study provide clinically relevant insight into how sensory and environmental conditions affect gait stability in individuals using bilateral transtibial prostheses. Understanding how factors such as visual input, walking compliance surface, and arm posture affect propulsion and pelvic symmetry may help clinicians and prosthetists design more effective rehabilitation strategies and evaluate prosthetic performance under challenging walking conditions. These results may also help to identify conditions that increase the risk of instability and may support the development of improved stability assessment protocols during prosthetic gait training.

Ethical consideration

The subject was provided with a full explanation of the experimental conditions and participated in this study voluntarily. Experimental procedures took place in a comfortable environment with good illumination and the presence of an assistant during the trials. In each measurement, a reasonable amount of time was allowed for the participant to get ready and warm up his muscles before testing. Ethical consideration: The study was reviewed and accepted by the Department of Prosthetics and Orthotics Engineering, College of Engineering, Al-Nahrain University, under approval number NU-BME 6/2026, with the supervision of the research advisor.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript entitled "**Experimental Evaluation of Walking Stability of Bilateral Transtibial Prosthetic User: A Case Study**."

Disclosure statement

The authors declare that there are no financial or non-financial competing interests.

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Data availability statement

The experimental data used to support the finding of this study are available from the corresponding author upon reasonable request.

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