DIGITAL APPROACHES TO LOWER-LIMB PROSTHESIS OPTIMIZATION

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Lower-limb prosthesis optimization remains a complex clinical challenge, as gait compensations and alignment-related deviations are often difficult to identify through only visual assessment. This paper demonstrates how integrated digital gait assessment can provide objective, clinically relevant insight into prosthesis-related movement patterns. A laboratory study was conducted using marker-based motion capture, ground reaction force measurement, and treadmill-based plantar pressure analysis to characterize gait kinematics, kinetics, and load distribution during walking and stance. The results reveal multi-segment compensations involving pelvic control, transverse-plane knee motion, ankle–foot function, and asymmetric weight-bearing strategies. To extend descriptive findings toward mechanistic understanding, an OpenSim-based musculoskeletal modeling workflow is introduced as a decision-support pipeline for joint-level interpretation. Together, the results illustrate how complementary digital methods can support evidence-based prosthesis fitting and alignment decisions, while highlighting a practical pathway toward scalable, technology-assisted rehabilitation workflows.

Keywords:
lower-limb prosthesis optimization,
gait assessment,
clinical decision support,
musculoskeletal modeling,
technology-assisted rehabilitation

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1 Introduction

Lower-limb amputation remains a major and growing rehabilitation challenge, driven by chronic vascular conditions, diabetes, aging populations, trauma, and conflicts. While the global epidemiology varies by region and cause, recent burden-of-disease analyses show that traumatic amputations alone represent a substantial and persistent health burden worldwide (Yuan, Bei, et al., 2023). At the same time, national projections illustrate that limb loss prevalence is expected to increase markedly in the coming decades, largely due to vascular disease and diabetes trends (Rivera, Julio A., et al. 2024).

Beyond the initial surgical outcome, long-term mobility depends heavily on the prosthesis–user interface and the user's ability to regain stable, efficient gait. However, walking with a lower-limb prosthesis is commonly associated with deviations in spatiotemporal and kinetic gait characteristics, compensatory strategies, elevated metabolic demand, and secondary musculoskeletal issues (Lathouwers et al., 2023).

Residual limb discomfort is also a critical barrier to prosthesis use: systematic evidence indicates a high prevalence of residual limb pain after lower-extremity amputation, which can directly limit daily function and prosthesis tolerance (List et al., 2021). These challenges translate into a practical clinical problem: many users do not achieve consistently symmetric, confident gait patterns, and prosthetic optimization often requires iterative adjustments that are time-consuming and expertise-intensive.

In response, digital health and rehabilitation engineering increasingly leverage portable sensing and computational modeling to provide more accessible, quantitative insight. Wearable inertial measurement units (IMUs) have become a particularly promising pathway because they are relatively low-cost, unobtrusive, and can enable gait monitoring beyond laboratory environments. Recent reviews have highlighted that inertial sensing can support objective gait characterization in individuals with limb loss, with applications spanning movement analysis, fall–risk–related metrics, and technology-assisted prosthetic development (Demeco et al., 2023). Complementary to sensing, musculoskeletal modeling and simulation offers a structured way to interpret movement data mechanistically - linking observable kinematics and external forces to internal quantities such as joint moments, joint reaction forces, and muscle–tendon loading (Seth et al., 2011).

Importantly, the choice and integration of digital methods affects clinical workflows, resource allocation, and the scalability of evidence-based prosthetic services. This paper positions these trends within a practical research question relevant to modern rehabilitation services: How can digital assessment and biomechanical modeling technologies be integrated to support evidence-based optimization of lower-limb prostheses while remaining feasible for broader clinical use?

2 Digital technologies for prosthesis optimization

Digital approaches for lower-limb prosthesis optimization can be grouped into (chapter 2.1) laboratory-grade quantitative gait analysis (typically combining optical motion capture with force measurement), (chapter 2.2) portable and wearable sensing for point-of-care or real-world monitoring, and (chapter 2.3) biomechanical modeling and simulation for biomechanical interpretation.

2.1 Optical motion capture and laboratory-based quantitative gait analysis

Marker-based optical motion capture (MoCap) systems are widely regarded as reference methods for three-dimensional gait analysis and are frequently used as a benchmark for evaluating emerging motion assessment technologies. In prosthetics research, MoCap is commonly applied to capture detailed kinematic data and is often combined with force plates to enable the estimation of joint moments, joint reaction forces, and other kinetic variables relevant to prosthetic alignment and gait compensation (Baker, 2013; Nolasco, L. A., et al., 2023).

For individuals with lower-limb amputation, laboratory-based gait analysis provides high-resolution insight into asymmetries, compensatory strategies, and prosthesis–user interactions under controlled conditions. Such analyses have been shown to support a deeper understanding of how prosthetic components, alignment, and user adaptation influence gait mechanics and functional performance (Gailey et al., 2008; Lathouwers et al., 2023). As a result, MoCap-based systems are frequently described as the most comprehensive approach for quantitative gait assessment in prosthetic research settings.

Despite these advantages, several studies highlight substantial barriers to the routine clinical implementation of optical motion capture. These include the need for dedicated laboratory infrastructure, extensive setup time related to marker placement and system calibration, and the requirement for highly trained personnel to acquire and interpret data (Muro-de-la-Herran et al., 2014; Wishaupt, R., et al., 2024).

2.2 Wearable sensing and IMU-based gait analysis

Wearable sensing, most notably through inertial measurement units (IMUs), has become a central focus in contemporary gait assessment because it enables portable, relatively low-cost, and scalable measurements beyond specialized laboratories. Recent evidence syntheses emphasize that IMU-based systems can capture clinically meaningful gait information while reducing operational barriers such as infrastructure requirements, long setup times, and the need for dedicated gait-lab personnel (Prisco et al., 2025).

Across rehabilitation and prosthetics contexts, IMUs are typically used to derive:

- temporal gait events (e.g., heel strike and toe-off),
- spatiotemporal indicators (e.g., cadence, step/stride time, stance/swing timing),
- in multi-sensor configurations, estimates of segment/joint kinematics.

IMU deployments range from multi-sensor full-body solutions (often used to approximate joint kinematics) to minimal sensor setups intended primarily for gait event detection and temporal parameter monitoring. Recent work in prosthesis-user cohorts demonstrates that IMU-based pipelines can be validated against optical motion capture and then applied to quantify gait parameters relevant to prosthesis use and alignment evaluation (Han et al., 2024).

2.3 Biomechanical modeling and simulation for prosthesis optimization

Biomechanical modeling and simulation provides a complementary pathway to experimental gait assessment by linking observable movement to internal biomechanical quantities that are difficult to measure directly in vivo (e.g., joint moments, joint reaction forces, and muscle–tendon loading). Contemporary musculoskeletal simulation platforms enable researchers and clinicians to perform inverse kinematics/dynamics analyses and explore mechanistic "what-if" scenarios relevant to rehabilitation decision-making and device configuration (Seth et al., 2011).

In the context of lower-limb prosthetics, simulation is increasingly used to examine how prosthetic configuration, alignment, and limb-loss related constraints may influence gait mechanics and compensatory strategies. Recent studies have introduced and shared OpenSim-based models specifically tailored to amputee populations (e.g., transfemoral limb loss and osseointegration scenarios), supporting both inverse-dynamics analyses and predictive/optimal-control simulations (Raveendranathan et al., 2023; Miller et al., 2024; Carloni, R., et al., 2024).

3 Methodology

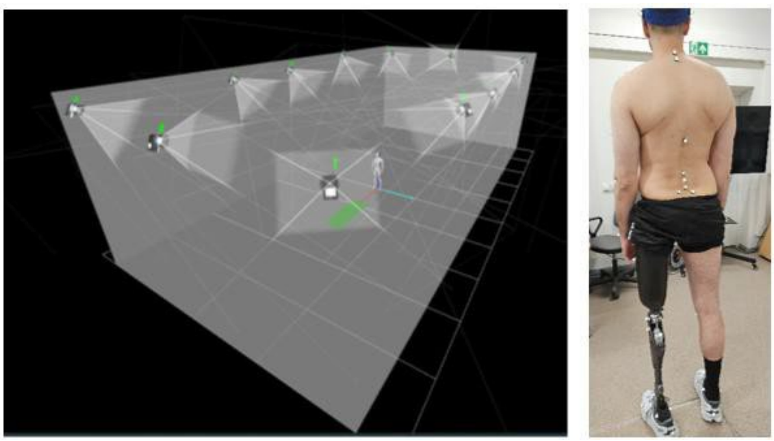

Figure 1: Laboratory gait analysis setup (optical cameras and force plates) and subject with markers attached

Source: Own

In the study of biomechanical gait characteristics, a subject with a left above-knee amputation (male, 28 years old, body mass 85 kg, height 1.95 m) volunteered to participate. Gait trials were repeated six times with 1 minute break between them.

Three-dimensional kinematic data were collected using a marker-based optical motion capture system (Qualisys) comprising 12 Oqus 7 cameras operating at a sampling frequency of 120 Hz. Markers were attached to anatomically important parts of the body according to the recommendations of the Rizzoli Orthopedic Institute. Ground reaction forces were synchronously recorded using two AMTI force plates.

In addition, treadmill-based gait analysis was performed using a Rehawalk HP Cosmos treadmill combined with a Zebris FDM-T pressure measurement system, which integrates a plantar pressure sensor matrix operating at 120 Hz. This setup enabled complementary assessment of foot–ground interaction and load distribution during prosthetic gait. Furthermore, a musculoskeletal modeling workflow is under development using OpenSim to enable model-based interpretation of gait data, with particular focus on joint reaction force–oriented analysis.

As this investigation represents a single-subject demonstration study, results are reported descriptively without inferential statistical testing. The focus is placed on illustrating the type and depth of biomechanical information that can be obtained using digital gait assessment technologies and how such information may support prosthesis fitting and alignment decisions. From an organizational perspective, this workflow reduces subjective interpretation and supports structured, repeatable clinical decision-making.

4 Results

4.1 Laboratory gait analysis results

A single-subject laboratory gait assessment at self-selected walking speed revealed a consistent pattern of prosthesis-side compensations and alignment-related deviations. In the frontal plane, the pelvis demonstrated reduced prosthesis-side pelvic elevation, indicating a contralateral pelvic drop and limited hip stabilization during stance on the prosthetic limb.

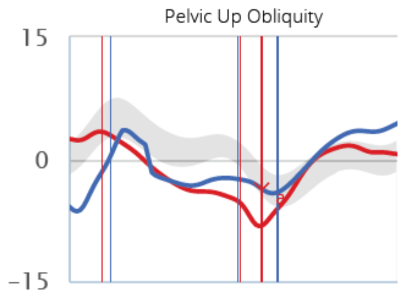

Figure 2: Pelvic obliquity per gait cycle (the blue curve represents the healthy limb, while the red curve represents the prosthetic limb)
Source: Own

At toe-off, pelvic obliquity reached -8.23° on the prosthesis side compared to 3.40° on the healthy limb. The grey shaded band represents ±1 standard deviation from the mean normative value derived from a control group of 18 healthy adults. This pattern is clinically relevant because reduced frontal-plane pelvic control may contribute to whole-body compensation strategies, including increased reliance on the healthy limb and upper-body adjustments during gait.

Lower-limb joint kinematics further indicated reduced bilateral hip internal rotation, suggesting limited transverse-plane mobility or constrained movement strategies during walking. At the knee, the prosthesis-side knee exhibited increased internal rotation, a deviation that is more plausibly related to prosthetic alignment and transverse-plane control.

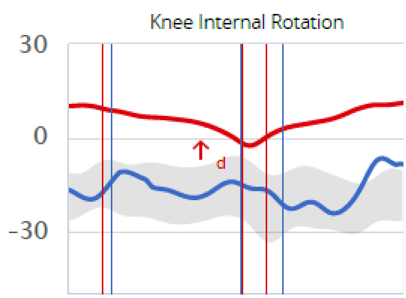

Figure 3: Knee internal rotation per gait cycle (the blue curve represents the healthy limb, while the red curve represents the prosthetic limb)
Source: Own

At the ankle–foot level, sagittal-plane kinematics revealed asymmetry in push-off behavior. At toe-off, the healthy limb demonstrated substantial plantarflexion (-28.2°), whereas the prosthetic side reached only 3.6°, indicating an absence of active push-off mechanics on the prosthetic limb. This reduced plantarflexion capacity is consistent with the functional characteristics of prosthetic ankle–foot systems and likely contributes to altered propulsion and compensatory loading patterns. Also, the prosthetic limb exhibited limited rotational variability, with values of approximately 3° across the gait cycle, while the sound limb showed a pronounced peak internal rotation of 11.35°. This pattern suggests increased reliance on transverse-plane adjustments of the intact limb to maintain forward progression and overall gait stability.

Kinetic outputs complemented these observations. Internal hip valgus moments were within normative limits bilaterally, indicating generally adequate hip loading capacity under the tested condition. However, the healthy limb demonstrated a reduced internal knee valgus moment, which may reflect altered load distribution and highlights the importance of strength and control capacity on the intact side in unilateral prosthesis users.

Table 1: Summary of key gait deviations identified by laboratory gait analysis

Feature	Parameter	Observed pattern	Interpretation
Pelvic motion	Pelvic obliquity	Decreased prosthesis-side pelvic elevation	Reduced hip stabilization during stance on the prosthetic limb
Hip kinematics	Hip internal rotation	Decreased bilaterally	Limited transverse-plane hip mobility during gait
Knee kinematics (prosthetic limb)	Knee internal rotation	Increased	Alignment- or control-related transverse-plane deviation
Ankle kinematics (prosthetic limb)	Ankle dorsiflexion	-28.2° (healthy) vs 3.6° (prosthetic)	Limited ankle–foot function and absence of active push-off
Hip kinetics	Internal hip valgus moment	Within normal limits bilaterally	Adequate frontal-plane hip loading capacity
Upper-body kinematics	Shoulder flexion	Increased bilaterally	Forward-flexed posture and trunk compensation
Spatiotemporal	Step length	0.76 vs 0.89 m (Shorter on healthy limb)	Asymmetric stepping following prosthetic stance
Spatiotemporal	Stance time	65.9% vs 58.8% (Increased prosthetic stance)	Stability-oriented gait

4.2 Plantar pressure and stance analysis

Treadmill-based stance and plantar pressure analysis provided additional insight into static load distribution and postural control characteristics during standing. The Zebris stance assessment revealed a clear asymmetric load distribution between limbs, with higher total loading observed on the healthy limb compared to the prosthetic limb. Average force distribution indicated that the prosthesis side contributed approximately 41% of the total load, whereas the healthy limb bore approximately 59%, reflecting a protective unloading strategy of the prosthesis side during stance. Segmental analysis of plantar loading further demonstrated marked asymmetry in foot loading patterns. On the prosthesis side, load was concentrated almost exclusively in the forefoot region, 100% load, with negligible contribution from the backfoot. In contrast, the healthy limb exhibited a more physiologically distributed load between forefoot and backfoot regions, indicating more effective rearfoot support and weight acceptance.

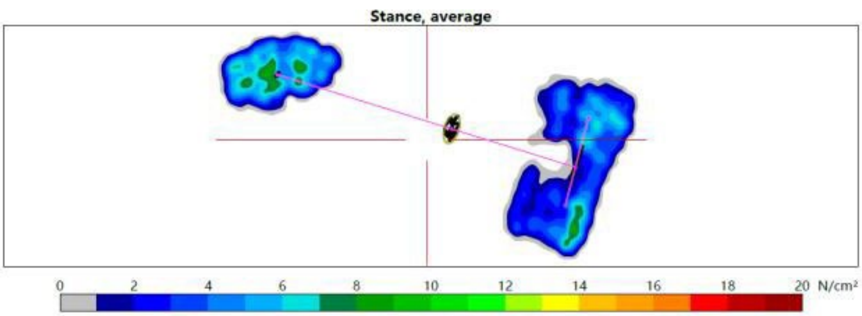

Figure 4: Plantar pressure distribution during stance (left side represents prosthetic limb)
Source: Own

These results demonstrate how pressure-based assessment can reveal clinically relevant information about prosthesis-side unloading and balance control that is not directly observable from kinematic analysis alone.

4.3 OpenSim-based workflow for biomechanical interpretation

Building on the laboratory-derived kinematic and kinetic datasets, an OpenSim-based musculoskeletal modeling workflow is being established to support the mechanistic interpretation of prosthesis-related gait deviations. The workflow is designed to integrate motion capture kinematics and ground reaction forces to enable joint-level analysis with a particular focus on joint reaction force (JRF)–oriented interpretation.

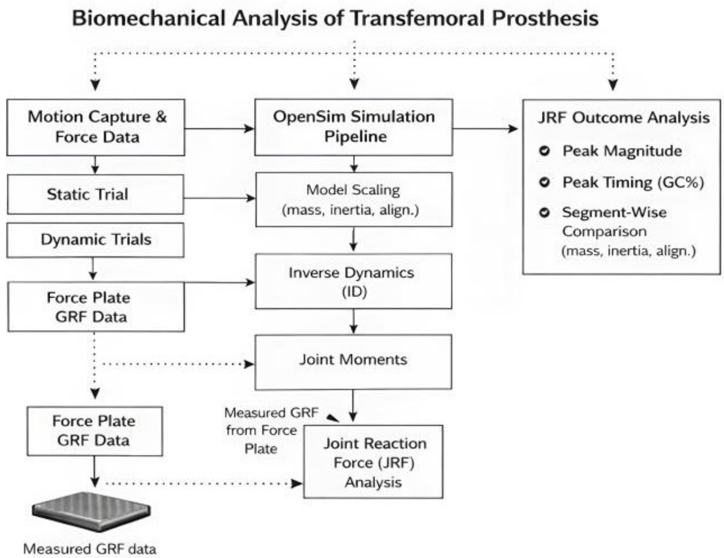

Figure 5: OpenSim simulation integration workflow
Source: Own

This workflow-oriented approach positions modeling not as a replacement for laboratory assessment, but as a decision-support extension that can help translate descriptive gait metrics into biomechanically meaningful insights relevant to prosthesis optimization.

5 Discussion and Conclusion

This study demonstrates how laboratory-grade digital gait assessment can provide detailed and clinically meaningful insight into prosthesis-related gait behavior. Motion capture analysis revealed multi-segment compensations associated with prosthesis side stance control and transverse-plane alignment, while plantar pressure assessment highlighted asymmetric weight-bearing strategies and altered foot–ground interaction during static conditions. Together, these findings illustrate that prosthesis-related adaptations manifest across kinematic, kinetic, and balance-related domains, underscoring the limitations of observation-based assessment alone.

Beyond the descriptive findings, the results support a digitally informed approach to lower-limb prosthesis optimization. High-resolution laboratory assessment enables objective identification of alignment and control-related deviations, while complementary pressure-based measures provide additional context regarding load distribution and postural strategies. The OpenSim-based workflow presented as a progress outcome further extends these results toward mechanistic interpretation, offering a pathway to translate observable gait patterns into joint-level loading hypotheses relevant to fitting and alignment decisions.

Several limitations should be acknowledged. The results are based on a single participant and a single walking condition, and are therefore not intended for generalization. Nevertheless, the study's strength lies in demonstrating the type and depth of information that can be obtained using integrated digital assessment methods. Future work will focus on applying the presented workflow across larger cohorts, incorporating scalable sensing solutions, and advancing musculoskeletal modeling toward validated, clinically feasible decision-support tools for evidence-based prosthesis optimization.

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