Original Article

Effects of Flexible Transfemoral Prostheses on Dynamic Balance in Unilateral Amputees: A Quasi-Experimental Within-Subject Study

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ABSTRACT

Background: Dynamic balance impairment is a major functional challenge in individuals with transfemoral amputation and is closely associated with mobility limitations and increased fall risk. Flexible transfemoral prostheses are widely prescribed to improve ambulation. However, limited biomechanical evidence exists examining how flexible transfemoral prostheses influence dynamic balance performance using standardized functional clinical assessments. This study aimed to examine the effect of flexible transfemoral prosthesis use on dynamic balance in unilateral transfemoral amputees.

Methods: This quasi-experimental within-subject study followed the TREND reporting guideline. Thirty unilateral transfemoral amputees were recruited using purposive sampling from the Department of Prosthetics and Orthotics at Poltekkes Kemenkes Surakarta, Indonesia. Inclusion criteria were medical stability and ability to perform multidirectional stepping; exclusion criteria included bilateral amputation and neurological disorders. The independent variable was ambulation condition (axillary crutch ambulation versus flexible transfemoral prosthesis use), and the dependent variable was FSST completion time. Dynamic balance was assessed using the Four Square Step Test (FSST). Analyses were conducted using paired t-tests with 95% confidence intervals.

Results: Participants were predominantly male (76.7%) with a mean age of 33.6 ± 9.4 years and a mean post-amputation duration of 4.2 ± 2.1 years. FSST completion time significantly decreased during flexible transfemoral prosthesis use compared with axillary crutch ambulation (mean difference = 8.97 seconds; 95% CI, 7.72–10.22; $p < 0.001$), demonstrating a very large effect size (Cohen's d = 2.68).

Conclusion: Flexible transfemoral prosthesis use significantly enhances dynamic balance in unilateral transfemoral amputees. Flexible transfemoral prostheses should be considered an essential component of function-oriented rehabilitation strategies to optimize postural control and safe mobility. Future longitudinal and instrumented biomechanical studies are warranted to further elucidate underlying adaptation mechanisms.

Keywords: Transfemoral Amputation; Prosthesis Design; Dynamic Balance; Postural Control; Rehabilitation.

Implications for Practice:

- Flexible transfemoral prostheses can improve patient safety through evidence-based balance rehabilitation strategies.
- Rehabilitation protocols should incorporate standardized dynamic balance assessment, such as the FSST, to guide prosthetic prescription and monitoring.
- Functional prosthetic interventions can be adapted to diverse clinical settings, including resource-limited rehabilitation environments

Introduction

Lower limb amputation substantially affects mobility, balance, and overall quality of life. Among amputation levels, transfemoral amputation presents complex rehabilitation challenges due to the loss of the knee joint, which plays a fundamental role in gait mechanics and postural stability (Monaco et al., 2022; Yazgan et al., 2021). Individuals with unilateral transfemoral amputation frequently experience impaired dynamic balance, increased energy expenditure during ambulation, and elevated fall risk (Omana et al., 2023; Silver-Thorn et al., 2018).

Systematic reviews consistently report reduced balance performance and diminished balance confidence among individuals with lower limb amputation, highlighting the need for targeted stability-oriented interventions (Johansson et al., 2023). Meta-analytic evidence further indicates substantially elevated fall incidence in this population compared with non-amputee controls (Dhariwal et al., 2025).

Globally, lower limb amputation remains prevalent due to trauma, diabetes, and vascular disease, with increasing incidence in low- and middle-income countries (LMICs). Rehabilitation systems in LMICs often face limited access to advanced prosthetic technologies and shortages of trained rehabilitation professionals, which may limit access to microprocessor-controlled prostheses and advanced biomechanical assessments (Monaco et al., 2022; Rash et al., 2025). Consequently, evaluating clinically feasible prosthetic designs within resource-constrained settings is essential. The global burden of limb loss continues to increase, with projections indicating a substantial rise in amputation prevalence over the coming decades (Ziegler-Graham et al., 2008).

Dynamic balance reflects the ability to regulate the body's center of mass within a dynamically shifting base of support. This process depends on coordinated neuromuscular control, sensory integration, and biomechanical alignment (Claret et al., 2019). In transfemoral amputees, altered load distribution and compensatory movement strategies compromise stability during transitional and multidirectional tasks, particularly during obstacle negotiation and rapid directional changes (Omana et al., 2023; Petrini et al., 2019).

Prosthetic intervention strategies have long emphasized component selection as a determinant of functional mobility outcomes (Abou et al., 2022). Comparative analyses between non-microprocessor and microprocessor-controlled knee mechanisms have demonstrated differences in falls and balance-related outcomes (Liang et al., 2022). Biomechanical investigations also show that prosthetic ankle-foot stiffness and mechanical compliance significantly influence balance control strategies and mediolateral stability (Andrysek et al., 2020). Experimental work confirms that variations in prosthetic component design can alter dynamic balance responses during functional mobility tasks (Kahle et al., 2021).

The Four-Square Step Test (FSST) provides a standardized multidirectional stepping assessment of dynamic balance. It has demonstrated strong reliability and construct validity, including correlations with fall indices in adult populations (Eom et al., 2023). The FSST has also been adapted into virtual reality environments, reinforcing its methodological robustness for evaluating dynamic balance performance (Aharoni et al., 2021).

Structured exercise-based interventions improve postural control and mobility in amputee populations (Dupuis et al., 2024). Emerging technologies incorporating embedded sensors and vibrotactile feedback have further demonstrated potential to enhance balance perception and postural regulation (Valette et al., 2025). However, despite advances in prosthetic technology and training-based interventions, limited biomechanical evidence specifically isolates the influence of flexible transfemoral prosthesis use on dynamic balance using standardized multidirectional functional assessment.

This study is grounded in biomechanical control theory and motor control adaptation frameworks. Prosthetic flexibility influences weight transfer efficiency and mechanical compliance during stance-to-swing transitions, which directly affect postural control strategies (Fuenzalida Squella et al., 2018; Rosenblatt et al., 2025). Improved weight transfer facilitates center-of-mass regulation during multidirectional stepping, thereby enhancing dynamic balance performance. Impaired balance performance in individuals with lower limb amputation has been consistently reported in systematic reviews, highlighting increased fall risk and reduced balance confidence (Omana et al., 2023; Vu et al., 2019).

Although prior research emphasizes microprocessor-controlled prostheses and gait parameters such as speed and metabolic cost, fewer studies specifically examine flexible transfemoral prostheses and dynamic balance using standardized functional assessments such as the Four Square Step Test (FSST) (Monaco et al., 2022; Silver-Thorn et al., 2018). Comparative studies between non-microprocessor and microprocessor-controlled knees have demonstrated differences in falls and balance-related outcomes (Liang et al., 2022). Structured exercise and balance training programs have been shown to improve postural control and mobility outcomes in individuals with lower limb amputation (Dupuis et al., 2024).

To our knowledge, few studies have used a standardized multidirectional stepping assessment within a within-subject design to specifically evaluate dynamic balance performance with flexible transfemoral prosthesis use, particularly in LMIC rehabilitation contexts. However, limited biomechanical evidence exists on how flexible transfemoral prostheses influence dynamic balance performance as measured by functional clinical assessments. Therefore, this study aimed to examine whether flexible transfemoral prosthesis use reduces FSST completion time, an indicator of dynamic balance performance, in unilateral transfemoral amputees.

Methods

Study Design

This quasi-experimental within-subject study followed the TREND (Transparent Reporting of Evaluations with Nonrandomized Designs) guideline.

Participants

Thirty unilateral transfemoral amputees were recruited using purposive sampling from the Department of Prosthetics and Orthotics, Poltekkes Kemenkes Surakarta – Indonesia. Inclusion criteria included medical stability and ability to perform multidirectional stepping tasks. Exclusion criteria included bilateral amputation and neurological disorders affecting balance. No participants withdrew from the study.

A formal power analysis was not conducted due to clinical feasibility; however, the within-subject design increased statistical efficiency by controlling inter-individual variability.

Instruments

Dynamic balance was assessed using the Four-Square Step Test (FSST), an examiner-administered standardized performance-based test evaluating multidirectional stepping. The FSST demonstrates excellent test–retest reliability (ICC > 0.90). Lower completion times indicate better dynamic balance.

Intervention

Flexible transfemoral prostheses were fitted and aligned by certified prosthetists following standardized clinical procedures. Participants underwent a two-week adaptation period before testing. Prosthetic use was confirmed through clinical follow-up documentation. The control condition consisted of usual axillary crutch ambulation. The intervention was conceptually grounded in biomechanical control theory and motor control adaptation principles, which posit that improved prosthetic compliance enhances weight transfer efficiency and proximal joint stabilization during dynamic tasks.

Data Collection

Data were collected between August and December 2023 by trained assessors. Standardized testing order was applied. Data were stored electronically in password-protected files. No missing data occurred. Demographic variables, including age, sex, side of amputation, height, body weight, time since amputation, and cause of amputation, were recorded. Dynamic balance was assessed using the FSST under two ambulation conditions: axillary crutch ambulation and flexible transfemoral prosthesis ambulation. Participants completed two trials per condition, and the fastest valid time was recorded.

Data Analysis

Analyses were conducted using SPSS version 26. Normality was assessed using the Shapiro–Wilk test. Paired t-tests were used to compare FSST completion time between ambulation conditions. Ninety-five percent confidence intervals were calculated. Statistical significance was set at $p < 0.05$.

Ethical Considerations

The study adhered to the Declaration of Helsinki and received ethical approval from the Institutional Ethics Committee of Poltekkes Kemenkes Surakarta (No. LB.02.02/1.1/693.6/2022). All participants provided written informed consent, and data were anonymized prior to analysis.

Results

Thirty unilateral transfemoral amputees participated. The mean age was 33.6 ± 9.4 years; 76.7% were male. The mean time since amputation was 4.2 ± 2.1 years. **Table 1** illustrates the demographic characteristics of the participants.

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Table 1. Demographic Characteristics of Participants (n = 30)

Characteristic	Category	n (%)/ Mean ± SD
Age (years)	—	33.6 ± 9.4
Sex	Male	23 (76.7%)
	Female	7 (23.3%)
Side of amputation	Right	16 (53.3%)
	Left	14 (46.7%)
Time since amputation (years)	—	4.2 ± 2.1
Cause of amputation	Traumatic	18 (60.0%)
	Vascular/medical	12 (40.0%)
Height (cm)	—	161.23 ± 7.06
Body weight (kg)	—	57.70 ± 11.31

Dynamic Balance Performance

FSST completion times were normally distributed (Shapiro–Wilk p = 0.07). Paired t-test analysis demonstrated a statistically significant reduction in FSST completion time during flexible transfemoral prosthesis use compared with axillary crutch ambulation (mean difference = 8.97 seconds; 95% CI, 7.72–10.22; t(29) = 14.68; p < 0.001). The effect size was very large (Cohen's d = 2.68). As shown in **Table 2,** flexible transfemoral prosthesis use significantly reduced FSST completion time compared with axillary crutch ambulation.

Table 2. Comparison of FSST Completion Time Between Ambulation Conditions (n = 30)

Variable	Mean ± SD	Mean Difference	95% CI	p-value
Axillary crutch ambulation	19.84 ± 3.21	-		
Flexible transfemoral prosthesis use	10.87 ± 2.94	8.97	7.72–10.22	<0.001

Note: Paired t-test; CI = confidence interval.

Discussion

This study demonstrates that flexible transfemoral prosthesis use significantly improves dynamic balance compared with axillary crutch ambulation in individuals with unilateral transfemoral amputation. The magnitude of improvement observed in FSST completion time indicates clinically meaningful functional gains and supports a biomechanically grounded interpretation of prosthetic-assisted postural control.

From a biomechanical perspective, flexible prosthetic designs enhance weight transfer efficiency and promote more effective proximal joint stabilization, thereby improving center-of-mass regulation during multidirectional stepping tasks. Prior biomechanical investigations have shown that prosthetic component stiffness and mechanical compliance directly influence gait symmetry, balance control strategies, and postural stability in individuals with lower limb amputation (Moisan et al., 2022). In this context, flexible transfemoral prostheses may facilitate smoother stance-to-swing transitions and more efficient load redistribution, thereby improving dynamic balance performance.

These findings are also consistent with broader evidence indicating that prosthetic configuration significantly influences fall risk and mobility outcomes in amputee populations. A recent systematic review and meta-analysis reported that individuals with lower limb amputation experience substantially elevated fall incidence compared with non-amputee populations, emphasizing the need for interventions targeting dynamic stability (Ettema et al., 2021). By demonstrating measurable improvements in a standardized multidirectional stepping assessment, the present study provides function-specific evidence that flexible prosthetic designs may contribute to fall-risk mitigation strategies.

Furthermore, experimental studies examining the influence of prosthetic components on functional mobility have reported that variations in knee and ankle-foot mechanics can alter dynamic balance responses and postural adjustments during transitional tasks (Gailey et al., 2023). Unlike prior studies that primarily focused on gait speed or metabolic cost, the current study isolates dynamic balance using a standardized clinical assessment within a within-subject design. This methodological approach strengthens causal inference regarding prosthesis-assisted balance adaptation.

Emerging sensor-integrated prosthetic systems incorporating vibrotactile feedback demonstrate promising advances in postural perception (Valette et al., 2025). However, such technologies may not be universally accessible. The present findings indicate that meaningful improvements in dynamic balance can be achieved through biomechanically optimized flexible transfemoral prostheses without reliance on high-cost technological components.

Importantly, these findings are particularly relevant in low- and middle-income country (LMIC) rehabilitation contexts. In settings where access to microprocessor-controlled prostheses may be constrained by cost and workforce limitations, flexible mechanical designs represent a clinically feasible alternative. The use of the FSST as a standardized multidirectional stepping assessment strengthens the interpretability of findings. Its established reliability and association with fall indices (Eom et al., 2023), along with technological adaptations into immersive environments (Aharoni et al., 2021), support its validity as a dynamic balance metric.

Alternative explanations, including potential learning effects associated with repeated FSST performance, were considered. However, participants were habitual prosthesis users who completed an adaptation period before testing. The magnitude of the observed improvement, combined with the biomechanical rationale, suggests that the findings reflect genuine prosthesis-assisted postural adaptation rather than simple task familiarization.

Overall, this study contributes to biomechanical rehabilitation science by empirically linking prosthetic flexibility to measurable improvements in dynamic balance performance, as measured by a standardized clinical assessment. The integration of biomechanical control theory with functional outcome measurement provides a structured framework for understanding how prosthetic design influences postural regulation in transfemoral amputees.

Implications and limitations

This study contributes to biomechanical rehabilitation theory by demonstrating that prosthetic flexibility is associated with measurable improvements in dynamic balance performance. The findings extend function-driven rehabilitation models by emphasizing the importance of weight transfer efficiency and proximal joint control in postural regulation.

Several limitations should be acknowledged. The study employed a nonrandomized within-subject design and involved a modest sample size from a single clinical setting, which may limit generalizability. Additionally, the assessment relied on a single performance-based outcome measure without instrumented biomechanical analysis. Future research incorporating longitudinal designs and kinematic or kinetic assessments is recommended to further elucidate adaptation mechanisms.

Relevance to Practice

Rehabilitation professionals should integrate standardized dynamic balance assessment into routine prosthetic evaluation and decision-making. Flexible transfemoral prosthesis prescription may be prioritized for individuals who demonstrate instability during multidirectional tasks. In resource-limited settings, flexible mechanical designs may serve as functionally effective and clinically feasible solutions to enhance patient safety and mobility outcomes.

Conclusion

Flexible transfemoral prosthesis use significantly improves dynamic balance in individuals with unilateral transfemoral amputation compared with axillary crutch ambulation. The observed functional gains support a biomechanical interpretation emphasizing enhanced weight transfer and postural control. Flexible transfemoral prosthetic designs should be incorporated into rehabilitation strategies to optimize safe mobility, particularly in settings with limited access to advanced prosthetic technologies. Future longitudinal and instrumented biomechanical studies are warranted to further clarify the underlying adaptation mechanisms.

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CrediT Authorship Contributions Statement

Nur Rachmat: Conceptualization, Methodology, Supervision, Writing - Original Draft, Software, Validation, Formal Analysis, Writing - Review & Editing, Investigation, Resources, Data Curation, Project Administration

Bambang Kuncoro: Writing - Original Draft, Review & Editing, Visualization, Funding Acquisition

Conflicts of Interest

There is no conflict of interest.

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