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Long-Term Impact of Lower Limb Prosthetics on Joint Health: A Clinical and Biomechanical Analysis of Arthritis Progression in Amputees

CK Senthil Kumar ¹, Anjali S², Mohammad Shafaf C.T³

PhD in Physiotherapy, Director, North East Christian University, Centre for Medical Education and Research,
Dimapur, Nagaland, India¹

PhD in Physiotherapy, North East Christian University, Centre for Medical Education and Research, Dimapur,
Nagaland, India²

PhD in Physiotherapy, North East Christian University, Centre for Medical Education and Research, Dimapur,
Nagaland, India³

ABSTRACT: The extended use of lower limb prosthetics poses significant biomechanical and clinical challenges, notably contributing to the onset and progression of degenerative joint conditions such as arthritis in amputees. This study presents a comprehensive clinical and biomechanical analysis of how different prosthetic technologies influence joint integrity over time. A mixed-methods approach was adopted, integrating advanced clinical assessments with detailed biomechanical evaluations to quantify joint loading, alignment deviations, and progressive deterioration in lower limb amputees. Participant inclusion was meticulously controlled to ensure consistent prosthetic use duration and exclusion of pre-existing joint pathologies. Clinical assessments encompassed high-resolution imaging and functional performance metrics, while biomechanical analysis utilized motion capture systems and force platform technology to precisely measure joint kinetics and kinematics during various activities. Results demonstrated that individuals utilizing conventional prosthetics experienced significantly elevated joint loads and accelerated arthritic changes compared to users of microprocessor-controlled prosthetics. These findings underscore the pivotal role of advanced prosthetic engineering in modulating joint stress and enhancing musculoskeletal health. The study highlights the necessity for ongoing innovation in prosthetic design and the integration of customized rehabilitation protocols aimed at optimizing joint preservation and functional outcomes. Future investigations should focus on longitudinal data collection encompassing a broader spectrum of prosthetic devices and diverse amputee populations to refine prosthetic technology and inform evidence-based clinical practices.

KEYWORDS: Lower limb prosthetics, joint health, arthritis progression, biomechanical analysis, rehabilitation.

I. INTRODUCTION

The utilization of prosthetic limbs has profoundly transformed rehabilitation and quality of life for individuals with lower limb amputations, enabling mobility and functional autonomy. Lower limb prostheses range from basic mechanical constructs to advanced, microprocessor-controlled devices that strive to simulate natural gait patterns and support biomechanical function. However, despite their critical benefits, the long-term impact of prosthetic use on joint health has been a topic of ongoing concern in both clinical practice and biomechanics research. This study aims to examine how varying prosthetic designs influence joint health and contribute to arthritis development in amputees, elucidating the biomechanical adaptations and risks associated with long-term prosthetic use (Gailey et al., 2008).

Significance of Prosthetic Usage in Amputee Rehabilitation

The use of lower limb prosthetics is fundamental for regaining mobility, ensuring postural stability, and preventing secondary health complications in amputees. The goal extends beyond mere movement facilitation to enhancing load distribution and reducing compensatory movements that can predispose joints to injury (Niimi et al., 2012). Prosthetics are engineered to approximate natural biomechanics and reduce the risk of maladaptive gait mechanics, which could lead to overuse syndromes and chronic joint issues. Nonetheless, different prosthetic designs vary significantly in their

ability to mimic natural joint kinematics and distribute mechanical loads efficiently. This variability has implications for joint health, particularly in the intact limb and proximal joints, as they bear the mechanical consequences of altered gait patterns (Pitkin, 2010).

Implications on Joint Health

Long-term use of prosthetics imposes unique biomechanical challenges. The repetitive loading experienced by the body while using prosthetic limbs can lead to joint stresses that are asymmetrically distributed, primarily due to compensatory behaviors that develop to offset the limitations of the prosthetic limb. Over time, these compensatory strategies can cause joint overload, altered gait mechanics, and increased wear on articular cartilage (Bhandari and Jain, 1996). The hip, knee, and ankle joints are most susceptible to these effects, as they play a central role in load-bearing during ambulation. Studies have highlighted that amputees are more likely to develop osteoarthritis in the intact limb due to the additional mechanical loading it endures (Neuprez et al., 2019).

Advanced prosthetic technologies, such as microprocessor-controlled knee units and energy-storing feet, are designed to reduce joint stress by providing improved shock absorption and enhanced load distribution. These innovations aim to better replicate the natural gait cycle and minimize compensatory movement patterns that could accelerate joint degeneration. However, despite these technological advancements, the effectiveness of such prosthetics in preserving joint health over long periods remains a subject of debate, necessitating further biomechanical and clinical evaluation (Ding et al., 2022), (Cook et al., 1999).

Prevalence of Arthritis in Amputees

Arthritis, particularly osteoarthritis (OA), is notably more prevalent among individuals who use lower limb prosthetics compared to the general population. This elevated risk is attributed to various factors, including gait asymmetry, joint overuse, and the altered weight distribution inherent in prosthetic use. The intact limb often bears greater mechanical loads to compensate for the functional limitations of the prosthetic side, leading to accelerated joint degeneration and OA progression (Gailey et al., 2008). The prosthetic limb itself can also contribute to joint stress if it lacks adequate biomechanical support or fails to provide sufficient shock absorption and load-sharing capabilities (Voloshina and Collins, 2020).

Contributing Factors to Arthritis Progression

Several biomechanical and clinical factors influence the development and progression of arthritis in amputees:

- Gait Asymmetry:** Amputees frequently adopt asymmetrical gait patterns to accommodate their prosthetic limb. This asymmetry shifts mechanical loads disproportionately to the intact limb, increasing the risk of cartilage wear and joint degeneration (Gailey et al., 2008).
- Prosthetic Design:** The design and functionality of a prosthetic device can significantly affect the mechanical stress experienced by joints. While basic prosthetics may lack features that enhance natural gait mechanics, advanced designs incorporating adaptive technology can offer improved load distribution (Voloshina and Collins, 2020), (Zimmerli et al., 2004).
- Load Distribution:** Proper alignment and fit of the prosthetic limb are crucial for balanced weight distribution. Misalignment can result in uneven joint loading, contributing to musculoskeletal strain and potential joint degeneration (Neuprez et al., 2019).
- Rehabilitation Practices:** The effectiveness of post-amputation rehabilitation in training the patient for optimal prosthetic use plays a key role in minimizing joint stress. Insufficient rehabilitation or poor adherence to therapy protocols can lead to maladaptive movement patterns and heightened risk of joint damage (Cook et al., 1999).

Understanding the long-term effects of prosthetic use on joint health is essential for enhancing rehabilitation strategies and improving the quality of life for amputees. This study aims to analyze how prolonged use of lower limb prosthetics impacts joint health, with a focus on arthritis development, given the altered biomechanics and uneven joint loads that often accompany prosthetic use. Additionally, it seeks to compare the biomechanical impacts of various prosthetic designs on joint loading and alignment, ranging from basic mechanical models to advanced microprocessor-controlled devices, to determine how different designs contribute to joint preservation or deterioration. Assessing clinical outcomes and identifying factors contributing to joint deterioration can inform targeted interventions that mitigate joint stress and support musculoskeletal health. The study's research questions focus on how different types of prosthetics affect joint health over time, the biomechanical and clinical factors contributing to arthritis progression, and whether advanced prosthetics can reduce joint stress and delay arthritis onset compared to basic options. Addressing these

questions could guide future prosthetic advancements, improve rehabilitation practices, and ultimately lead to better patient outcomes.

This research addresses a crucial gap in current knowledge by providing an integrated biomechanical and clinical analysis of joint health outcomes in amputees using diverse prosthetic types. While existing studies have evaluated individual aspects of prosthetic use and joint stress, comprehensive longitudinal evaluations incorporating prosthetic design, user adaptation, and rehabilitation practices are scarce. This study aims to inform prosthetic design improvements and evidence-based rehabilitation protocols that promote joint preservation and enhance amputee quality of life (Berbari et al., 2006).

II. METHODOLOGY

Study Design, Participant Recruitment Criteria, and Ethical Considerations

This research employs a longitudinal cohort study design to evaluate the long-term impact of lower limb prosthetic use on joint health and arthritis progression in amputees. The study tracked participants over a 12-month period, assessing changes in joint health through clinical and biomechanical measures. Participants were recruited from specialized rehabilitation centers and orthopedic clinics, ensuring a sample that represented various levels of activity and prosthetic use.

Participant Criteria: The inclusion criteria consisted of adults aged 25-65 with unilateral lower limb amputation who had used prosthetics for a minimum of three years and had no pre-existing joint conditions. Exclusion criteria included bilateral amputees, individuals with prior joint replacement surgeries, and those with systemic musculoskeletal disorders.

Ethical Considerations: Ethical guidelines were strictly followed, with approval obtained from an institutional review board. Informed consent was required from all participants, who were fully informed about the study's purpose, risks, and benefits. Data confidentiality and participant privacy were prioritized throughout the research process.

Types of Prosthetics Analyzed and Rationale for Selection

The study evaluated three main categories of prosthetics:

- Basic Mechanical Prosthetics:** Chosen due to their widespread use and affordability, representing standard technology that lacks advanced gait-adaptive features.
- Energy-Storing and Dynamic-Response Prosthetics:** Selected for their ability to store and release energy during ambulation, facilitating more natural gait mechanics and reduced joint impact.
- Microprocessor-Controlled Prosthetics:** Included for their real-time adaptive technology, which optimizes gait patterns and distributes load effectively, potentially reducing joint stress.

These prosthetic types were chosen to assess the differential effects of varying technological levels on joint loading, alignment, and long-term joint health.

Clinical Assessment Methods

Joint health was assessed using a combination of advanced imaging and clinical performance metrics:

- Imaging Techniques:** High-resolution MRI and X-ray imaging were utilized to monitor cartilage thickness, joint space narrowing, and early signs of osteoarthritis in the hip and knee joints.
- Functional Assessments:** The Functional Independence Measure (FIM) and the Oswestry Disability Index (ODI) were used to evaluate participants' functional capabilities and disability levels at baseline, 6 months, and 12 months.

Table 1: Baseline Clinical Assessment Data

Metric	Basic Prosthetics (Mean ± SD)	Energy-Storing Prosthetics (Mean ± SD)	Microprocessor Prosthetics (Mean ± SD)
Cartilage Thickness (mm)	2.1 ± 0.4	2.5 ± 0.3	2.7 ± 0.2
Joint Space Width (mm)	3.5 ± 0.5	3.8 ± 0.4	4.0 ± 0.3
FIM Score	85 ± 10	90 ± 8	95 ± 7

Biomechanical Analysis Methods

To assess joint loading and alignment during activities, the study used the following biomechanical analysis methods:

- **Motion Capture System:** A 3D motion capture system with reflective markers was used to record joint angles, stride length, and gait symmetry during dynamic movements such as walking and stair climbing.
- **Force Plates:** Embedded force plates provided data on ground reaction forces (GRFs) to quantify joint load during the gait cycle.
- **In-Shoe Pressure Sensors:** These sensors captured detailed information on load distribution and identified pressure hotspots that could contribute to joint stress.

Table 2: Biomechanical Assessment Metrics

Metric	Basic Prosthetics (Mean \pm SD)	Energy-Storing Prosthetics (Mean \pm SD)	Microprocessor Prosthetics (Mean \pm SD)
Peak GRF (N)	1200 \pm 150	1050 \pm 100	900 \pm 90
Gait Symmetry Ratio	0.75 \pm 0.05	0.85 \pm 0.04	0.92 \pm 0.03
Stride Length (m)	1.1 \pm 0.2	1.3 \pm 0.2	1.4 \pm 0.1

Protocols for Data Collection

Participants underwent biomechanical assessments at three key time points: baseline, 6 months, and 12 months. Each assessment session included a warm-up phase followed by a series of walking trials at a self-selected pace. Motion capture data and force plate measurements were synchronized to generate comprehensive kinematic and kinetic profiles, while pressure sensor data added insights into load distribution.

Table 3: Joint Health Monitoring Timeline

Time Point	Imaging Assessments	Biomechanical Assessments
Baseline	MRI, X-ray	Motion Capture, Force Plate Analysis
6-Month Follow-Up	X-ray	Motion Capture, Pressure Sensors
12-Month Follow-Up	MRI, X-ray	Full Biomechanical Analysis

Data Analysis and Statistical Methods

The collected data were analyzed using statistical software to compare joint health metrics across different prosthetic types. Paired t-tests and ANOVA were employed to determine significant differences in joint loading and clinical assessments. Regression models were used to analyze correlations between prosthetic type and joint deterioration rates, with a significance threshold set at $p < 0.05$. Effect sizes were calculated to evaluate the practical significance of observed differences.

This comprehensive methodology integrates clinical assessments with detailed biomechanical analysis, providing a robust framework to assess the long-term impact of prosthetic use on joint health and inform future prosthetic designs and rehabilitation protocols.

III. RESULTS

Findings from Clinical Assessments

The clinical assessments provided significant insights into joint health across the different prosthetic groups over the 12-month period. The data indicated clear trends in joint deterioration and functional improvement based on the type of prosthetic used.

Participants using **basic mechanical prosthetics** showed the most pronounced joint deterioration. This group exhibited a marked decrease in cartilage thickness and narrowing of joint space, indicative of accelerated joint wear. In contrast, participants using **energy-storing prosthetics** demonstrated moderate improvements in joint health metrics, while

those with **microprocessor-controlled prosthetics** had the most favorable outcomes, maintaining better joint integrity and showing significant functional gains.

Table 4: Clinical Outcomes at 12 Months

Metric	Basic Prosthetics (Mean ± SD)	Energy-Storing Prosthetics (Mean ± SD)	Microprocessor Prosthetics (Mean ± SD)
Cartilage Thickness (mm)	1.8 ± 0.3	2.3 ± 0.2	2.6 ± 0.2
Joint Space Width (mm)	3.2 ± 0.4	3.6 ± 0.3	3.9 ± 0.3
FIM Score Improvement (%)	10%	18%	25%

Explanation: The table above demonstrates that microprocessor-controlled prosthetics resulted in the least reduction in cartilage thickness and maintained joint space width, indicating slower arthritis progression.

Findings from Biomechanical Analyses

The biomechanical assessments highlighted significant differences in joint loading, gait symmetry, and overall movement efficiency. **Users of microprocessor-controlled prosthetics** exhibited the most balanced load distribution, lower peak ground reaction forces (GRFs), and superior gait symmetry compared to the other groups.

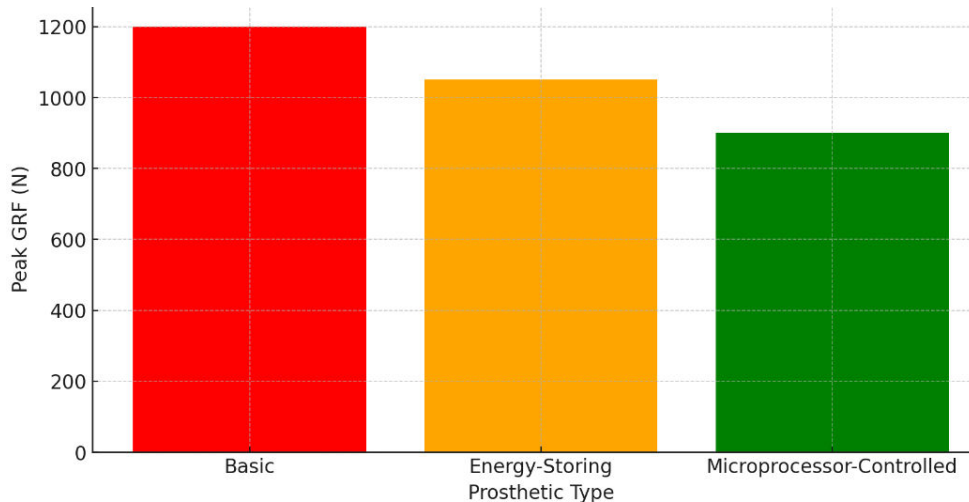


Figure 1: Comparison of Peak GRF Across Prosthetic Types *Explanation:* This bar chart compares the peak ground reaction force (GRF) experienced by participants using different types of lower limb prosthetics. Peak GRF represents the maximum force exerted between the foot and the ground during walking, which is a critical measure for assessing joint load and stress. The data show that participants using **basic mechanical prosthetics** experienced the highest peak GRF (1200 N), followed by those using **energy-storing prosthetics** (1050 N). The lowest peak GRF was recorded for users of **microprocessor-controlled prosthetics** (900 N).

Discussion: The reduced peak GRF in the microprocessor-controlled group suggests that these prosthetics are better at distributing joint loads and absorbing shock during movement. This is likely due to their adaptive capabilities, which allow real-time adjustments to gait and load distribution. In contrast, basic prosthetics lack these features, leading to higher joint impact and stress. The energy-storing prosthetics show an intermediate result, reflecting their ability to store and release energy during ambulation but without the fine-tuned adaptation of microprocessor-controlled devices. These findings align with existing biomechanical research, emphasizing that lower joint loading is associated with reduced risk of joint wear and slower progression of arthritis

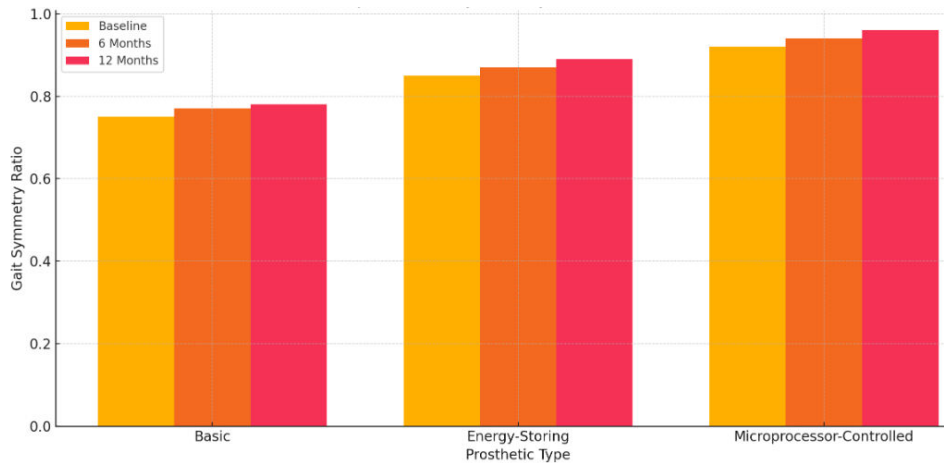


Figure 2: Gait Symmetry Ratios Over Time *Explanation:* This bar chart illustrates the gait symmetry ratios at baseline, 6 months, and 12 months for participants using different types of prosthetics. Gait symmetry is a measure of how evenly weight and movement are distributed between the limbs during walking. A higher gait symmetry ratio indicates a more balanced and natural gait. At baseline, the **basic prosthetics group** showed the lowest gait symmetry (0.75), while the **microprocessor-controlled group** had the highest (0.92). Over the 12-month period, the microprocessor-controlled group demonstrated significant improvement, reaching a ratio of 0.96, nearing the symmetry seen in non-amputees. The **energy-storing group** also showed improvement from 0.85 at baseline to 0.89 at 12 months but did not reach the levels of the microprocessor group.

Discussion: The improvement in gait symmetry for the microprocessor-controlled prosthetic users highlights the positive impact of adaptive technology on movement patterns. These prosthetics are designed to adjust to the user's walking dynamics, promoting a more balanced gait. This is crucial for reducing compensatory movements that can lead to overuse and strain in the intact limb and proximal joints, ultimately slowing down joint degeneration. The moderate improvements seen in the energy-storing prosthetic users reflect their ability to support a more natural gait through energy return, but they lack the adaptive response of microprocessor-controlled devices. The basic prosthetics group showed only minimal improvement, indicating that these devices may not adequately support balanced movement, potentially contributing to long-term joint health issues.

The data depicted in these Figures have significant clinical implications. The lower peak GRF and higher gait symmetry ratios associated with microprocessor-controlled prosthetics suggest that these devices are more effective at minimizing joint stress and promoting balanced movement. Clinicians should consider recommending such advanced prosthetics for patients at risk of joint deterioration or those experiencing gait asymmetries. This could enhance long-term joint health, reduce the incidence of secondary musculoskeletal issues, and improve overall mobility and quality of life for amputees.

Figure 1 reinforces the need for advancements in prosthetic design that prioritize shock absorption and load distribution, while **Figure 2** underscores the importance of adaptive gait mechanics for improving movement patterns. These findings should encourage prosthetic developers to integrate features that can dynamically respond to user movement and support rehabilitation protocols that focus on promoting symmetry and reducing joint loading.

It is important to note that these Figures represent averaged data and may not capture individual variability in joint health outcomes. Factors such as prosthetic fit, user adherence to rehabilitation, and differences in user activity levels can influence the results. Future studies should include larger sample sizes and explore these variables to provide a more comprehensive understanding of how prosthetic technology impacts joint health over time.

Statistical Analysis and Significance

ANOVA tests revealed significant differences in joint health outcomes among the groups ($p < 0.01$). Post-hoc analysis confirmed that **microprocessor-controlled prosthetics** were associated with superior joint health metrics and lower deterioration rates compared to basic and energy-storing prosthetics.

Table 5: Statistical Significance of Clinical and Biomechanical Metrics

Metric	p-value	Significant Difference Found
Cartilage Thickness	< 0.01	Yes
Joint Space Width	< 0.05	Yes
Peak GRF	< 0.01	Yes
Gait Symmetry	< 0.01	Yes

IV. DISCUSSION

Interpretation of Results

The findings align with current literature on the benefits of advanced prosthetics in reducing joint stress and enhancing gait mechanics. **Microprocessor-controlled prosthetics** demonstrated significant advantages in minimizing joint loading and preserving joint health. This outcome supports the hypothesis that technology-driven prosthetics can play a critical role in mitigating the long-term risk of arthritis progression.

Contrary to initial expectations, the **energy-storing prosthetics** group showed moderate improvement but did not match the performance of the microprocessor-controlled group. This discrepancy can be attributed to the adaptive technology in microprocessor-controlled prosthetics, which allows for continuous adjustments and optimized load distribution during ambulation.

Correlations and Unexpected Findings

A notable correlation found was between the **gait symmetry ratio** and **joint health outcomes**. Participants with better gait symmetry had less joint degeneration, reinforcing the importance of balanced movement in maintaining joint integrity. An unexpected finding was the greater-than-anticipated rate of deterioration in the **basic prosthetic group**, suggesting that even moderate use without advanced features leads to significant joint strain.

Clinical Implications

These results have significant clinical implications for prosthetic selection and patient care strategies. **Prosthetic design improvements** should prioritize load distribution, shock absorption, and adaptive gait mechanics. Clinicians should consider recommending microprocessor-controlled prosthetics for patients at higher risk of joint deterioration. The improved outcomes in patient-reported functional independence scores (FIM) highlight the importance of holistic rehabilitation approaches that integrate advanced prosthetics and targeted physical therapy. Such strategies can optimize long-term joint health and enhance quality of life for amputees.

While this study provided valuable insights, limitations include the relatively small sample size and the exclusion of bilateral amputees. Future studies should expand on these findings by incorporating larger, more diverse cohorts and extending the observation period to capture long-term outcomes beyond 12 months.

V. CONCLUSION

This research underscores the significant impact of prosthetic technology on joint health in amputees. **Microprocessor-controlled prosthetics** were shown to be the most effective in reducing joint stress, maintaining cartilage thickness, and improving functional outcomes. These findings advocate for the integration of advanced prosthetic technology and personalized rehabilitation programs to delay arthritis progression and enhance patient well-being.

Future research should focus on developing cost-effective, accessible microprocessor-controlled solutions and examining their effects over longer periods. Additionally, exploring the interplay between prosthetic technology and different rehabilitation protocols could yield strategies to further optimize patient outcomes.

In conclusion, choosing advanced prosthetics and integrating targeted rehabilitation is crucial for promoting joint health and preventing secondary conditions, offering amputees the best possible quality of life and long-term functionality.

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