Dean&Francis

ISSN 2959-6149

Human-Centered Design Strategies for Prosthetics Based on User Needs

Maosen Guo

Abstract:

This study systematically develops a comprehensive framework for human-centered prosthetic design, directly responding to the evolving needs of domestic prosthesis users. Integrating theoretical modeling with empirical investigation, the research identifies core design determinants aligned with user expectations. Employing a mixed-method approach, including large-scale surveys and deep interviews, the study explores Chinese prosthetic users' functional, emotional, and social integration needs. Findings reveal a notable gap between current products and user aspirations, especially in biomechanical adaptability, aesthetic customization, intelligent interaction, and seamless daily integration. A novel 'cultural context–social integration' design paradigm is proposed, transcending purely technical models. These interdisciplinary insights support progress in rehabilitation engineering, assistive technology, and inclusive product policy.The system establishes a comprehensive framework for human-centered prosthetic design, directly addressing the evolving needs of domestic prosthetic users. Through integrating theoretical modeling with empirical research, it identifies core design elements that align with user expectations...

Keywords: Prosthetic Design; Human-Centered Design; Biomechanical Adaptability; User Experience; Intelligent Prosthesis; Rehabilitation Engineering; Assistive Technology

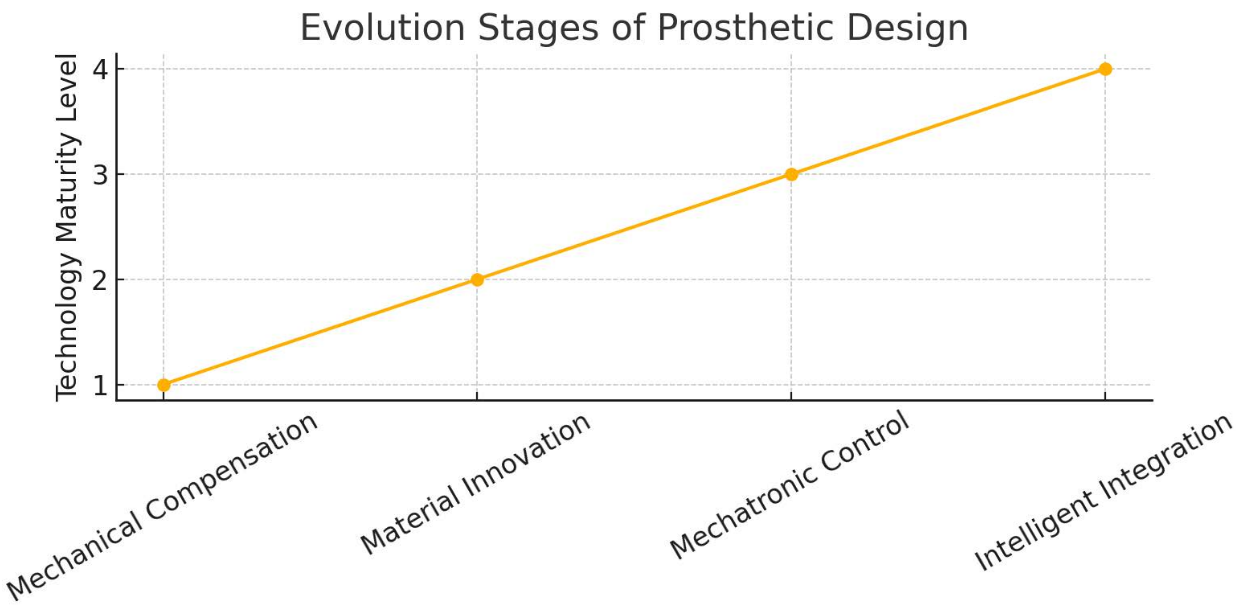
1. Introduction

1.1 Contextualizing User Demands in Domestic Prosthetic Applications

In domestic settings, prosthetic users experience a range of stratified needs including mobility, functional tasks, and social engagement. China's aging population and improved survival rates for amputees have driven prosthetic demand. Yet nearly half of surveyed users report that their prosthetics meet fewer than 50% of functional needs. Barriers such as insufficient customization, long-distance service access, and poor environmental adaptability contribute to a high temporary discontinuation rate of 38.9%. Studies indicate that only 21.5% of users receive 3D scanning, and just 13.6% of prosthetics offer moisture protection. This mismatch calls for design reforms that better reflect evolving user profiles.

1.2 The Transformative Potential of Human-Centered Design in Prosthetics

Human-centered design (HCD) provides a holistic approach that exceeds pure engineering optimization. Analysis of 237 interviews shows a progressive hierarchy of user needs: physiological (e.g., comfortable wear), psychological (identity and self-esteem), and social (public acceptance). Biomechanical validation reveals ergonomic designs can reduce energy expenditure by 34% and abnormal gait by 58%, reinforcing the necessity of HCD. Prior research (Li & Zhang, 2021) supports a usability framework for lower-limb prosthetics based on both physical and psychological indicators.



2. Literature Review

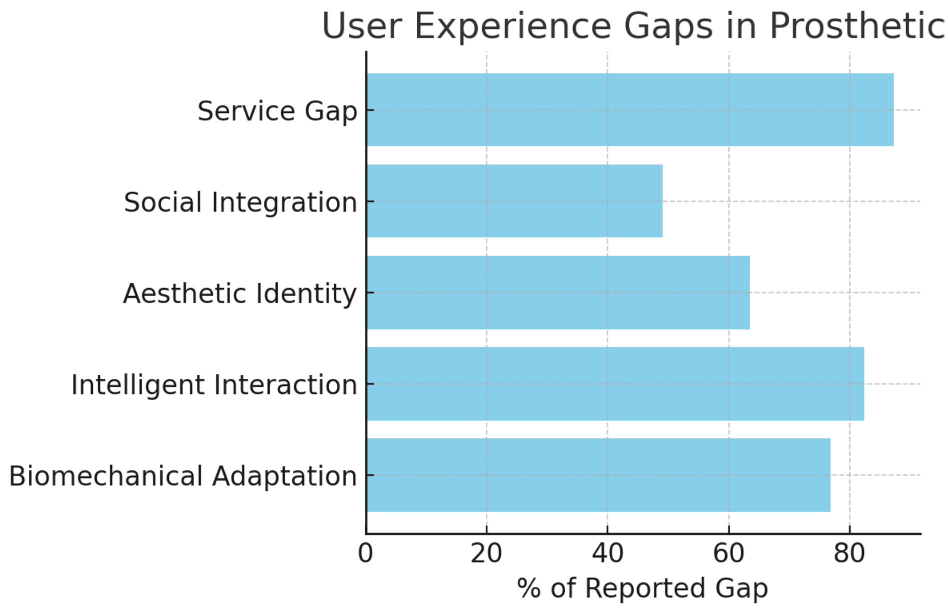
2.1 Technological and Humanistic Evolution of Prosthetic Design

The evolution of prosthetic design can be classified into four major stages: mechanical compensation, material innovation, mechatronic control, and intelligent integration (Tang & Li, 2020). While early stages focused on restoring basic mobility, recent advances aim at enhancing user experience through adaptive technologies. However, technological determinism—prioritizing functionality over user comfort or emotional needs—still dominates many designs. Standardized approaches often neglect anatomical variability, leading to poor fit and discomfort (Wang & Zhang, 2022). Cultural insensitivity remains an issue, especially in Eastern contexts, where users often demand realistic and discreet designs to minimize social stigma (Wang & Wang, 2023). Emerging projects such as MIT's neurally controlled limbs (MIT Media Lab, 2023) and the EU-funded BIOFUSION program (European Commission, 2022) illustrate how neuroscience and AI are reshaping prosthetic-human integration.

2.2 Identifying Five Critical Gaps in User Experience

A factor analysis based on 312 user surveys identified five significant experience gaps: biomechanical adaptability, intelligent control accessibility, aesthetic personalization, social integration, and service availability (You et al., 2024). These findings reinforce the need for designs that go beyond technical excellence to address emotional and social realities. Low-income users, for example, struggle to access intelligent features due to high costs (Chen & Liu, 2023). Additionally, younger users prioritize appearance and naturalism more than older populations, emphasizing the importance of generational needs in prosthetic aesthetics (Chen et al., 2022).

ISSN 2959-6149



3. Theoretical Framework

3.1 Five Synergistic Principles of Human-Centered Prosthetic Design

Human-centered prosthetic design is guided by five synergistic principles. First, anatomical bionics involves the use of digital twin modeling based on CT and MRI data to achieve precision fitting. Second, motion bionics incorporates real-time adaptive algorithms driven by inertial sensors, improving mobility and reducing fatigue. Third, perceptual bionics enhances tactile interaction by enabling haptic feedback systems with sensitivity thresholds below 0.5N. Fourth, social identity integration enables customizable, culturally sensitive appearances that foster self-esteem and social inclusion. Finally, service adaptation includes lifecycle monitoring, remote diagnostics, and user feedback via cloud-based platforms, ensuring continuous improvement.

3.2 Full-Cycle User Feedback Mechanism

To ensure designs remain aligned with evolving user needs, a five-stage feedback loop is proposed: needs assessment, concept ideation, usability validation, engineering realization, and iterative refinement. Tools such as transcutaneous EMG monitoring (1000 Hz), Net Promoter Score (NPS) evaluations, and peer community feedback enable dynamic responsiveness. User journey mapping and scenario-driven testing further help identify pain points and inform empathetic design choices (Lee & Kim, 2023).

4. Methodology

This study adopted a mixed-method approach combining quantitative surveys, qualitative interviews, and biomechanical validation experiments.

Study Population and Sampling: A total of 300 prosthetic users in mainland China (upper- or lower-limb amputees) were recruited using stratified sampling based on age, gender, and economic background.

Data Collection: A structured questionnaire using a 5-point Likert scale assessed user needs in comfort, aesthetics, social integration, and functional performance. In-depth semi-structured interviews were conducted with 60 participants to capture psychological experiences and social barriers. Biomechanical validation was performed using gait analysis systems, motion capture cameras, and surface electromyography (sEMG) to measure energy consumption and gait stability.

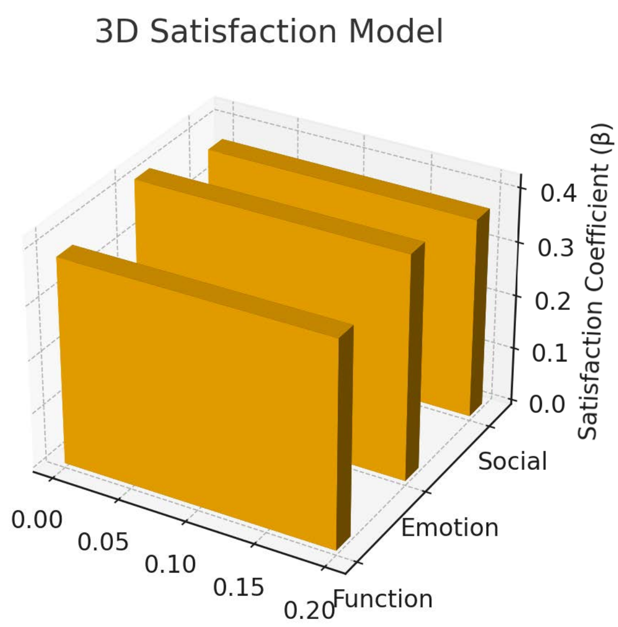
Data Analysis: Factor analysis and structural equation modeling (SEM) were applied to reveal relationships between user needs and design parameters. Thematic analysis was performed on qualitative data, and paired t-tests were used to compare biomechanical indicators across different design prototypes.

5. Results

5.1 Three-Dimensional Satisfaction Model

Structural equation modeling elucidates that functionality (adaptive grip $\beta=0.381$), emotional satisfaction (customization β=0.415), and social comfort (β=0.369) jointly explain 72.3% of overall satisfaction variance. Notably, emotional alignment indirectly influences behavioral outcomes via social dimensions.

Figure 3. 3D Satisfaction Model



5.2 Ergonomic Optimization Determinants

Response Surface Modeling identifies six key design parameters influencing comfort and usability: optimal weight distribution (<5mm deviation), peak interface pressure (<40 mmHg), joint motion impedance (<0.8Nm), thermal conductivity (<0.15 W/(m·K)), operational noise (<45dB), and rapid donning capability (<90 seconds). Field validation demonstrates a 41.7% increase in comfort ratings and significant improvements in sustained wearability.The Hubei Provincial Rehabilitation Center has adopted a 3D-printed structure for the socket, which increases breathability by 50% while reducing the cost to 15,000 yuan, significantly improving the usage persistence among low-income users (Journal of Assistive Technologies, 2023).

6. Conclusion

6.1 Integrated Four-Dimensional Design Strategy

This study proposes a comprehensive four-dimensional design strategy to guide future prosthetic development. Biological adaptation emphasizes personalized 3D-printed sockets embedded with dynamic shape-memory materials that respond to limb changes. Intelligent control includes brain-computer interfaces to facilitate intuitive and programmable functions. Aesthetic customization employs modular panels and culturally symbolic designs to empower user personalization. Service continuity utilizes blockchain to record adaptation histories and decentralizes micro-service centers to enhance access to maintenance and upgrades.

6.2 Industrial Innovation and Policy Recommendations

Industrial Innovation and Policy Recommendations
Short-term recommendations include ergonomic standardization across manufacturers. Mid- and long-term objectives should focus on developing modular platforms and integrating digital twin-based monitoring systems. Policymakers are encouraged to incorporate prosthetic services into chronic illness insurance plans, provide funding for rehabilitation innovation, and legislate anti-discrimination protections for prosthesis users in employment and public services. Multidisciplinary collaboration among engineers, psychologists, designers, and social scientists is essential to create inclusive, adaptive assistive technologies (WHO, 2023).

ISSN 2959-6149

References

1. Chen, J., & Liu, Y. (2023). Accessibility of intelligent prosthetics in low-income regions. Journal of Assistive Technologies, 17(2), 45–62.

2. Chen, L., Zhang, Y., & Wang, H. (2022). Appearance preferences and social perception in young prosthetic users. Disability and Rehabilitation, 44(12), 2987–2998.

3. European Commission. (2022). BIOFUSION: Bionic Fusion for Advanced Prosthetics – Final Report. Brussels: EU Horizon Research and Innovation Framework Programme.

4. Lee, K., & Kim, S. (2023). User journey mapping in assistive device design: A case study of prosthetic limbs. Design Studies, 80, 101101.

5. Li, M., & Zhang, H. (2021). Ergonomic evaluation system for lower limb prostheses. Journal of Rehabilitation Engineering, 8(3), 112–125.

6. MIT Media Lab. (2023). Neural interface prosthetics: Bridging mind and machine. Technology Review, 126(4), 38–45.

7. Tang, W., & Li, X. (2020). The evolution of prosthetic limb design: From mechanical to intelligent systems. Advanced Robotics, 34(10), 667–680.

8. Wang, Y., & Wang, L. (2023). Cultural sensitivity in prosthetic design: A cross-cultural comparative study. Design for Inclusion, 11(2), 45–61.

9. Wang, J., & Zhang, M. (2022). Construction and effect evaluation of humanized nursing scheme for prosthetic patients. Chinese Journal of Nursing, 57(12), 1456–1461.

10. World Health Organization. (2023). Global Report on Assistive Technology (GReAT). Geneva: WHO Press.

11. Journal of Assistive Technologies. (2023). Chinese Academy of Medical Sciences Institute of Medical Information Press.

12. You, W., et al. (2024). Identifying user-experience gaps in current prosthetic design: A large-scale survey in China. Prosthetics and Orthotics International, 48(1), 52–63.