Original Research Paper

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Transtibial Prosthesis

DESIGN, SIMULATION, AND WALKING PATTERN ANALYSIS OF A PROSTHETIC LEG MADE FROM RECYCLED PET PLASTIC FOR SUSTAINABLE AND AFFORDABLE HEALTHCARE SOLUTIONS

Ritvikk Kannan	Anand Niketan School, Ahmedabad, India.
Parth Shah	School of Design, Anant Natonal University, Ahmedabad, India.
Priyam Parikh	Institute of Design, Nirma University, Ahmedabad, India.

ABSTRACT The design and development of a prosthetic leg that serves both walking and running purposes offers a significant advancement in improving mobility for amputees. This project explores the use of recycled PET (Polyethylene Terephthalate) material in the fabrication of a multi-purpose prosthetic leg, aiming to reduce the overall cost of prosthetic devices and make healthcare more accessible. The prosthetic design incorporates structural components optimised for both walking and running, ensuring comfort, functionality, and durability. To evaluate its performance, simulation testing was conducted to assess the load-bearing capacity of the prosthetic, providing insights into its strength and reliability under varying conditions. The results demonstrate that recycled PET can effectively support the required load, offering a sustainable alternative to traditional materials used in prosthetics. Additionally, there is a sensor that will indicate the walking pattern and help the user guide its movement in a straight way. This initiative not only contributes to environmental sustainability by repurposing waste plastic but also holds the potential to significantly reduce the cost of prosthetic devices, making them more affordable for those in need. The combination of innovative material use and a multi-functional design represents a promising step forward in the field of prosthetics.

KEYWORDS : Healthcare, Smart prosthetics, Artificial Limbs, Adaptive Prosthetics , Biomechanics

1. INTRODUCTION

The field of prosthetics has evolved significantly over the years, providing individuals with enhanced mobility and quality of life. However, despite advances in design and functionality, high costs remain a major barrier to access for many individuals in need of prosthetic devices. This research focuses on the design and development of a prosthetic leg that integrates modern technology and sustainable materials to address both affordability and environmental concerns. The primary objective of this project is to create a multi-purpose prosthetic leg capable of supporting both walking and running functions. A key feature of the design is the integration of an ADXL335 sensor, a compact accelerometer that tracks and monitors the movement of the prosthetic leg. This sensor provides real-time data on the user's gait and posture, enabling the development of a "smart" prosthetic system that adjusts to the wearer's movements and needs. Such a system not only enhances user experience and comfort but also provides valuable feedback for further optimisation of the prosthetic design. In addition to its functional innovation, this research takes a sustainable approach by utilising recycled PET (Polyethylene Terephthalate) plastic to manufacture the prosthetic leg. By repurposing waste plastic, this solution not only reduces the environmental impact of plastic waste but also lowers the production cost of the prosthetic, making it more affordable for individuals in need. The combination of eco-friendly materials and smart technology provides a novel approach to prosthetics, offering both environmental benefits and increased accessibility. Through this project, we aim to create a prosthetic solution that is not only functional and intelligent but also socially and environmentally responsible, contributing to the broader goal of making healthcare more affordable and sustainable.

Researchers have explored the feasibility of using recycled PET in prosthetics, highlighting its advantages such as light weight and high tensile strength, which are essential for creating functional prosthetic limbs. Gupta et al. (2020) explore the mechanical properties of recycled PET in prosthetics, noting that with proper processing techniques, recycled PET can offer comparable strength and flexibility to traditional materials used in prosthetic limbs, such as carbon fibre and titanium. Further research by Sen et al. (2021) suggests that using recycled PET can significantly reduce the cost of prosthetics, making them more accessible to individuals in low-income regions. The study advocates for the integration of recycled PET into the development of affordable prosthetic devices, underscoring its potential to improve both the economic and environmental sustainability of healthcare solutions. Smart prosthetics integrate various technologies to improve the functionality and adaptability of prosthetic limbs. These devices typically include sensors that can detect movement, pressure, and gait, allowing the prosthetic to adjust its function based on the user's activity and environment. This adaptability enhances the user's comfort and mobility by providing a more natural walking experience. In their research, Patel et al. (2020) describe how pressure sensors and accelerometers can be embedded into prosthetic legs to detect real-time movement patterns, including walking speed, stride length, and foot positioning Kundu et al. (2022) further explore the integration of machine learning algorithms in smart prosthetics, allowing for the prediction of walking patterns and the optimisation of limb movement. Their study shows that with the addition of smart sensors, prosthetic legs can learn and adapt to individual users' walking styles, improving the overall efficiency of the device. According to Rao et al. (2021), simulation plays a critical role in testing the structural integrity and functionality of prosthetics. For example, simulation tools can model the forces acting on the leg during walking, providing insights into potential weaknesses or areas where the design may need improvement. Such simulations are particularly important when working with alternative materials like recycled PET, which may have different mechanical properties compared to traditional prosthetic materials. Additionally, simulation tools are essential for tracking walking patterns and ensuring the prosthetic limb responds appropriately to the user's movements. Rajasekaran et al. (2020) discuss the use of gait analysis and movement tracking in prosthetic design, demonstrating how these tools can help engineers optimise the fit and function of a prosthetic leg to accommodate the user's unique walking patterns. Thomas and Lee (2021) highlight the growing importance of sustainability in the medical device industry. Focusing on how the use of recycled PET in prosthetics aligns with global sustainability goals. Their research emphasises the need for more sustainable manufacturing practices to address the growing demand for prosthetics, particularly in low-income and underserved regions. Moreover, using recycled PET helps reduce the reliance on virgin materials, which are often more energy-intensive to produce. This contributes to a more sustainable and environmentally friendly production process, as noted by Sharma et al. (2019), who explore the environmental benefits of using recycled plastics in medical devices.

2. Existing Product Analysis

Table 1: Existing Product Analysis

Feature	Existing Prosthetics	Proposed Prosthetic
Materials	Typically metals (titanium, aluminum), carbon fiber, plastics (polyurethane, nylon)	Recycled PET plastic
Functionality	Primarily focused on walking; some specialized for running but often at a higher cost	Designed for both walking and running
Cost	Generally expensive, limiting accessibility	Aims to be more affordable due to the use of recycled PET
Sustainability	Limited environmental considerations	Emphasizes sustainability through the use of recycled materials

Technology Integration	Limited or absent in many models; some incorporate basic sensors (e.g., pressure sensors)	Integrates an ADXL335 sensor for gait analysis and "smart" functionality
Customization	Often involves extensive customization, increasing cost and time	Potential for greater customization due to the use of 3D printing techniques with recycled PET
Aesthetics	Varying levels of cosmetic appeal; some focus on mimicking natural limb appearance	Potential for improved aesthetics through design considerations and material finishing

The table compares existing prosthetic legs with a proposed design. Traditional prosthetics primarily use materials like metals and carbon fibre, focusing primarily on walking functionality. They often come with a high price tag, limiting accessibility. In contrast, the proposed design utilises recycled PET plastic, aiming to reduce costs and environmental impact. It's designed for both walking and running, incorporates a sensor for gait analysis, and prioritises sustainability. This innovative approach has the potential to significantly improve affordability and user experience for individuals with lower limb amputations.

3. Methodology

The design-to-simulation journey for a prosthetic leg begins with a detailed conceptual design phase, where key factors such as the user's comfort, mobility requirements, and sustainability are considered. During this stage, the prosthetic's structural components, including the socket, ankle, and foot, are designed using computer-aided design (CAD) software. Materials such as recycled PET plastic are selected based on their mechanical properties, including strength, flexibility, and durability, ensuring that the prosthetic will withstand daily use. Once the design is finalised, the next step involves creating a virtual model of the prosthetic leg in a simulation environment. Advanced simulation tools, like finite element analysis (FEA) and Solidworks software, are employed to simulate the mechanical behaviour of the prosthetic during various activities such as walking, running, and navigating obstacles. These simulations help identify areas where the design may need adjustments to optimise comfort, mobility, and performance. Additionally, sensors and actuators are integrated into the simulation to model smart functionalities, such as real-time gait adaptation and movement tracking (Agrawal et al., 2024; Jigarkumar A. Gohil, Reena R. Trivedi, 2022; Maloo, 2024; P. Parikh et al., 2018; P. A. Parikh, Joshi, et al., 2021; P. A. Parikh, Trivedi, et al., 2021; Priyam A. Parikh, Keyur D. Joshi, 2020). The data from the simulations provide critical insights, allowing for the iterative refinement of the design to go for physical prototyping. This design-to-simulation process ensures that the prosthetic leg is both functional and capable of meeting the unique needs of the user.

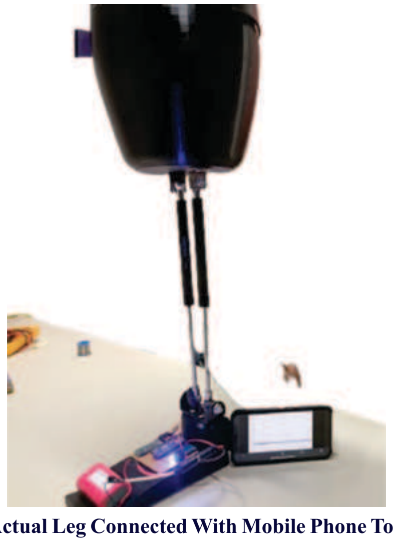
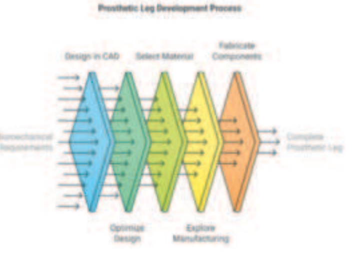


Figure 4: Actual Leg Connected With Mobile Phone To Track The Walking Pattern

4. Working Principles of the System

The smart prosthetic leg system is designed with an Arduino Nano microcontroller and an ADXL 335 accelerometer sensor embedded in the socket, which serves as the control unit. The system operates based on real-time movement and gait analysis, providing feedback on the user's walking pattern. The ADXL 335 sensor, connected to the prosthetic leg socket, continuously detects acceleration and movement along three axes (X, Y, and Z). The sensor measures the changes in the orientation and movement of the prosthetic leg, detecting the walking pattern as the user moves. The data received from the ADXL 335 sensor is transmitted to the Arduino Nano microcontroller (Garg & Parikh, 2024; Kashish Chandak, Aman Sanadhya, Jigar Gohil, Reena Trivedi, Priyam Parikh, Mihir Chauhan, 2024; P. Parikh et al., 2014, 2022, 2023; P. A. Parikh et al., 2020, 2022, 2023). The Arduino processes this data, analysing the movement patterns and identifying key aspects of the gait such as step direction, speed, and position. Based on the processed signals, the Arduino Nano sends control signals to two output devices installed on the socket the LED provides visual feedback to the user, indicating the direction and progress of the walking pattern and the buzzer emits an audible signal to alert the user about the detected movement direction or to signal specific gait patterns, such as a detected imbalance or change in walking phase. The prosthetic leg is designed to carry a load of up to 70 kg, which is crucial for ensuring its reliability and durability. The leg incorporates a gas strut that helps distribute the load evenly and absorbs shock during the walking cycle. The system can withstand the user's body weight without compromising its performance, ensuring that the prosthetic operates efficiently under real-world conditions. The system also includes the capability to track and record the movement, providing useful data on the user's walking patterns. This data can be used for future optimisation, adjustments to the prosthetic fit, or rehabilitation purposes, enhancing the overall user experience and offering insights into gait improvements over time.



Block Diagram of the System

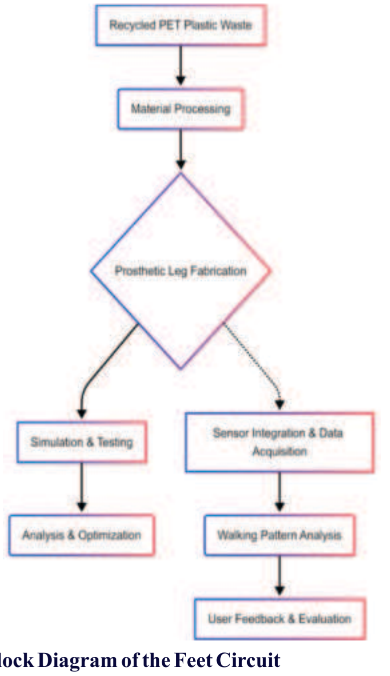


Figure 3: Block Diagram of the Feet Circuit

Flow Chart of the System

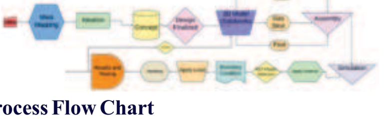


Figure 4: Process Flow Chart

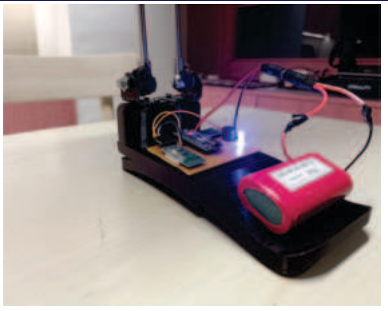


Figure 5: Setup with ADXL335 to Collect the Angular Data

5. Design and Simulation of Foot

The design and simulation of a prosthetic foot focus on replicating the natural human foot's functions. This includes shock absorption during heel strike, energy storage and return during toe-off, stability and balance, and adaptability to varying terrains. Key considerations include material selection, prioritising strength, durability, weight, flexibility, cost-effectiveness, and sustainability. Simulation techniques like finite element analysis (FEA) and multibody dynamics are employed to predict stress, strain, and deformation under different loading conditions. These simulations guide design iterations, optimising the foot's performance and minimising stress concentrations.

Figure 6 : Actual 3d Model of Foot

Figure 7: Material Properties of PET Plastic

Figure 8: Mesh Information on Foot

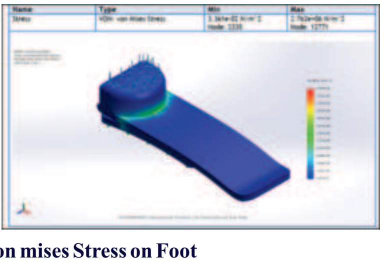


Figure 9: Von mises Stress on Foot

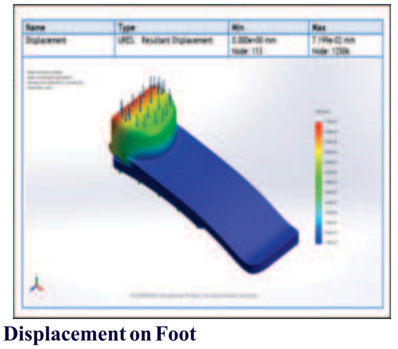


Figure 10: Displacement on Foot

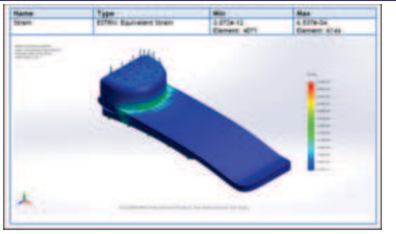


Figure 11: Strain on Foot

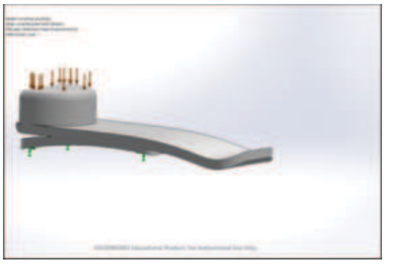


Figure 12: Deformed Shape of Foot

6. RESULT DISCUSSION

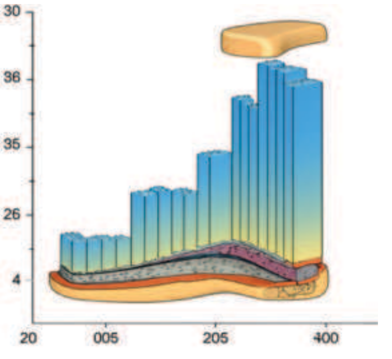


Figure 12: Different Loading Conditions of Foot

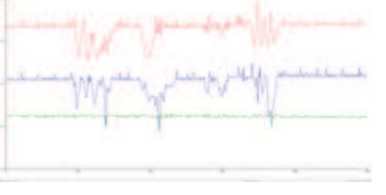


Figure 13: Accelerometer Data Showing Unwanted Twist in the Feet

Figure 13 Depicts the Angular Displacement of the Feet in X and Y Axes Along with $\sqrt{x^2 + y^2}$ to Monitor the Sudden Twist in the Feet While Walking.

The simulation process, conducted under a 70 kg load on the prosthetic foot with a high-quality mesh size, yielded promising results, confirming the structural integrity and durability of the design. The stress, strain, and displacement values were all within safe limits, indicating that the foot can withstand the applied load without compromising its material strength or causing any permanent damage. Importantly, the results showed minimal deformation, with the foot maintaining its original shape, ensuring that it will not experience permanent alteration or failure over time. These findings validate the use of recycled PET plastic for the prosthetic foot, demonstrating that it is capable of providing reliable performance under real-world conditions while maintaining both functional and aesthetic integrity.

CONCLUSION

This research highlights the potential of recycled PET plastic as an affordable, sustainable material for prosthetics, offering a reliable solution that can be mass-produced while reducing environmental impact. Future work will involve the case study of the athletes who are in need of prosthetics for their training and monitoring their walking and running patterns. Also make the second idea of prototyping, which will help the real-world testing to further refine the design and confirm its practical application, ultimately making healthcare more accessible and environmentally friendly.

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