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RESEARCH ARTICLE

Designing and evaluation of different materials for socket prosthesis in cattle

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The study was conducted to evaluate and compare three materials- polypropylene (PP), thermoplastic polyurethane (TPU), and polymethyl methacrylate (PMMA)- for the fabrication of prosthetic limbs in three amputee cattle. A mould of each residual limb was prepared by wrapping a plaster of Paris (POP) bandage around the stump. The mould was then subjected to three-dimensional tomographic reconstruction to accurately capture the shape and contours of the residual limb. Based on the scanned data, a digital socket model was designed using computer-aided design (CAD) software. The digital model was subsequently transferred to a 3D printer, which fabricated the socket through a layer-by-layer additive manufacturing process. After printing, all rough edges were smoothed using sandpaper to ensure a comfortable fit. The materials were compared based on their coefficients of thermal expansion and mechanical properties. The results demonstrated that thermoplastic polyurethane (TPU) was the most suitable material for prosthetic socket fabrication in cattle due to its high compressive strength, superior flexibility, and enhanced adaptability to the residual limb.

Keywords: Cattle, Compressive strength, 3D printing, Mechanical properties, Prosthetic socket, Synthetic polymers, Thermal expansion

Prosthetic limbs in cattle help restore mobility and improve the quality of life after injury or limb loss. They reduce pain and prevent further health complications caused by an uneven weight distribution. This allows the animal to resume normal activities, thereby contributing to better welfare and productivity.

The selection of materials for prosthetic socket fabrication is crucial for ensuring comfort, durability, and mechanical reliability. Prosthetic sockets serve as the interface between the amputee's residual limb and prosthetic device, requiring materials that provide adequate mechanical strength, thermal stability, and biocompatibility.

Additive manufacturing (3D printing) builds 3D objects layer-by-layer from digital models using materials such as plastics and metals. In regenerative medicine, it enables the creation of customized prostheses and support structures using CT images. It also allows the production of complex porous scaffolds with precise shapes for both medical and veterinary use.

Among the numerous polymers available, polypropylene (PP), thermoplastic polyurethane (TPU), and polymethylmethacrylate (PMMA) are widely used because of their distinct properties. PP is valued for its lightweight nature, flexibility, and moderate strength, making it a common choice for prosthetic applications. On the other hand, TPU is recognized for its high elasticity, impact resistance, and superior mechanical durability, which can contribute to better patient comfort and long-term usability. PMMA, a rigid and transparent polymer, provides excellent dimensional stability and low thermal expansion; however, its brittleness can be a limiting factor in high-load applications.

The performance of these polymers under mechanical stress and thermal fluctuations directly influences the effectiveness of the prosthetic devices. By evaluating these properties, this study aimed to provide a comparative analysis of PP, TPU, and PMMA to determine their suitability for prosthetic socket fabrication using a 3D printer for cattle.

Materials and Methods

The materials used in this study included polypropylene (PP), thermoplastic polyurethane (TPU), and polymethylmethacrylate (PMMA), all of which are widely utilized in prosthetic applications because of their mechanical and thermal properties. Each polymer sample was fabricated into standardized test specimens according to ASTM D638 and ASTM D695 guidelines for tensile and compression testing, respectively. The samples were prepared by 3D printing to ensure uniform dimensions and eliminate defects that could affect the results.

The thermal properties, specifically the coefficient of thermal expansion (CTE), were evaluated using a high-precision dilatometer (DILL74HM®) with vacuum tight sample chamber at IIITDM, Jabalpur (M.P.), which measured the dimensional changes in the samples across a temperature range of 25°C to 100°C. The results were analyzed to determine the extent of expansion or contraction of each material under varying thermal conditions. A lower CTE indicates better dimensional stability, which is crucial for the prosthetic socket performance.

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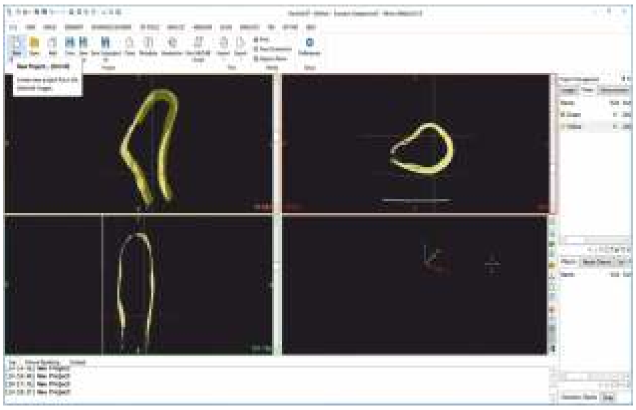

Fig. 1: MIMICS software to derive 3D model (Materialise Interactive Medical Image Control System).

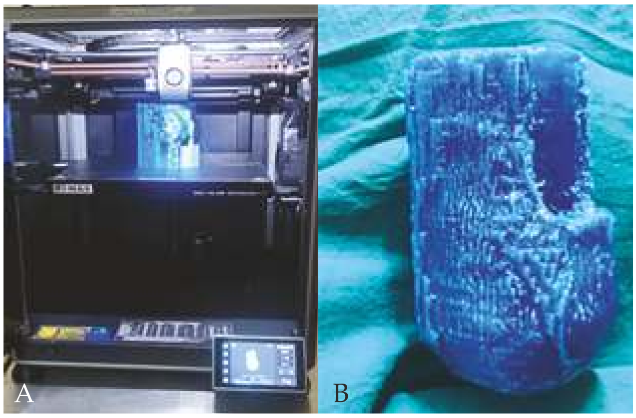

Fig. 2: Fabrication of Socket prosthesis: (A) Printing socket in vertical orientation; (B) 3D printed socket.

Mechanical testing was conducted using a universal testing machine (UTM) to determine the compressive strength and ultimate failure load. The compression test was performed at a constant displacement rate of 1 mm/min to simulate the loading conditions experienced by prosthetic sockets during use. The maximum load sustained by each sample before failure was recorded, and stress-strain curves were generated to analyze the behaviour of the materials under compressive forces. The results provided insights into the load-bearing capacities of the selected polymers.

An ideal lightweight flexible non-allergic prosthetic limb was prepared as described by Thennavan (2015). Measurements of the amputated limb stump and contra-lateral limb were done to design the cattle prosthesis. A negative cast was created using the Plaster of Paris to capture the stump's shape, and radiographic examinations ensured that the limb was free of infections or bone abnormalities. Computed tomography (CT) scans of the mould were made with a 0.5 mm slice thickness at 120 kV and 25 mA, and the images were saved in the DICOM format (Fig. 1). These were processed using MIMICS software to reconstruct a 3D model of the socket. The socket was fabricated using a Creality K1 Max 3D printer with FDM technology, as shown in (Fig. 2), using materials such as polypropylene (PP), thermoplastic polyurethane (TPU), and polymethylmethacrylate (PMMA) with a set layer thickness of 0.5 mm. Each material had the following specific printing parameters: TPU (30 mm/s, 235°C, 50°C bed, no fan), PP (40 mm/s, 250°C, 80°C bed), and PMMA (50 mm/s, 260°C, 100°C bed). After printing, the sockets were cleaned to remove the defects and scaffolds.

The data obtained from the thermal and mechanical tests were statistically analyzed using ANOVA to determine significant differences among the polymers.

Results and Discussion

Thermal expansion

The CTE values varied among the tested polymers, with TPU exhibiting the highest expansion coefficient (100-200 × 10^{-6}/°C), followed by PP (81-100 × 10^{-6}/°C), and PMMA (34-77 × 10^{-6}/°C). TPU's high thermal expansion suggests greater flexibility and higher susceptibility to dimensional changes, whereas PMMA's low CTE ensures structural stability under temperature fluctuations. These results indicate that TPU may undergo deformation under varying environmental conditions, making it less suitable for applications that require strict dimensional stability. By contrast, PMMA stability ensures a reliable fit over extended periods of use.

Mechanical properties

The compressive strength and ultimate failure load of TPU were recorded as 81.88 MPa and 6.55 kN, respectively, indicating its high load-bearing capability. PP exhibited moderate values with a 74.25 MPa compressive strength and 5.94 kN failure load. PMMA had the lowest mechanical performance with 63.38 MPa compressive strength and 5.07 kN failure load, reflecting its brittle nature (Table 1). The stress-strain curves for TPU showed significant elasticity before failure, whereas PMMA exhibited a steep decline in strength, indicating rapid fracture upon exceeding its failure threshold (Fig. 3). These findings suggest that TPU is the best choice for high-impact and flexible prosthetic sockets, whereas PMMA is better suited for applications requiring minimal deformation but lower mechanical demands.

Graphical analysis

The graphical representation of the load-displacement curves further emphasizes the disparities among the three polymers. TPU displayed a gradual increase in strain, maintaining structural integrity until a high-stress point was reached. PP exhibited moderate strain resistance, with some deformation observed before failure. On the other hand, PMMA showed a sharp drop in stress after reaching its peak load, highlighting

Table 1: Mechanical properties.

Material used for fabrication of socket	Group	Ultimate failure load (kN)	Compressive strenth (MPa)
Polypropylene	G1	5.94	74.25
Thermoplastic polyurethane	G2	6.55	81.88
Polymethylmethacrylate	G3	5.07	63.38

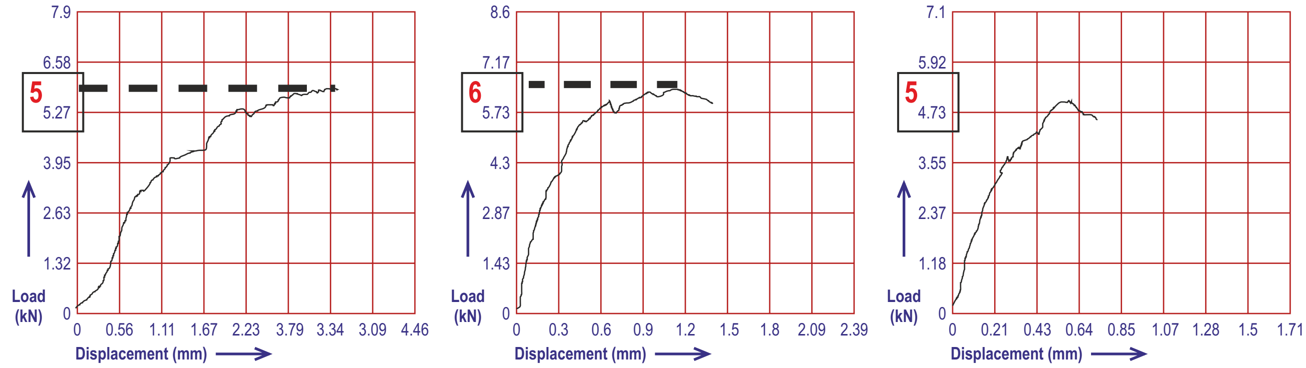

Fig. 3: Load vs. displacement graphs: (A) Polypropylene; (B) Thermoplastic polyurethane; (C) Polymethyl-methacrylate.

Fig. 4: Post-prosthetic evaluation for weight bearing assessment: (A) Polypropylene prosthetic limb; (B) Thermoplastic polyurethane prosthetic limb; (C) Polymethyl- methacrylate prosthetic limb.

its brittle nature. The bar graphs comparing the ultimate failure loads demonstrated that TPU significantly outperformed both PP and PMMA, reinforcing its suitability for prosthetic socket applications where mechanical strength and flexibility are critical. Post-development, the fabricated prosthetic sockets were evaluated in clinical cases to assess their feasibility, functionality, and suitability for practical use in amputee cattle (Fig. 4).

It was concluded that TPU is the most suitable material for prosthetic socket fabrication in cattle because of its high compressive strength, superior flexibility, and adaptability. PP, while offering moderate strength and flexibility, may serve as a viable alternative, where cost and weight reduction are the primary concerns. Conversely, despite its low thermal expansion, PMMA exhibits significant brittleness, which limits its application in load-bearing prosthetic sockets for cattle.

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