CFD Analysis and 3D Printing of a Data-Driven Trans-femoral Prosthetic Socket Design to Control Heat Flow for Comfort

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Summary

Wounds and ulcers often arise from prolonged use of the closed design of conventional prosthetic sockets. To address this, a prosthetic socket was designed with integrated holes based on a 2^n pattern (n=1 to 5). These holes are optimized through stress map data to enhance heat dissipation between limb tissues and socket walls, improving comfort for extended use. Computational fluid dynamics (CFD) analysis, considering the properties of soft tissues and PLA, revealed a 2°C temperature reduction at the interface and a 4.5 W increase in heat transfer with 32 holes. A PLA socket with this optimal design was successfully printed using the fused filament fabrication (FFF) process.

Introduction

Conventional prosthetic sockets often cause skin issues due to their closed design during prolonged use [1]. Additive manufacturing (AM) offers a solution by enabling customized sockets with intricate geometries, such as lattice structures or vents [2]. This study introduces a 2^n (where n = 1 to 5) hole-pattern vent strategy in the trans-femoral prosthetic socket (TPS) to improve heat dissipation while maintaining structural stability. CFD analysis was conducted to evaluate temperature distribution and heat flow using ANSYS 2022.

Methods

The CAD model of a TPS was obtained via 3D scanning of the amputee's limb. Subsequently, the static simulation was performed, and obtained the deformation v/s load and stress v/s strain curve. The maximum stress map is above the required range; therefore, we decided to remove material by creating the vents in order of 2^n strategy (where n = 1 to 5). For each strategy, the static simulation was performed and obtained the results; all the results satisfied the required stress or deformation values. Therefore, on all the combinations, the CFD analysis was performed to evaluate the temperature and heat flow. The digital manufacturing from scanning to analysis is presented in Figure 1(a).

Table 1: Materials properties for CFD analysis

Materials	Density (kg/m^3)	Specific heat (J/kg. K)	Thermal conductivity (W/m.K)
Limb (Soft Tissues)	1.09	3470	0.37
PLA Socket	1250	1800	0.13

The material properties considered for the static and CFD analysis are shown in Table 1. The FFF-based extrusion process is used to fabricate the TPS using PLA.

Results and Discussion

The hole-vent strategy produced five designs with 2 to 32 holes. Deformation was approximately 1 mm for sockets without holes and with 2 holes, increasing to 1.35 mm for 4, 8, and 16 holes. All deformations remained within the acceptable 2 mm range under a 400 N compressive load, with 40% of the load distributed on the sides.

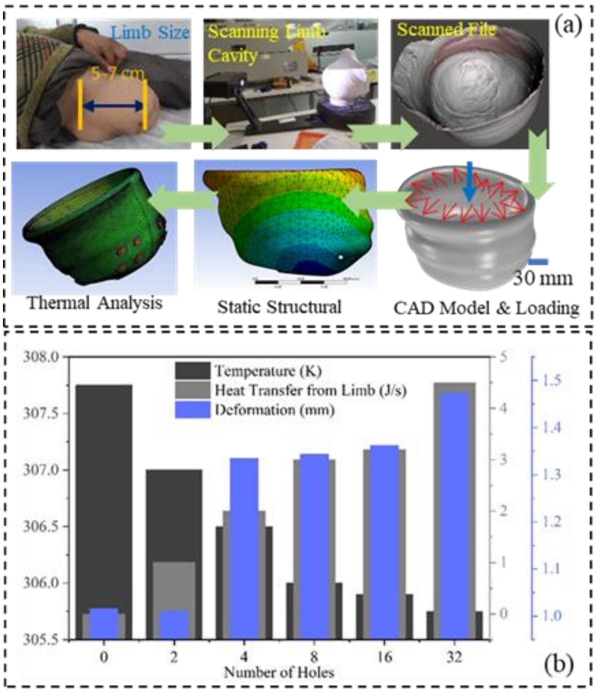

Figure 1: (a) Digital manufacturing process to construct CAD model and FEA, and (b) Deformation, heat transfer, and temperature plots with respect to the number of holes.

CFD analysis evaluated heat transfer and temperature variation along the socket wall. Heat transfer values ranged from 1 to 4.5 W, while the temperature dropped from 307.75 to 305.75°K. After 4 holes, the temperature decreased by approximately 1°K and remained constant for designs with 8, 16, and 32 holes. The TPS design with 32 holes, offering optimal heat dissipation and mechanical stability, was fabricated using the FFF process. The results are shown in Figure 1(b).

Conclusion

The study optimized a TPS using a 2^n hole-vent strategy, improving heat dissipation and comfort while ensuring stress and deformation requirements. CFD analysis showed increased heat transfer and a 2°C temperature drop. The final 32-hole design was fabricated using the FFF process.

References

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[2] S. Lemaire *et al.*, (2024)," *J. Mech. Behav. Biomed. Mater.*, vol. **155**, no. April, p. 106538.