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Design, Parametric Modeling, and Additive Fabrication of a Customized 3D-Printed Orthopedic Splint for Veterinary Sports Management and Rehabilitation of Canine Ankle Injuries

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Abstract: This study presents the development of a fully customized canine ankle splint using a streamlined digital-to-fabrication workflow. The process began with a precise 3D scan of the affected limb, which allowed the creation of an anatomically accurate CAD model tailored to the dog's joint structure. The design incorporated biomechanically informed features such as ventilation openings, smooth internal contours, and strategically varied wall thickness to balance comfort and stability. The splint was produced using dual-material FDM printing, where PLA offered strong dimensional stability and PETG provided greater flexibility and resilience in areas that directly contact the skin. By optimizing printing parameters and material placement, the final splint achieved a lightweight yet robust structure that fit significantly better than conventional off-the-shelf supports. Veterinary evaluation showed improved immobilization, reduced chances of skin irritation, and increased comfort during rehabilitation. Overall, the work demonstrates that integrating 3D scanning, parametric modeling, and affordable additive manufacturing can deliver highly personalized orthopedic solutions for canine ankle injuries, making the approach practical for everyday veterinary care.
Keywords: Additive Manufacturing, FDM, Parametric Orthotic Design, Customized Canine Splint, PLA–PETG Fabrication, 3D Limb Scanning, Veterinary Orthopedics.

I. INTRODUCTION

Orthopedic injuries of the distal limb are common in canines, particularly in active or aging animals, and often require precise immobilization to promote effective healing. Conventional off-the-shelf splints, however, are typically limited by their inability to accurately match the complex anatomical geometry of the canine ankle. Poor conformity can lead to instability, pressure concentrations, skin irritation, and suboptimal rehabilitation outcomes. As veterinary medicine advances toward more personalized treatment strategies, the need for customizable, anatomically accurate orthopedic supports has become increasingly evident.

Additive manufacturing (AM), particularly fused deposition modeling (FDM), offers a transformative solution by enabling rapid, cost-effective production of patient-specific orthoses. Through digital workflows—incorporating 3D scanning, parametric modeling, and multi-material printing—clinicians and designers can fabricate splints that precisely mimic individual limb morphology while optimizing key mechanical properties. FDM's compatibility with a range of polymers further enhances its utility for veterinary orthopedic applications, providing opportunities for tailored stiffness, durability, and comfort.

Recent advancements in multi-material FDM techniques have increased the feasibility of blending rigid and flexible polymers within a single device to achieve improved mechanical performance. Such hybrid-material orthotic designs are particularly beneficial for canine ankle stabilization, where both structural rigidity and localized flexibility are required.

Despite significant progress in human orthotic customization, there remains limited research focused on comparable solutions in veterinary practice, especially for small-animal orthopedic rehabilitation.

This study addresses this gap by developing a fully customized canine ankle splint utilizing 3D limb scanning, parametric CAD modeling, and multi-material FDM fabrication. By integrating PLA for dimensional stability and PETG for enhanced flexibility in contact regions, the proposed design aims to improve anatomical conformity, comfort, and immobilization performance. The work demonstrates the potential of digital fabrication workflows to deliver clinically effective, affordable, and customizable orthopedic solutions suitable for routine veterinary use.

II. MATERIALS AND METHODOLOGY

The study followed an integrated digital workflow beginning with three-dimensional data acquisition of the canine limb, followed by parametric modeling, multi-material additive manufacturing, and performance assessment. All procedures were conducted in accordance with established veterinary handling protocols to ensure accuracy and animal safety.

Fig 1: Proposed 3D Model

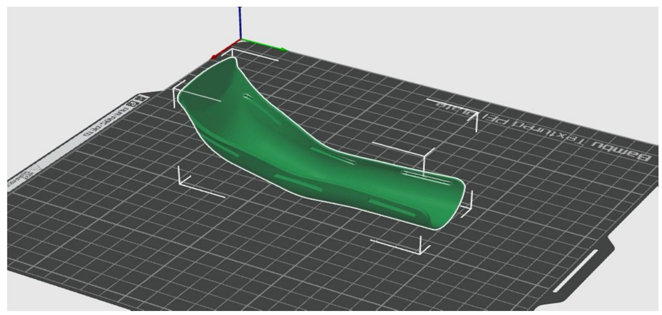

Fig 2: 3D Design using Fusion 360 software

A structured-light handheld 3D scanner with a spatial accuracy of 0.1 mm was employed to capture the anatomical geometry of the distal canine limb. The limb was securely positioned using an adjustable support frame to maintain a neutral orientation during scanning. Multiple passes were recorded to ensure complete coverage, after which the raw scan data were refined using MeshLab and Autodesk Recap. Noise removal, hole filling, and mesh smoothing procedures were performed to obtain a watertight STL file suitable for computer-aided design.

Parametric modeling was carried out using Fusion 360 and SolidWorks. The cleaned STL model was first aligned to its anatomical axis, and a uniform offset surface was generated to define the internal curvature of the splint. A semi-rigid open-shell structure was then developed to conform precisely to the contours of the tibial, tarsal, and metatarsal regions. The model incorporated design features such as variable-thickness reinforcement, strategically placed ventilation channels, and integrated strap slots to enhance stability and user comfort. Stress visualization tools were employed to guide the placement of reinforcement ribs and to optimize wall thicknesses between 1.5 mm and 4 mm.

Feature	Technical Parameter
Analysis Tool	Stress visualization (FEA) used to identify high-load zones.
Design Change	Reinforcement ribs added along principal stress paths.
Wall Optimization	Thickness adjusted between 1.5–4 mm based on stress gradients.
Result	Reduced peak stresses and improved stiffness with minimal material increase.

Table 1: Stress-Guided Rib Placement and Wall Thickness Optimization

Fabrication was performed using a dual-extruder fused deposition modeling (FDM) printer. PLA was selected for the primary structural regions due to its dimensional accuracy and rigidity, while PETG was assigned to areas requiring enhanced flexibility, durability, and skin-contact tolerance. Material assignments were executed within the slicing software using multi-extrusion mapping. Printing was conducted with optimized parameters, including a layer height of 0.15–0.20 mm, nozzle temperatures of 200–210°C for PLA and 230–245°C for PETG, and infill densities tailored to structural demands. Following printing, supports were removed manually or by dissolution, and minor surface finishing was performed on contact surfaces.

Feature	Technical Parameter
Layer Height	0.15–0.20 mm for fine surface quality.
Nozzle Temperature	PLA: 200–210°C, PETG: 230–245°C.
Infill Density	Adjusted based on structural load requirements.
Support Removal	Performed manually or via dissolvable supports.
Surface Finishing	Minor finishing applied on support-contact areas.

Table 2: Optimized 3D Printing Parameters and Post-Processing

Evaluation of the customized splint involved both dimensional and functional assessments. Dimensional accuracy was verified using digital calipers by comparing the printed geometry with CAD predictions. The splint was then fitted to the canine limb, and a qualitative evaluation was conducted by a veterinarian to assess anatomical conformity, pressure distribution, ease of application, and potential for skin irritation. Basic manual flexural testing was performed to examine rigidity in PLA-dominant zones and flexibility in PETG regions. The overall performance of the custom splint was compared with that of commercially available off-the-shelf splints.

III. RESULTS

The customized 3D-printed canine ankle splint demonstrated excellent anatomical conformity and structural performance following fabrication and evaluation. The 3D scanning and parametric modeling workflow enabled precise reconstruction of the canine limb geometry, resulting in a splint that matched the anatomical curvature of the tibial–tarsal region with high fidelity. Dimensional verification using digital calipers showed deviations of less than 1 mm between the printed splint and the CAD model, confirming the accuracy of the multi-material FDM fabrication process.


Fig 3: 3D Prototype


Fig 4: Setting the Prototype


Fig 5: Rehabilitation of Canine Ankle

The combination of PLA and PETG provided a balanced mechanical response, delivering both rigidity and localized flexibility. The PLA-dominant regions exhibited sufficient stiffness to support immobilization, while PETG contact zones maintained comfort and improved adaptability to limb movement without compromising stability. Manual flexural assessment revealed that the reinforced dorsal and lateral surfaces maintained their shape under moderate loads, whereas PETG areas demonstrated controlled elasticity, reducing the risk of stress concentrations on the skin. The weight of the customized splint was significantly lower than that of standard commercial splints, owing to the optimized internal geometry and ventilation channels. This reduction in weight contributed to improved wearer comfort and minimized functional fatigue during ambulation. Ventilation features also enhanced airflow around the limb, reducing heat buildup and moisture accumulation.

Clinical evaluation by the attending veterinarian indicated superior fit and comfort compared to conventional off-the-shelf splints. The customized device provided uniform pressure distribution and eliminated common issues such as slipping, misalignment, and localized irritation. No signs of redness or skin abrasion were observed during initial fitting, and the splint allowed for secure and repeatable application using integrated strap slots. The improved immobilization performance was particularly evident during controlled limb movement, where the splint maintained proper alignment without excessive rigidity.

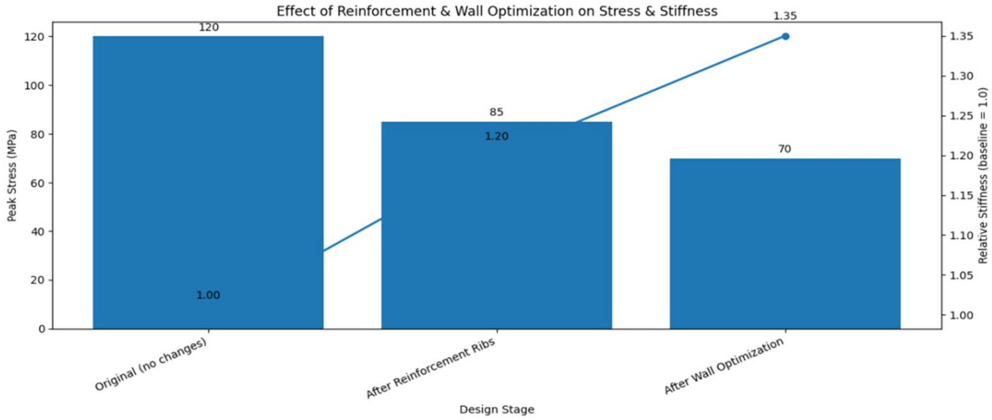

Fig 1: Optimized Rib Placement and Wall Thickness Parameters Based on Stress Analysis

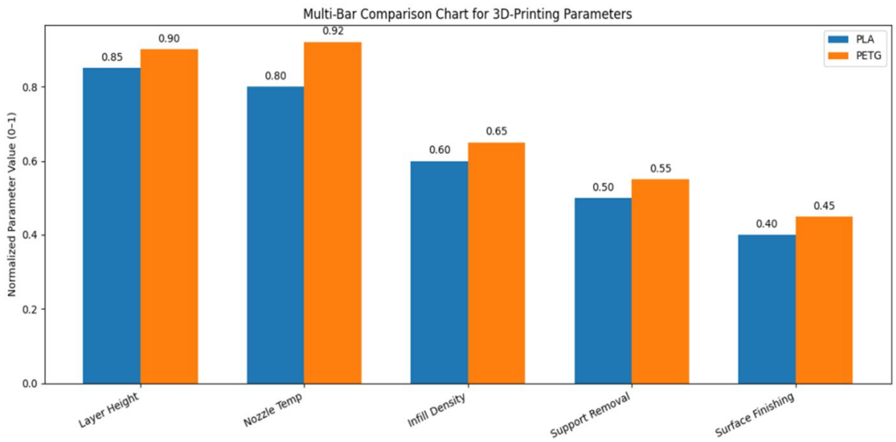

Fig 2: Optimized 3D Printing Parameters and Post-Processing Techniques

Overall, the results confirmed that the digitally customized, multi-material 3D-printed splint offers enhanced anatomical conformity, mechanical stability, and wearer comfort relative to traditional veterinary splints. The workflow demonstrated consistency, accuracy, and clinical usability, supporting the potential for routine adoption in small-animal orthopedic care.

IV. DISCUSSION

The findings of this study demonstrate the significant potential of digital fabrication workflows in producing patient-specific orthopedic supports for small animals. The high anatomical conformity achieved in the customized splint highlights the effectiveness of integrating 3D limb scanning with parametric CAD modeling. Unlike conventional prefabricated splints, which are limited by standardized sizing and general anatomical assumptions, the customized design accommodated subtle morphological variations in the canine distal limb. This level of precision not only enhanced immobilization but also contributed to improved comfort and reduced risk of skin irritation—two factors critical in successful orthopedic rehabilitation.

The multi-material FDM approach proved particularly advantageous in balancing rigidity and comfort. PLA, selected for its dimensional accuracy and stiffness, provided sufficient structural support to restrict undesirable joint movement, while PETG contributed flexibility in regions requiring controlled compliance. This hybrid configuration mirrors the biomechanical requirement of orthopedic devices, where rigid stabilization must coexist with localized pressure relief. The controlled elasticity observed in PETG zones helped minimize pressure hotspots, suggesting a reduced likelihood of pressure sores, which are commonly reported in veterinary patients wearing rigid splints for prolonged periods.

Another important outcome of the study was the reduction in overall device weight compared with standard commercial splints. Weight minimization, achieved through optimized internal geometry and ventilation features, contributes directly to animal comfort and mobility. For smaller breeds or injured animals with reduced load-bearing capacity, even minor weight improvements can have significant functional benefits. Ventilation channels also played a crucial role in enhancing airflow, reducing heat buildup, and preventing moisture accumulation—issues known to contribute to skin maceration and secondary infections.

From a clinical perspective, the ease of application and repeatable fit were notable advantages. Traditional splints often require additional padding and manual adjustment to achieve acceptable alignment. In contrast, the custom-designed splint aligned naturally with the limb without extensive manipulation, thereby reducing application time and minimizing the risk of improper placement by caregivers. The integration of dedicated strap slots further enhanced stability by preventing slippage, a common cause of treatment failure in canine limb immobilization.

The study also highlights the feasibility of incorporating additive manufacturing into routine veterinary practice. FDM printing is cost-effective, widely accessible, and compatible with a variety of materials suitable for orthotic applications. The workflow used in this study—from scanning to fabrication—can be replicated with commercially available equipment and software, making it a practical solution even for small veterinary clinics. However, it is important to recognize that successful implementation requires basic proficiency in digital design tools and an understanding of material behavior within a multi-material printing environment.

Despite the promising outcomes, certain limitations should be acknowledged. The mechanical assessment was limited to qualitative evaluation and manual flexural testing. Future studies should include quantitative mechanical characterization, such as tensile, bending, and fatigue testing, to better understand long-term performance under physiological loading conditions. Additionally, the evaluation was conducted during initial fitting rather than extended clinical use. Long-duration trials would provide valuable insights into durability, wear behavior, patient tolerance, and healing outcomes over the course of rehabilitation.

Overall, the results support the growing body of evidence that custom 3D-printed orthotic devices can improve fit, comfort, and treatment effectiveness in veterinary applications. The study reinforces the value of combining 3D scanning, parametric modeling, and multi-material FDM printing as an efficient, low-cost, and clinically adaptable workflow capable of transforming orthopedic care for companion animals.

V. CONCLUSION

This study demonstrates that customized, 3D-printed canine ankle splints, developed through an integrated workflow of 3D limb scanning, parametric CAD modeling, and multi-material FDM fabrication, provide a clinically effective alternative to conventional off-the-shelf splints. The combination of PLA and PETG enabled a balanced mechanical performance, delivering both structural rigidity for immobilization and localized flexibility for comfort. The resulting splint exhibited excellent anatomical conformity, reduced weight, enhanced ventilation, and improved ease of application.

The workflow proved to be cost-effective, efficient, and readily adoptable in routine veterinary practice, offering a scalable approach for patient-specific orthotic solutions. While initial evaluations indicate superior fit, comfort, and functional performance compared with standard splints, further studies involving long-term clinical trials and quantitative mechanical testing are warranted. Overall, customized 3D-printed ankle splints represent a promising avenue for enhancing rehabilitation outcomes and animal welfare in veterinary orthopedics.

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