Design, Analysis and Fabrication of Articulated Foot Orthrosis

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Abstract — This project focuses on designing, analyzing, and fabricating an Articulated Foot Orthosis (AFO) to address foot drop, improving gait stability and mobility. Using CATIA V5, a 3D model was developed with an articulated ankle joint allowing adjustable dorsiflexion. Finite Element Analysis (FEA) in ANSYS assessed stress distribution and structural integrity under gait conditions. Materials like PLA, ABS, and CFRP were evaluated, with PLA selected for its superior mechanical properties and lightweight nature. The AFO was fabricated using 3D printing, ensuring a custom fit and enhanced comfort. Gait analysis demonstrated improved ankle dorsiflexion, foot clearance, and overall stability. This research underscores the potential of integrating CAD, 3D printing, and FEA to develop patient-centric AFOs, offering an effective solution for foot drop and gait impairments.

Keywords: Articulated Foot Orthosis, Foot Drop, Gait Stability, Finite Element Analysis, 3D Printing, CATIA V5, ANSYS, Polylactic Acid

I. INTRODUCTION

Articulated Foot Orthoses (AFOs) are essential medical devices designed to support and improve the functionality of individuals with foot drop and other lower limb impairments. These devices play a crucial role in enhancing gait stability, correcting deformities, and providing controlled ankle dorsiflexion during walking. This project focuses on the design, analysis, and fabrication of an AFO using advanced engineering tools and materials. The research integrates Computer-Aided Design (CAD) for 3D modeling, Finite Element Analysis (FEA) for structural evaluation, and 3D printing for fabrication. Materials such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Carbon Fiber Reinforced Polymer (CFRP) were analyzed to determine their suitability for AFO construction. The study aims to optimize the AFO design for strength, weight, and comfort, addressing challenges like skin irritation, limited mobility, and cost. By leveraging modern technologies, this project seeks to develop a patient-centric AFO that improves gait symmetry, reduces pain, and enhances the quality of life for individuals with neurological and musculoskeletal impairments. The findings contribute to the advancement of orthotic solutions, paving the way for more personalized and effective AFO designs in the future.The material properties are taken as shown in tables 1,2&3.

S.NO	PROPERTY	VALUES	UNITS
1.	Density	1.4	g/cm³
2.	Young's modulus	1.8	GPa
3.	Poisson ratio	0.35	
4.	Bulk modulus	2E+09	Pa
5.	Shear modulus	6.6667E+08	Pa

Table 1: Mechanical Properties of the Polylactic Acid (PLA) Material

S.NO	PROPERTY	VALUES	UNITS
1.	Density	1.04	g/cm³
2.	Young's modulus	1.8	GPa
3.	Poisson ratio	0.38	
4.	Bulk modulus	2E+09	Pa
5.	Shear modulus	6.6667E+08	Pa
6.	Tensile Yield Strength	30	MPa

Table 2: Mechanical Properties of the Acrylonitrile Butadiene Styrene (ABS)Material

S.NO	PROPERTY	VALUES	UNITS
1.	Density	1.6	g/cm³
2.	Young's modulus	70	GPa
3.	Poisson ratio	0.1	
4.	Bulk modulus	2.9167E+10	Pa
5.	Shear modulus	31.818	GPa
6.	Tensile Ultimate Strength	600	MPa

Table 3: Mechanical Properties of the Carbon Fiber Reinforced Polymer (CFRP)Material

II. LITERATURE REVIEW:

Alam et.al., [1] This study examines articulated ankle-foot orthoses (AFOs) for treating drop-foot, a condition linked to stroke and neurological disorders. It highlights the limitations of passive AFOs, which restrict movement, and active AFOs, which face bulkiness and power issues. Various designs, including oil dampers, pneumatics, and series elastic actuators, are reviewed for their ability to prevent foot-slap and toe-drag. Innovations like magnetorheological fluids and energy harvesting show promise, but challenges remain in making AFOs lightweight, compact, and adaptive. Future research should focus on advanced control systems to enhance adaptability, comfort, and overall quality of life for users.

James Manzerhe et.al., [2] This study explores the design and fabrication of a cost-effective Ankle Foot Orthosis (AFO) for individuals with Cerebral Palsy (CP), specifically addressing drop foot. Using Finite Element Analysis (FEA), various thermoplastic materials like Acetal Resin, ABS, and LCP were analyzed to balance stiffness, comfort, and cost. A simplified cantilever beam model evaluated material performance, identifying 6mm thickness as optimal. The final AFO was laser-cut from thermoplastic sheets and heat-formed into a 3D structure. Results confirm the feasibility and scalability of this method, offering an affordable solution to enhance mobility and quality of life for individuals with CP.

Ghanim Sh. Sadiq et.al., [3] This review explores Ankle Foot Orthosis (AFO) types, materials, and advancements. AFOs aid conditions like foot drop, cerebral palsy, and stroke, categorized into metal, plastic, and carbon types. Metal AFOs offer adjustability, plastic AFOs are lightweight, and carbon AFOs provide strength. Innovations include dynamic AFOs like TurboMed for enhanced dorsiflexion, 3D-printed AFOs for customization, and eco-friendly Kenaf composites for reduced weight and cost. Material selection and design are crucial for optimizing functionality. Further research is needed to validate new technologies, ensuring improved rehabilitation outcomes and personalized, effective solutions for patients.

Prashanth R Kubasad et.al., [4] This study analyzes the design of a passive Ankle Foot Orthosis (AFO) using the transient structural method and Finite Element Analysis (FEA). Polypropylene and HDPE were evaluated for stress, deformation, and factor of safety. Static analysis showed Polypropylene had lower stress and deformation, making it more suitable. Dynamic analysis using ANSYS confirmed its effectiveness, with a 3mm Polypropylene AFO supporting up to 55 kg. The research emphasizes material selection and geometric optimization in AFO design. Future work may explore experimental validation and higher static loads, contributing to more efficient orthotic devices for individuals with gait disabilities.

Rogati et.al., [5] This study examines the design, manufacturing, and evaluation of custom passive dynamic ankle-foot orthoses (PD-AFOs) for drop-foot patients. PD-AFOs improve gait by absorbing and releasing energy, with advancements in 3D scanning and additive manufacturing enabling precise customization. A review of 75 studies covers scanning technologies, customization criteria, production techniques, and functional evaluation. Laser-based and structured-light scanners enhance modeling, while SLS and FDM dominate production. Custom PD-AFOs improve comfort and gait but lack standardized stiffness guidelines. The study highlights the need for standardized testing and customization principles, emphasizing the potential of advanced manufacturing for patient-specific orthotic solutions.

Tai-Ming Chu and Narender P. Reddy., [6] This study analyzes stress distribution in ankle-foot orthoses (AFOs) for stroke patients with drop foot using 3D finite element analysis (FEA). The model simulates stress during gait, identifying peak stress in the neck and heel regions, with the neck being most prone to fatigue. Stress is highest during heel contact and toe-off, influenced more by AFO stiffness than soft tissue properties. The findings emphasize material selection and fabrication for durability and comfort. While limited by linear material assumptions, the study suggests future research on nonlinear properties, varied designs, and gait speeds to enhance AFO performance and longevity.

Young-Shin Lee et.al., [7] This study analyzes the structural behavior of plastic ankle-foot orthoses (AFOs) using finite element analysis (FEA) and experimental methods. Three AFO models with varying neck widths were evaluated, considering polypropylene’s nonlinear properties. Strain measurements during simulated gait revealed maximum strain around the neck, with FEA values about twice as high as experimental results. Findings showed that structural stability is not solely dependent on width. Discrepancies were linked to material nonlinearity and geometric simplifications. The study underscores AFO design complexity and calls for further experiments to refine functional design, contributing to improved orthotic performance and patient outcomes.

Md. Hazrat Alia et.al., [8] This study explores 3D printing and additive manufacturing in ankle-foot orthosis (AFO) development, focusing on Carbon Fiber Reinforced Polymer (CFRP). Using finite element analysis (FEA) in ANSYS, it compares articulated and non-articulated AFOs under stress. The research traces AFO evolution from traditional materials to advanced composites like CFRP, ABS, and PLA. CFRP offers superior strength and durability but at a higher cost. Results show articulated CFRP AFOs reduce deformation and stress, while PLA and Nylon 12 models are more sustainable. The study provides insights into optimizing AFO design and material selection for improved performance and patient outcomes.

N. V. Ramos et.al., [9] This study uses finite element analysis (FEA) to predict fracture conditions in ankle-foot orthoses (AFOs) during gait. Analyzing stress distribution at shock absorption (11%), midstance (32%), and heel rise (52%), results show high stress during shock absorption and heel rise, aligning with common fracture areas. Various materials, including polypropylene, PTFE, PMMA, and ABS, were evaluated, with polypropylene proving most effective. Findings highlight the impact of material flexibility and load conditions on AFO durability. The study underscores FEA's value in optimizing AFO design and fabrication, advocating further research on personalized geometries to enhance patient outcomes and reduce failures.

Alireza Nouri et.al., [10] This journal reviews materials and manufacturing techniques for ankle-foot orthoses (AFOs), essential for supporting gait-impaired patients. It traces AFO evolution from leather and metal to modern polymers and composites, emphasizing strength, stiffness, and biocompatibility. The study explores biomechanics, gait pathologies, and key design factors like stiffness and wearability. Manufacturing methods include prefabrication, conventional customization, and additive manufacturing (AM), with AM enabling lightweight, customized designs. The review highlights the need for further research to optimize materials and fabrication, particularly in AM, to enhance AFO performance and accessibility. Advancements in AFO technology aim to improve patient mobility and outcomes.

Hasan Mhd Nazha et.al., [11] This journal analyzes passive articulated and non-articulated ankle-foot orthoses (AFOs) for gait rehabilitation, categorizing them by design, control mechanisms, and clinical applications. Articulated AFOs, made from thermoplastics or carbon composites, allow controlled movement, while non-articulated AFOs are rigid. The review covers metal, plastic, posterior-leaf-spring, and ground-reaction AFOs, highlighting their benefits and limitations. Emerging technologies like 3D printing and shape-memory alloys enhance customization and efficiency. Clinical trials confirm AFO effectiveness in improving gait and mobility in stroke and cerebral palsy patients. The study emphasizes further research to optimize designs and integrate advanced materials for better patient outcomes.

Yamamoto S et.al., [12] This case series examines an articulated ankle-foot orthosis (AFO) with plantarflexion resistance for stroke patients with hemiplegia. The AFO features a spring mechanism to enhance dorsiflexion and reduce knee hyperextension. Evaluations of two stroke patients showed improved walking speed, stride length, ankle dorsiflexion, and vertical center of mass displacement, with reduced knee hyperextension. While the AFO improved first and second rocker functions, limitations in third rocker function were noted. The study highlights the potential of articulated AFOs in gait rehabilitation but recommends further research with larger sample sizes and long-term use to validate these findings.

Souji Tanaka et.al., [13] This study compares an oil damper AFO (AFO-OD) and a nonarticulated AFO in subacute stroke patients. The AFO-OD provides plantarflexion stiffness without dorsiflexion resistance, while the nonarticulated AFO offers stiffness in both directions. Among 41 patients (36 completed), the AFO-OD group showed greater dorsiflexion and peak ankle power absorption but no significant differences in plantarflexion moment or spatial-temporal parameters. Findings highlight the impact of AFO stiffness on ankle kinematics and the need for personalized interventions. The study emphasizes individualized AFO selection for optimal gait rehabilitation and calls for further research on long-term effects and custom AFOs.

S.F. Khan and I. Radzmi., [14] This study redesigns ankle-foot orthoses (AFOs) using topology optimization to improve weight and comfort. Traditional polypropylene AFOs are labor-intensive, increasing cost and production time. Using CAD and finite element analysis (FEA), the study evaluates polypropylene, HDPE, and PLA at 3mm, 4mm, and 5mm thicknesses. Results show HDPE provides the most flexibility, while 4mm offers the best stress-displacement balance. Shape optimization reduces weight by 26% for 3mm and 4mm models and 19% for 5mm. The study highlights additive manufacturing (AM) as a promising method for efficient, customized AFO production, enhancing patient comfort and reducing fatigue.

Arnaud Delafontaine et.al., [15] This study examines how rigid ankle-foot orthoses (AFOs) affect gait initiation (GI) in healthy adults, analyzing biomechanical and EMG parameters. Nineteen participants performed GI under three conditions: without AFO, with AFO on the stance leg, and bilaterally. AFOs reduced tibialis anterior and soleus activity, decreased center of pressure displacement, and lowered forward velocity of the center of mass. They also increased mediolateral velocity and step width, compromising balance. Findings suggest that while AFOs prevent foot drop, they may impair dynamic balance and propulsion. The study recommends assistive AFO designs to improve stability and optimize gait control.

Muhsin J. Jweeg et.al., [16] This study examines the effects of temperature on a new non-articulated prosthetic foot made from high-density polyethylene (HDPE), comparing it to a Solid Ankle Cushioned Heel (SACH) foot. Mechanical and numerical analyses assessed fatigue life and dorsiflexion at 23°C and 60°C. Results showed the new design had superior fatigue life and dorsiflexion. Finite element analysis in SolidWorks and ANSYS confirmed a fatigue safety factor of 4.9. Findings suggest the HDPE prosthetic foot enhances durability and performance, particularly under temperature variations, making it a viable option for below-knee amputees, especially in regions like Iraq with high prosthetic demand.

Rethlefsen et.al., [17] This study examines the effects of fixed (FAFOs) and articulated ankle-foot orthoses (AAFOs) on gait in children with spastic diplegic cerebral palsy (CP). Gait analysis of 21 subjects showed that both AFOs increased dorsiflexion at initial contact, with AAFOs providing greater dorsiflexion at terminal stance and preserving plantarflexor power at preswing. Knee position remained unaffected, with knee-extensor strength influencing knee extension. AAFOs allow more natural ankle movement, making them suitable for children with adequate passive dorsiflexion. The study highlights the importance of knee-extensor strength in orthotic selection and calls for further research on bracing for crouched gait cases.

Aqsa Khan et.al., [18] This study examines the effects of articulated and static ankle-foot orthoses (AFOs) on gait kinematics in foot drop patients, particularly those with chronic stroke. Involving 100 unilateral foot drop patients, the study found that articulated AFOs significantly improved step length, stride time, cadence, and joint angles, reducing toe drag and enhancing stability. While articulated AFOs improved gait efficiency and reduced fall risk, some research presents mixed findings on their superiority over rigid AFOs. The study highlights the need for further research on AFO design but supports the benefits of articulated AFOs in enhancing mobility and gait consistency in foot drop patients.

III. METHODOLOGY:

The technique for the plan, examination, and fabrication of the Verbalized Foot Orthosis (AFO) involves an efficient approach joining computer aided plan (CAD), limited component examination (FEA), and 3D printing innovations. The prepare starts with the conceptualization and plan of the AFO utilizing CATIA V5 computer program. The plan joins an articulated lower leg joint to permit controlled dorsiflexion addressing the useful impediments related with foot drop. Key anatomical points of interest and patient specific necessities are considered amid the plan phase to guarantee ideal fit and usefulness as appeared in fig 1.

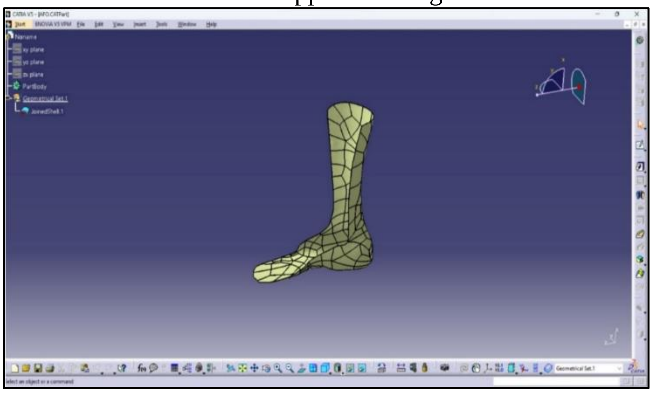


Fig. 1: AFO model in CATIA V5 Software

Once the 3D demonstrate is finalized, it is imported into ANSYS Workbench for auxiliary investigation as appeared in fig 2. The show experiences fitting, where appropriate component sorts and work sizes are chosen to guarantee exact comes about as appeared in fig 3. Fabric properties for Polylactic Corrosive (PLA), Acrylonitrile Butadiene Styrene (ABS), and Carbon Fiber Reinforced Polymer (CFRP) are alloted, and boundary conditions recreating real-world stride scenarios are connected. Inactive auxiliary investigation is performed to assess add up to distortion and equivalent stretch beneath stacking conditions, guaranteeing the AFO can withstand the powers experienced amid walking.

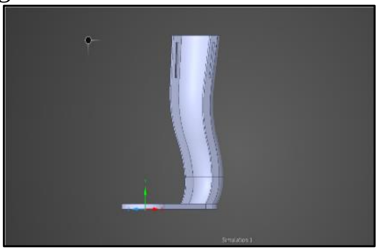


Fig. 2: Final 3D Model

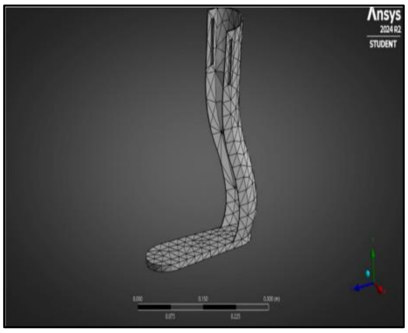
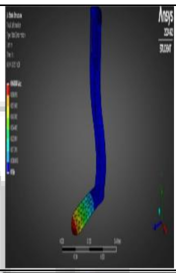
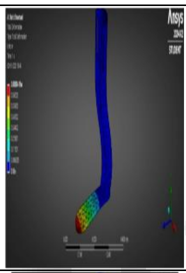
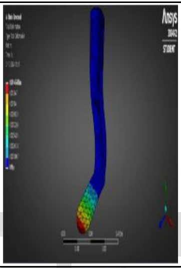
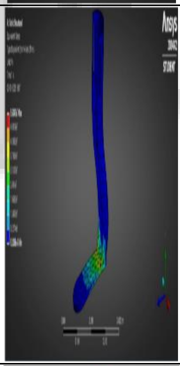
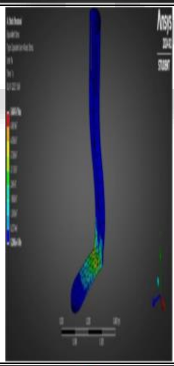
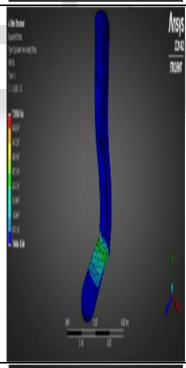
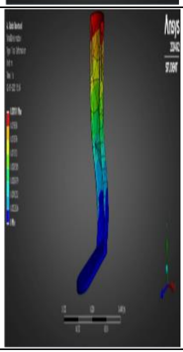
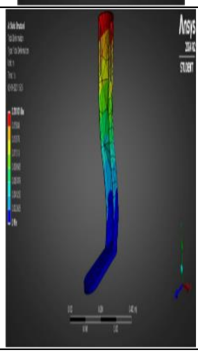
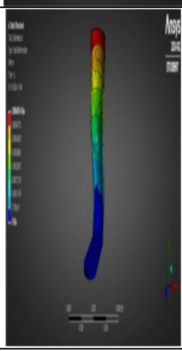


Fig. 3: Mesh elements in FEA initial conditions

IV. SIMULATION RESULTS:

Analysis results are shown in table 4 & 5.

Properties	Articulated model with PLA	Articulated model with ABS	Articulated model with CFRP
Total Deformation			
Equivalent Stress			
Total Deformation			

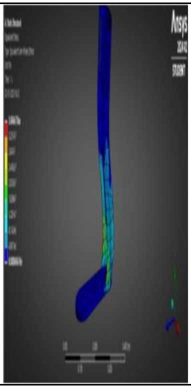
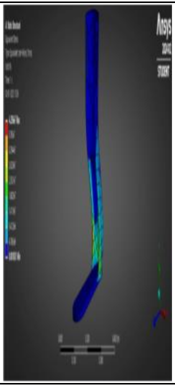
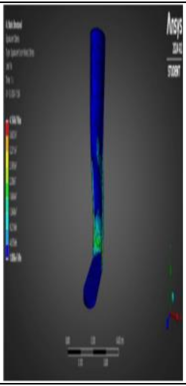
Equivalent Stress			

Table 4: Simulation results for the articulated AFO model

Properties	Articulated model with PLA	Articulated model with ABS	Articulated model with CFRP
Max. total deformation	1.5m	0.4m	1.35m
Max. equiv. stress	91.37 Pa	2.91 Pa	69.77 Pa

Table 5: Total analysis result of AFO

V. FABRICATION:

Based on the analysis results, the design is optimized for strength and weight minimization. The final design is then fabricated using 3D printing techniques, specifically Fused Deposition Modeling (FDM), (as shown in fig4&5) due to its ability to produce complex geometries with high precision. PLA is selected as the primary material due to its superior mechanical properties and biodegradability.

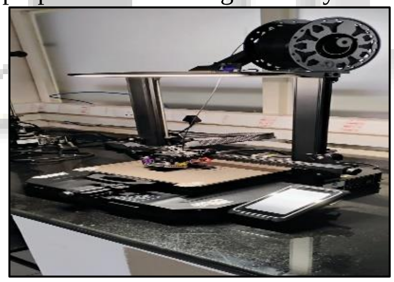


Fig. 4: Making AFO Using FDM Method

Fig. 5: Articulated Foot Orthosis (AFO)

Post-fabrication, the AFO undergoes functional testing to validate its performance in improving gait symmetry, ankle dorsiflexion, and foot clearance. The entire process emphasizes patient-centric design, leveraging advanced technologies to create a lightweight, durable, and effective orthotic solution for individuals with foot drop.

VI. CONCLUSION:

This research successfully designed, fabricated, and analyzed an articulated foot orthosis (AFO) to address the functional limitations associated with foot drop. The integration of CAD, 3D printing, and FEA facilitated the development of a patient-centric AFO with optimized design and performance. Finite element analysis, utilizing PLA as the primary material, revealed acceptable levels of total deformation and equivalent stress under simulated gait loading conditions. This analysis provided valuable insights into the structural integrity and stress distribution within the AFO, guiding design modifications for improved strength and weight minimization. The fabricated AFO demonstrated significant improvements in ankle dorsiflexion, foot clearance, and overall gait symmetry during gait analysis testing. These findings highlight the effectiveness of the AFO in addressing the challenges faced by individuals with foot drop and improving their quality of life. This research contributes to the advancement of AFO design and fabrication methodologies, paving the way for more personalized and effective solutions for individuals with neurological and musculoskeletal impairments.

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