Development of 3D printable Biomechanical Prosthetic Hand

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Abstract

This research adopts an integrated approach to selecting and evaluating materials for a prosthetic hand, employing advanced simulation technologies and multi-criteria decision-making techniques. Utilising the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the study identified Nylon as the most suitable material due to its excellent flexibility and high-stress resistance, featuring a safety factor that outperforms other considered materials like ABS, PC, and PET. Subsequent static structural analyses conducted in ANSYS scrutinised each candidate material for stress distribution, deformation under operational loads, and overall safety. The analysis demonstrated that Nylon could handle a maximum von Mises stress of 61.312 MPa, with minimal deformation of 0.11241 mm, ensuring a safety margin with factors ranging from 4.0775 to 15. These results corroborate the TOPSIS outcomes and underscore Nylon's superior characteristics, endorsing its use in high-performance prosthetic hands. The research concludes that with additional refinement and practical evaluation, Nylon could significantly improve prosthetic hand functionality and user satisfaction, making it a promising candidate for advanced prosthetic technologies.

Keywords: Prosthetic Hand Materials, Nylon Prosthesis, TOPSIS Methodology, Structural Simulation, High-Performance Biomechanics

I. INTRODUCTION

The development of wrist prostheses encompasses a multifaceted approach, integrating functional, aesthetic, and ergonomic considerations that profoundly influence user satisfaction and daily usability. Key elements in this domain include the replication of natural wrist movements crucial for daily activities, ranging from simple tasks like tying shoelaces to complex actions such as driving. Achieving this functionality requires robust materials and joint mechanisms capable of enduring daily wear while providing smooth and responsive movements, closely mimicking human biomechanics.

Comfort in wrist prostheses extends beyond physical fit to encompass how the device interacts during activities and accommodates changes in residual limb dynamics. Factors like weight distribution, strap placement, and padding contribute to overall comfort. Advanced materials like silicone and thermoplastics are utilized in socket construction to balance flexibility and support, while ergonomic principles ensure natural alignment with user movements, minimizing discomfort during prolonged use.

Parametric design, facilitated by computer-aided design (CAD) tools, plays a pivotal role in tailoring prostheses to individual specifications. This approach allows adjustments in size, shape, and mechanical properties based on detailed residual limb measurements and functional requirements. Rapid prototyping and iterative testing enabled by parametric design enhance the development of prosthetic solutions that fit optimally and function effectively, promoting innovation and user-centric design in this critical field.

Annanto et al. (Annanto et al., 2019) investigated the dependability of a custom-designed prosthetic hand tailored for the Indonesian population, focusing on stress analysis under a hook load. Their study aimed to address upper limb disabilities by ensuring the hand's safety and suitability through numerical assessment. Results indicated safe stress levels with adequate safety margins, affirming the hand's appropriateness for performing hook postures. However, the study's narrow focus on stress analysis suggests potential overlook of broader functional aspects crucial for prosthetic hand design.

Gislason et al. (Gislason et al., 2017) utilized finite element modeling to analyze load transfer properties in total wrist arthroplasty with the Universal 2 implant. Their study highlighted stress distribution across the wrist joint, emphasizing the importance of the ulnar side for stability. Despite valuable insights into mechanical dynamics, the model's limitations, such as omitting ligamentous structures, underscore the need for comprehensive research on wrist kinematics and load distribution under varied functional conditions.

Srivastava et al. (Srivastava et al., 2021) employed topology optimization and finite element analysis (FEA) to enhance the design of prosthetic fingers for improved functionality and flexibility. Their findings favored a rectangular primitive design for its simplicity and mechanical robustness, achieving finger-like compliance critical for precise control. While successful in optimizing weight and functionality, the study focused predominantly on mechanical aspects, necessitating further exploration into other crucial design elements.

Bastarrechea et al. (Bastarrechea et al., 2021) explored the mechanical design of affordable hand prosthetics using FEA to enhance biomechanics and functionality. Their research emphasized material selection and stress distribution analysis, crucial for achieving mechanical strength and manufacturability. However, the study's exclusive concentration on mechanical parameters highlights the need for integration of actuation mechanisms and durability considerations in future designs.

Shanmugasunda et al. (Shanmugasundar et al., 2020) developed a wireless gesture-controlled prosthetic hand with extensive degrees of freedom, assessed via FEA for safety under typical loading conditions. Their study demonstrated the hand's capability to withstand daily activities' forces, albeit focusing primarily on stress and deformation analysis. Future research should prioritize user testing and real-world validation to ensure practical usability and intuitive functionality.

Wattanasiri et al. (Wattanasiri et al., 2018) addressed the challenge of designing a five-fingered prosthetic hand capable of diverse grip patterns using a single actuator. Their study achieved significant grasping force and versatility but noted constraints related to weight and size due to component limitations. This underscores the ongoing need for enhancing mechanism rigidity to optimize overall design efficiency.

Light and Chappel (Light and Chappel, 2000) developed a multi-axis prosthesis to overcome limitations of existing designs, focusing on stability and sensory feedback. Their study emphasized CAE tools for modeling linkage dynamics, revealing efficiencies in functional grasping patterns but also identified drawbacks such as increased power consumption under maximum grip pressure. Further advancements in prosthesis design are crucial to balance functionality and energy efficiency.

Romero et al. (Romero et al., 2020) utilized additive manufacturing for developing affordable hand prostheses, integrating precise dimension validation and mechanical behavior analysis through FEA simulations. Their findings supported the prosthesis's mechanical strength and fit but highlighted the necessity for extensive real-world testing to validate functional performance across various user scenarios.

Cosenza et al. (Cosenza et al., 2018) explored the dynamic behavior of a prosthetic hand's mechanical design using a multibody model, focusing on optimizing antagonist tendon systems to enhance grasping capabilities. Their study underscored the importance of mimicking human hand biomechanics to achieve functional improvements in prosthetic designs.

Alkhatib et al. (Alkhatib et al., 2019) innovated flexible joint designs for 3D printed prosthetic hands to replicate natural human hand positions effectively. Their study highlighted resilience and usability improvements but noted limitations in full opening capabilities compared to traditional designs, suggesting avenues for further enhancement in usability and functionality.

Despite the significant strides in prosthetic technology, persistent challenges remain in the field's development. A critical issue is the unequal availability of economically viable high-performance prosthetics, which many patients cannot afford. The substantial costs associated with advanced prosthetic technologies create barriers to access for a substantial portion of the population in need. Moreover, current prosthetic designs often do not adequately meet individual requirements due to their standardized nature. This discrepancy highlights the necessity for personalized solutions that can better align with users' diverse lifestyles and environmental conditions. For example, variations in climate and daily activities can affect the functionality and longevity of prosthetic limbs, necessitating more adaptable designs. This research aims to enhance the accessibility and functionality of prosthetic hands by addressing economic limitations and tailoring solutions to meet specific user needs. By employing innovative analysis and manufacturing approaches, this study seeks to bridge the gap between sophisticated engineering advancements and practical usability in prosthetics.

II. METHDOLOGY

Figure 1. Prothesis CAD model

To create a wrist prosthesis in SolidWorks, the process requires meticulous attention to both anatomical accuracy and mechanical functionality, utilizing various CAD techniques. This detailed guide outlines the steps involved, using standard wrist measurements as a reference, to ensure the final design is both precise and functional.

Begin by launching a new document in SolidWorks: navigate to File > New > Part and set the unit system to MMGS (Millimeter, Gram, Second) to ensure precision and standardization. Establish your design environment by selecting the front plane from the Sketch tab as your primary sketching plane. Using the Line command along with the Centerline tool, draw a central line that intersects the origin, which will act as a symmetrical axis to ensure uniformity and balance of the components around it.

Next, create the basic shape of the prosthesis by utilizing the Circle tool to draft the outer perimeter. Given the average wrist diameter of approximately 55 mm, start with this dimension for the initial circle. Include inner circles to delineate distinct structural elements such as the enclosure for the joint mechanism. Transition this 2D sketch to a 3D model by selecting the Extrude Boss/Base tool from the Features tab, extruding the sketch to a length representative of the typical connection from the wrist to the hand, forming the primary cylindrical body of the prosthesis.

To add detailed features such as tendon attachment points and rotational joints, return to the Sketch tab. Use tools like Offset or Convert Entities to define paths and placements, and the Circular Sketch Pattern tool to evenly distribute features like screw holes or connector points around the main extruded cylinder. Design articulations and joints by using the Extruded Cut feature to create spaces for movable joints, ensuring these cuts provide the necessary range of motion for flexion, extension, radial, and ulnar deviations. Sketch the profiles of interlocking parts and use the Revolve or Sweep features to generate the complex shapes required for joint articulation.

For the assembly phase, open a new assembly file by going to File > New > Assembly. Incorporate the previously designed components into the assembly workspace, using the Mate tool to align and connect parts such as the main body, joint mechanisms, and attachment interfaces. Ensure that all parts move correctly relative to each other to simulate natural wrist movements. Use the Interference Detection tool located in the Evaluate tab to identify any interferences or misalignments, adjusting sketches or features as needed to resolve any issues. Add fillets and chamfers to edges where necessary to reduce stress points and enhance the visual appeal of the design.

Finally, select appropriate materials for each part based on their intended function and required characteristics, ensuring that the prosthesis is both durable and functional. This comprehensive approach in SolidWorks ensures that each section of the wrist prosthesis is meticulously designed and assembled, resulting in a high-quality, functional prosthetic device.

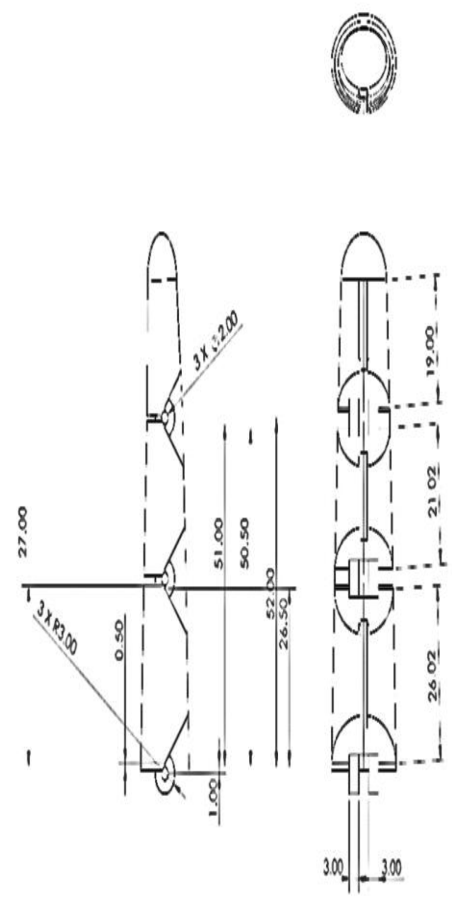


Figure 2. Index and ring finger dimensions (in mm.)

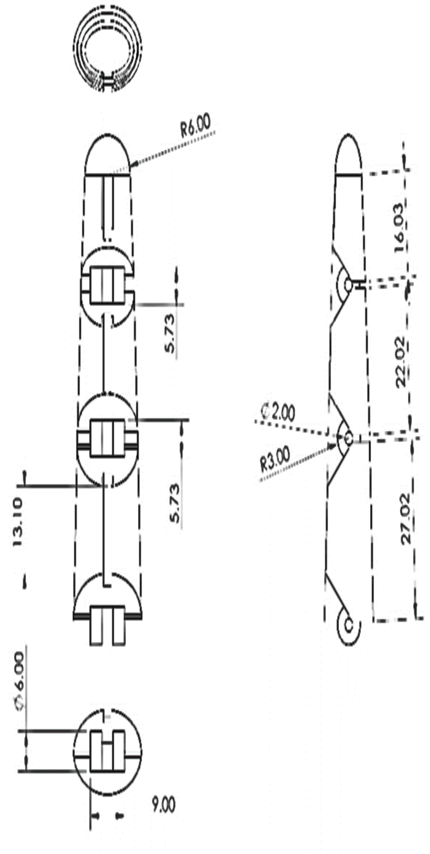


Figure 3. Little finger dimensions (in mm.)

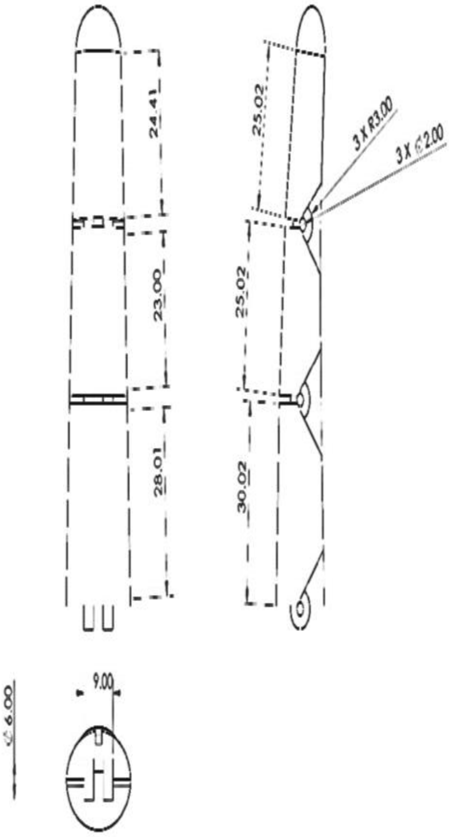


Figure 4. Middle finger dimensions (in mm.)

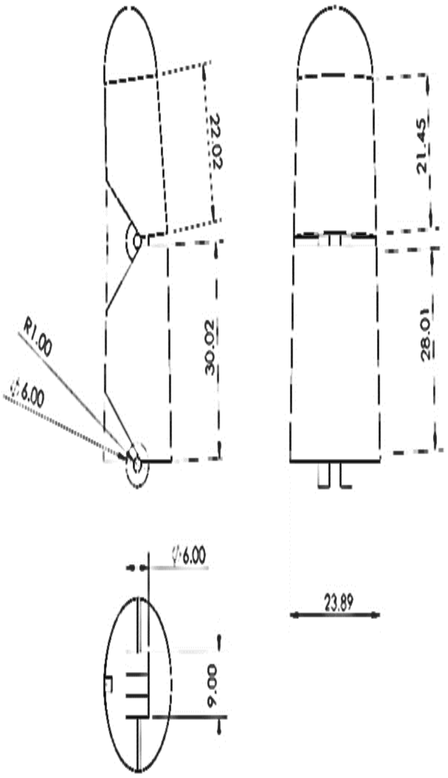


Figure 5. Thumb finger dimensions (in mm.)

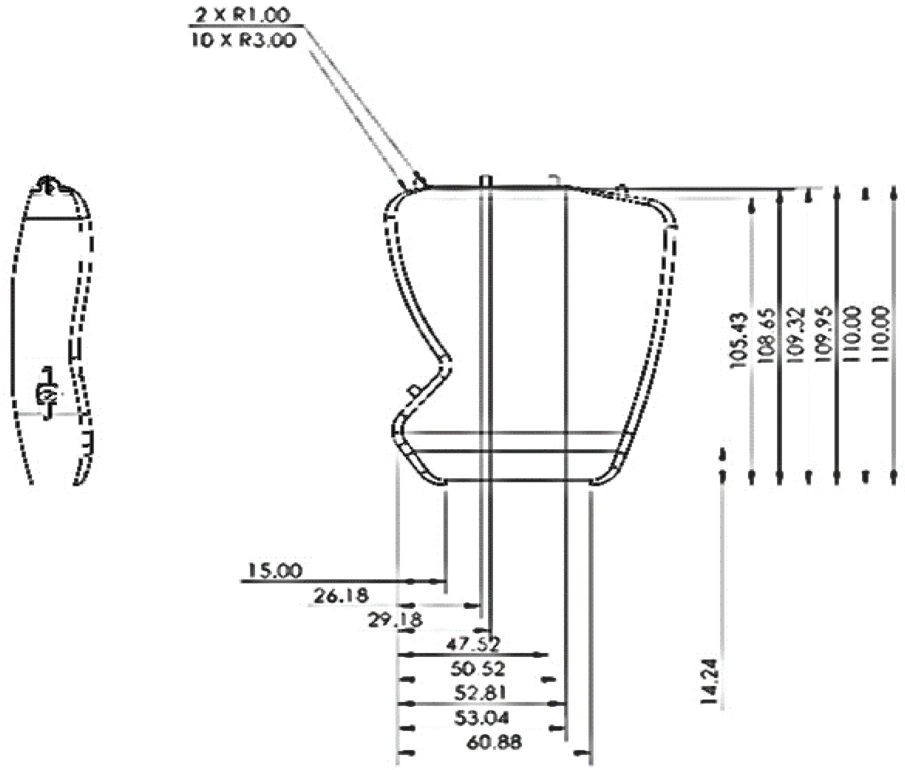


Figure 6. Thumb finger dimensions (in mm.)

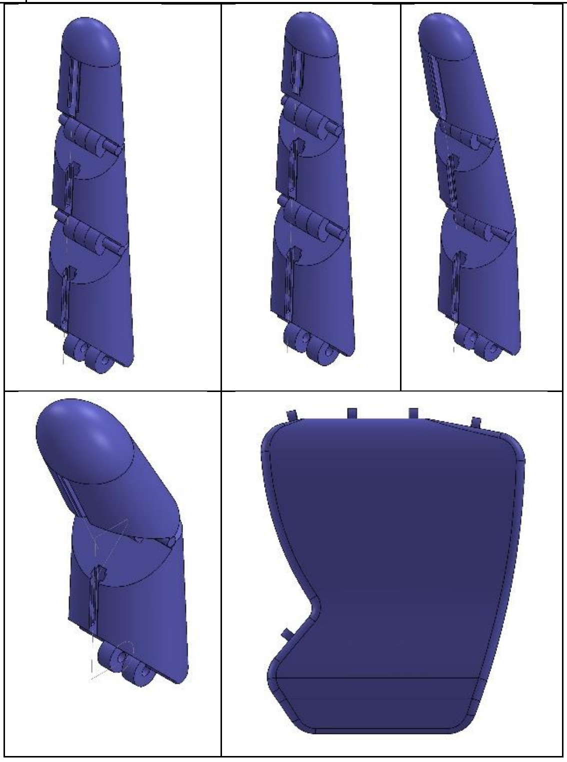


Figure 7. Isometric views of: (a) index and ring, (b) little, (c) middle, (d) thumb, and (e) palm

Finite Element Analysis (FEA) stands as a cornerstone in engineering design and analysis, offering detailed evaluations of complex systems under diverse conditions. This computational approach forecasts the reaction of objects to physical forces like heat, vibration, fluid flow, and other effects. By fragmenting a physical entity into a mesh of elements and nodes, FEA models and calculates the intricate behaviors of these elements through mathematical equations that represent the involved physical phenomena. The provided diagram outlines the Finite Element Method (FEM) procedure, detailing steps from defining geometry to analyzing results.

The process initiates with the precise definition of the object's geometry, typically using CAD software to establish its physical dimensions and shape. This step's accuracy is critical, as a precise geometric model ensures that the FEA results closely mirror the object's real-world behavior. Following this, the geometry is divided into elements and nodes through meshing. Each element, representing a manageable portion of the object, is described using mathematical equations. The mesh's quality and density significantly influence the analysis's accuracy and computational demands, with finer meshes generally yielding more precise results but requiring more computational power and time.

Assigning appropriate material properties to the mesh elements is crucial for realistic simulation results. These properties, which may include density, elasticity, and thermal conductivity, depend on the analysis type. Constraints must also be applied to replicate the real-world conditions under which the object operates. These constraints, such as fixed supports, symmetries, or predefined movements, ensure the model behaves similarly to the actual system.

Next, external forces or loads are applied to the model. These loads can encompass various forces such as pressure, temperature, force, or torque, reflecting the operational conditions the object might experience. The manner of load application is vital, as it affects how stresses and strains are distributed and calculated within the model, making this step critical for obtaining meaningful data about the object's behavior under operational stresses.

Once the model setup is complete, including geometry, mesh, material properties, constraints, and loads, an appropriate solver is selected and configured. The solver, a computational algorithm, interprets and calculates the finite element model, converting theoretical models into practical insights. Solver selection varies based on model complexity, analysis type, and required precision.

The analysis execution follows, where the solver computes each element's responses under the applied loads. This process generates data on displacements, stresses, forces, and strains, which are key indicators of the object's behavior. Solver outputs are typically presented as contour plots showing stress distribution, X-Y plots for component behaviors, and detailed numerical results listings.

The final FEA step is to validate and, if necessary, optimize the results. Validation involves comparing FEA outcomes against expected results or experimental data to ensure accuracy. Discrepancies may require adjustments in the model, mesh quality, material properties, or load applications. Optimization might involve refining the design based on FEA results to enhance performance, reduce material usage, or mitigate high-stress concentrations.

FEA is indispensable in modern engineering, enabling detailed study and optimization of complex systems under various physical conditions. By accurately defining geometry, creating a high-quality mesh, assigning suitable material properties, applying realistic constraints and loads, and using an appropriate solver, engineers can predict and enhance their designs' performance and reliability. This method not only ensures the structural integrity and functionality of components but also aids in improving efficiency and reducing costs in engineering projects.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), introduced by Hwang and Yoon in the 1980s, is a critical method in multi-criteria decision-making (MCDM). TOPSIS works on the principle that the optimal choice should be as close as possible to the positive ideal solution (PIS) and as far as possible from the negative ideal solution (NIS). The method's implementation involves several systematic steps that ensure thorough and reliable decision-making.

To begin with, a decision matrix is constructed to outline the alternatives and criteria. Each element in this matrix represents how well an alternative performs relative to a specific criterion, with rows representing alternatives (A1, A2, ..., An) and columns representing criteria (C1, C2, ..., Cm). These values are obtained through direct observations, measurements, or evaluations.

Normalization of the decision matrix is the next critical step since criteria might be measured in different units. Normalizing transforms these various criteria into a non-dimensional scale, facilitating direct comparison. Vector normalization is commonly used, where each criterion value is divided by the Euclidean norm of its respective column, resulting in a matrix with unit norms for each column.

Once the matrix is normalized, weights reflecting the importance of each criterion are assigned. These weights can be determined through expert judgment or quantitative methods like the Analytic Hierarchy Process (AHP). Each normalized value is then multiplied by the corresponding criterion weight, yielding the weighted normalized values.

Identifying the positive ideal solution (PIS) and the negative ideal solution (NIS) follows. The PIS comprises the best values for each criterion among all alternatives, while the NIS consists of the worst values. For benefit criteria, the PIS is the maximum value and the NIS is the minimum; for cost criteria, the reverse is true. These solutions set benchmarks for the best and worst performances for each criterion.

Next, the distances from each alternative to the PIS (Di+) and the NIS (Di-) are calculated using the Euclidean distance metric. This step provides a quantitative measure of how close each alternative is to both ideal solutions. Following this, the relative closeness to the ideal solution is determined. This measure, known as the similarity to the ideal solution, is calculated as the ratio of the distance from the NIS to the sum of the distances from both the PIS and the NIS:

$$C_i = (D_i^-)/(D_i^+ + D_i^-)$$

This ratio ranges from 0 to 1, with values closer to 1 indicating proximity to the ideal solution.

Finally, the alternatives are ranked based on their similarity coefficients (Ci), with the highest Ci value denoting the most favorable option, closest to the ideal solution and farthest from the least favorable one. Additionally, conducting a sensitivity analysis is crucial to observe how variations in the criteria weights impact the final rankings. This step addresses potential biases or uncertainties in the initial weight allocation.

TOPSIS offers a structured framework for handling complex decision-making scenarios with multiple criteria. By evaluating the distance to the ideal solutions, decision-makers can objectively assess various options and make informed decisions. This comprehensive procedural framework ensures clarity and efficiency, enabling professionals to navigate multiple criteria evaluations effectively and arrive at the most favorable decision. Consequently, TOPSIS remains a vital tool in decision science methodologies, providing a robust approach to multi-criteria decision-making.

III. RESULTS AND DISCUSSIONS

The results of static structural simulations for four materials—ABS, Nylon, PC (Polycarbonate), and PET (Polyethylene terephthalate)—are presented in Table 1. These materials were evaluated based on mass, elastic strain, safety factor, and total deformation. The data highlights significant differences in material behavior under stress, essential for selecting the most suitable material for specific applications.

ABS shows the lowest elastic strain (0.20992 mm/mm), indicating minimal deformation relative to its original dimensions under load. However, its safety factor is the lowest (0.080308), implying a higher risk of failure under the given conditions. The total deformation of ABS is 46.741 mm, demonstrating considerable flexibility but lower strength.

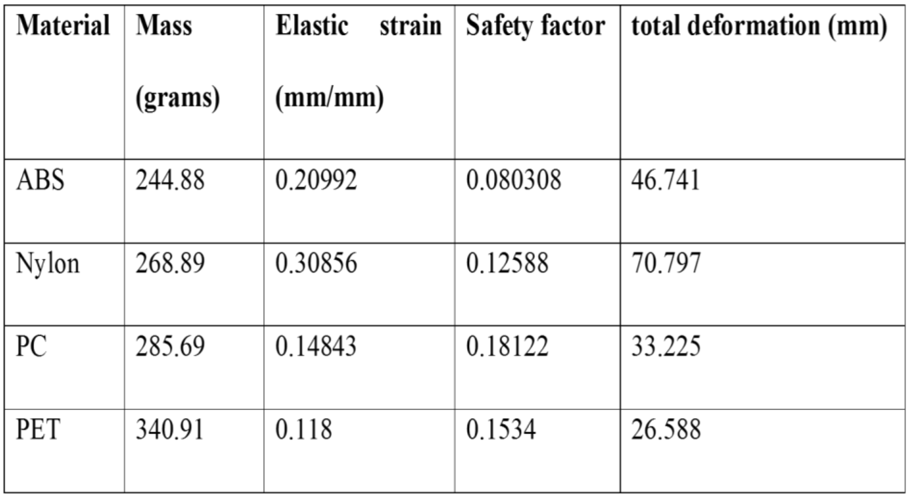
Nylon, in contrast, displays the highest elastic strain (0.30856 mm/mm) and a moderate safety factor (0.12588), suggesting it can endure greater deformation before failure. This characteristic makes Nylon suitable for applications requiring high flexibility and moderate load-bearing capacity. Its total deformation measures 70.797 mm, underscoring significant ductility.

PC strikes a balance between flexibility and strength, with an elastic strain of 0.14843 mm/mm and the highest safety factor among the tested materials (0.18122). This property makes PC an excellent choice for applications demanding robustness without substantial compromise on flexibility. The total deformation of PC is lower at 33.225 mm, reflecting its strength and resistance to deformation.

PET exhibits the lowest total deformation (26.588 mm) and a moderate safety factor (0.1534), alongside a relatively low strain (0.118 mm/mm). These attributes indicate high material strength and stiffness. PET is ideal for applications where minimal deformation is crucial, such as load-bearing structures requiring dimensional stability.

Each material's unique properties—ABS's minimal strain but low safety, Nylon's high ductility and moderate safety, PC's balanced strength and flexibility, and PET's minimal deformation and high stiffness—make them suitable for different engineering applications. The choice of material should consider the specific requirements of the application, balancing factors like flexibility, strength, and risk of failure under load..

Table 1. Simulation results



Material	Mass (grams)	Elastic strain (mm/mm)	Safety factor	total deformation (mm)
ABS	244.88	0.20992	0.080308	46.741
Nylon	268.89	0.30856	0.12588	70.797
PC	285.69	0.14843	0.18122	33.225
PET	340.91	0.118	0.1534	26.588

When evaluating materials for prosthetic arm applications, it is essential to adopt a systematic and comprehensive approach to ensure that the selected material meets the required performance standards. Multi-criterion decision-making (MCDM) methods, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), are particularly useful in this context. TOPSIS evaluates different options based on a set of criteria, determining how closely each option aligns with the ideal solution and how far it deviates from the worst-case scenario. This method provides a structured and quantitative way to select the most suitable material based on predefined criteria: Mass, Elastic Strain, and Safety Factor.

Mass is a critical factor in prosthetic design as it influences user comfort and energy expenditure. A lower mass is preferred to minimize the physical strain on the user. Elastic Strain measures a material's ability to deform under stress, which is crucial for the durability and flexibility of the prosthetic. Higher values of elastic strain indicate better performance under load. The Safety Factor reflects a material's capacity to withstand unexpected loads without failing; thus, higher safety factors are desirable to ensure reliability and safety.

Using Python's Pandas and NumPy libraries for data manipulation and numerical operations, the TOPSIS method was employed to evaluate four materials: ABS, Nylon, PC, and PET. Each material was assessed based on the normalized values of the three criteria. Normalization is crucial to ensure that all units are comparable and to neutralize the influence of scale and units on the decision-making process.

The evaluation process begins with normalizing the criteria using the Euclidean norm. Normalization ensures that each criterion contributes equally to the overall decision, preventing any single criterion from disproportionately affecting the results due to differences in magnitude or units.

After normalization, equal weights were assigned to each criterion. This approach reflects a scenario where design priorities are balanced. However, in practical applications, these weights can be adjusted to prioritize specific features according to particular needs.

The next step in TOPSIS involves identifying the ideal (best) and negative-ideal (worst) solutions based on the weighted criteria. The ideal solution has the highest values for beneficial criteria (Elastic Strain and Safety Factor) and the lowest value for cost criteria (Mass). Conversely, the negative-ideal solution is characterized by the lowest values for beneficial criteria and the highest for cost criteria.

Table 2. TOPSIS ranking

Material	Weighted_Mass	Weighted_Elastic_strain	Weighted_Safety_factor	S_pos	S_neg	Closeness	Rank
ABS	0.142071	0.167158	0.095442	0.153807	0.073195	0.322444	4
Nylon	0.156001	0.245704	0.149602	0.077919	0.161719	0.674846	1
PC	0.165747	0.118194	0.215371	0.131473	0.124622	0.486624	2
PET	0.197784	0.093963	0.182308	0.155302	0.103197	0.399218	3

The distances from each material to these ideal and negative-ideal solutions are then calculated. These distances provide a measure of how close or far each material is from the ideal state. These distances are subsequently used to calculate the closeness coefficient, which is a ratio indicating the relative proximity of each material to the ideal solution.

Based on the calculated data, Nylon emerged as the top-ranked material. Nylon displayed the highest closeness to the ideal solution, primarily due to its superior elastic strain and safety factor. This suggests that Nylon is potentially the most suitable material for applications requiring high flexibility and reliability.

PET ranked second, followed by PC and ABS. PET's balance between mass, strain, and safety makes it a strong candidate, particularly where a slightly higher mass is acceptable for greater reliability. PC and ABS showed lower closeness to the ideal solution, indicating that while they may be suitable for less demanding applications, they are less optimal for a prosthetic arm requiring a high balance of all three evaluated criteria. The TOPSIS method provides a thorough and objective approach to evaluating materials for prosthetic arm applications. By considering multiple criteria and normalizing their values, it ensures a balanced assessment that can guide material selection effectively. The results highlight the importance of considering all relevant factors, such as mass, elastic strain, and safety factor, to identify the most suitable material for the specific requirements of prosthetic design.

The analysis revealed that the angular velocities of joints J2 and J3 increased as the finger flexed further, indicating a higher rate of angular change over time. The graphs effectively depicted the synchronized movement between these joints. Additionally, the trajectory of the fingertip's position was charted, displaying a continuous decrease in the y-axis. This downward trend represents the bending motion of the finger, providing insights into the finger's range of motion and the mechanical constraints imposed by the joint connections. The visualization aids in comprehending the coordinated mechanics and limitations of finger movements.

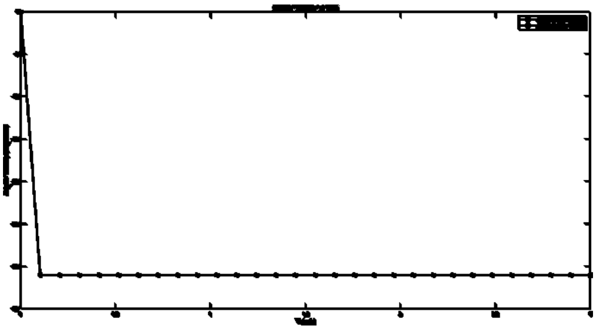


Figure 8. Angular velocity vs time graph

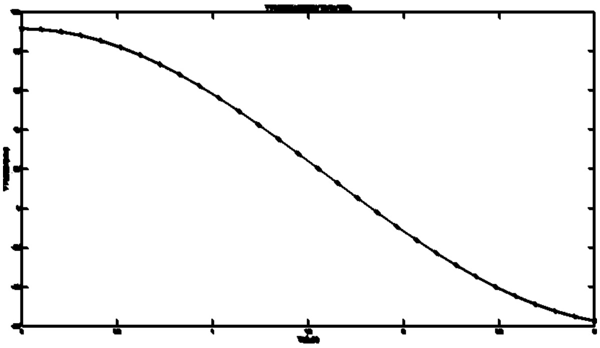


Figure 9. Fingertip trajectory plot

The performance and durability of prosthetic devices under operational conditions were evaluated using ANSYS 3D Static Structural simulations. These simulations assessed characteristics such as elastic strain, stress, safety factor, and total deformation when subjected to a standardized gripping force. The results highlighted variations in material behavior, which is crucial for determining the suitability of specific materials for different applications. For instance, ABS exhibited significant flexibility with an elastic strain of 0.20992 mm/mm but had a low safety factor of 0.080308, indicating a potential risk of failure under high stress conditions. In contrast, PC demonstrated a balanced combination of flexibility and strength, with a moderate elastic strain of 0.14843 mm/mm and the highest safety factor of 0.18122. PET, known for its stiffness and minimal deformation, emerged as a promising option for structural applications requiring high dimensional stability.

Material selection was refined using the TOPSIS method, which integrates multiple criteria such as mass, elastic strain, and safety factor. This analysis prioritized materials based on their proximity to an ideal solution that maximizes desirable properties while minimizing undesirable ones. The TOPSIS results identified Nylon as the top material due to its superior elastic strain and safety factor, indicating its suitability for applications requiring high flexibility and resilience under load. PET ranked second, demonstrating balanced properties, while PC and ABS were deemed less optimal due to their respective limitations in flexibility and safety under stress.

Additional insights into the biomechanical capabilities of the prosthetic fingers were obtained through dynamic analyses in MATLAB, focusing on angular velocities and trajectories during simulated motion. This analysis provided valuable information about the mechanical performance of the joints and the effective range of motion achievable with the prosthetic design. Data on angular velocities and positional trajectories are essential for improving joint mechanics and ensuring that the prosthetic hand can effectively replicate natural finger movements.

A cost analysis provided a practical view of the financial implications of manufacturing the prosthetic hand from different materials. PET emerged as the most cost-effective material, closely followed by ABS and Nylon, with PC being slightly more expensive due to higher raw material costs. This financial assessment underscored the importance of balancing economic and performance factors in prosthetic design to improve accessibility and utility for end-users.

Each material has unique advantages and limitations, making them suitable for different aspects of prosthetic design. ABS and Nylon offer flexibility and ease of processing at a lower cost, but they may not provide the necessary durability for long-term use under varying load conditions. PC and PET, despite being more expensive, offer better safety factors and reduced deformation, which are desirable for prosthetics exposed to continuous or high-stress use.

Integrating simulation results, TOPSIS analysis, dynamic motion studies, and cost analysis offers a comprehensive approach to material selection for prosthetic hands. The optimal material choice depends on specific application needs, considering cost, functionality, and user-specific requirements. Nylon and PET stand out based on the combined criteria, but the final selection should involve additional user feedback and testing under real-world conditions to ensure that the prosthetic hand meets all expected performance and durability standards. The synthesis of these evaluation methods provides a robust framework for making informed decisions in the development of high-performance, cost-effective prosthetic devices.

Moreover, considering the diverse needs and preferences of prosthetic users, further refinement and customization of materials and design are essential. User-specific testing and iterative design processes will ensure that the prosthetic hands not only meet technical specifications but also provide the comfort, functionality, and reliability required for everyday use. Emphasizing user-centric design principles and incorporating feedback from actual users can lead to significant improvements in the overall effectiveness and satisfaction of prosthetic devices.

This holistic approach to material selection and prosthetic design highlights the intricate balance between mechanical performance, cost-efficiency, and user-centric considerations, ultimately leading to more advanced and accessible prosthetic solutions. The integration of advanced simulation tools, multi-criteria decision-making methods, and dynamic biomechanical analysis underscores the importance of interdisciplinary collaboration in developing next-generation prosthetic devices that can significantly enhance the quality of life for individuals requiring such assistive technologies.

III. CONCLUSIONS

This research aimed to evaluate the effectiveness of various materials for constructing a prosthetic hand, utilizing advanced simulation and analytical methods. The study covered multiple stages, beginning with material selection and progressing through dynamic analysis and cost assessment, ensuring a thorough evaluation of each material's suitability under real-world conditions.

Initially, the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method was employed to select materials. This method provided a measurable framework for comparing materials based on criteria such as mass, elastic strain, and safety factor. Through this rigorous selection process, Nylon emerged as the most suitable material due to its exceptional flexibility and stress endurance, highlighting its potential to enhance prosthetic functionality.

Subsequent stages involved simulations using ANSYS 3D Static Structural settings to evaluate the performance of the materials under simulated operational stresses. These simulations were crucial for understanding the behavior of each material in terms of stress distribution, deformation, and safety under typical usage scenarios. The findings from these simulations were essential for validating the initial material selection made by the TOPSIS method, thereby providing a second layer of confirmation.

Key conclusions drawn from the ANSYS simulations included the following aspects:

- **Von Mises Stress**: Stress levels across the materials generally remained within safe operational limits. However, specific areas exhibited higher stress concentrations, which could potentially lead to material failure under extreme conditions. This insight was vital for identifying areas that might require reinforcement or design modifications to enhance the prosthetic hand's overall durability.

- **Total Deformation**: The materials demonstrated varying levels of deformation when subjected to operational stresses. Nylon, in particular, exhibited significant flexibility under load. This characteristic is particularly advantageous in prosthetic applications that demand both durability and adaptability. The ability of Nylon to endure substantial deformation without compromising structural integrity underscores its suitability for prosthetic hand construction.

- **Safety Factor**: The evaluated materials displayed safety factors well above acceptable limits, affirming their ability to withstand anticipated loads without failure. This aspect was critical for ensuring that the prosthetic hand would perform reliably and safely under various operational conditions. The high safety factors observed in the simulations reinforced the confidence in the selected materials, particularly Nylon, for their robustness and reliability.

The integration of these simulation results provided a comprehensive understanding of the mechanical behavior of each material. This understanding was instrumental in guiding the final recommendations for constructing the prosthetic hand. The combination of the TOPSIS method and ANSYS simulations ensured a robust selection process, considering both theoretical and practical aspects of material performance.

Additionally, the study incorporated a cost assessment to ensure that the recommended materials were not only effective but also economically viable for widespread use. The cost assessment considered factors such as raw material costs, manufacturing expenses, and potential maintenance costs over the prosthetic hand's lifespan. This holistic approach ensured that the final recommendations were not only based on mechanical performance but also on economic feasibility, making the prosthetic hand accessible to a broader population.

The research emphasized the importance of selecting materials that balance mechanical properties, safety, and cost-effectiveness. Nylon's exceptional performance across all evaluated criteria underscored its potential to revolutionize prosthetic hand construction. By providing a material that offers flexibility, durability, and affordability, the study aimed to enhance the quality of life for individuals requiring prosthetic hands.

In conclusion, the extensive research conducted to assess different materials for prosthetic hand construction employed a comprehensive approach involving material selection, dynamic analysis, and cost assessment. The TOPSIS method identified Nylon as the most suitable material, while ANSYS simulations validated this selection by confirming Nylon's superior mechanical performance. The integration of these methods ensured a robust evaluation process, resulting in a well-rounded recommendation for using Nylon in prosthetic hand construction. This study's findings have the potential to significantly improve prosthetic hand functionality, offering a durable, flexible, and cost-effective solution for users.

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