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Original Research

Rehabilitative Knee Brace for Anterior Cruciate Ligament Patient

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ABSTRACT

Anterior cruciate ligament (ACL) injuries are prevalent among athletes and commonly require surgical reconstruction followed by extensive rehabilitation. Knee braces serve as a critical support system in enhancing stability, reducing strain, and facilitating functional recovery post-surgery. However, traditional braces often suffer from discomfort and suboptimal stress distribution. This study presents a novel three- dimensional (3D) knee brace design aimed at improving mechanical performance and patient comfort. The design incorporated variations in hole geometry and lower brace height. Finite Element Analysis (FEA) was employed to evaluate the von Mises stress and displacement under bending and compression loads. Results indicated that a circular hole design combined with a 12 cm lower brace height minimized stress concentrations and optimized load support. These findings demonstrate the potential of design modifications in enhancing the effectiveness of rehabilitative knee braces for ACL injury recovery.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most common and severe sports-related injuries, with an estimated 150,000 to 200,000 cases occurring annually in the United States alone. ACL injuries predominantly affect athletes participating in high-demand sports such as football, basketball, and soccer. Movements involving sudden stops, pivoting, or changes in direction place immense stress on the ACL, often leading to partial or complete ligament ruptures. Recovery typically involves surgical intervention, followed by extensive physiotherapy and rehabilitation.

Knee braces play a pivotal role in rehabilitation by providing mechanical support, promoting joint stability, and facilitating the healing process. Traditional braces, often fabricated using rigid materials such as fiberglass and plaster, are associated with discomfort, poor adaptability, and suboptimal mechanical performance. Recent advancements in material science and computer-aided design (CAD) technologies have enabled the development of custom-fit, lightweight, and structurally optimized braces. Nevertheless, many commercially available designs still lack patient-specific optimization and biomechanical efficiency. Therefore, the aim of this study is to fill this research gap by conducting a detailed evaluation of knee brace designs through finite element analysis, specifically focusing on parameters such as stress distribution, displacement, and structural enhancement. The findings of this study will contribute to the development of optimized knee brace designs and improve the understanding of their performance, leading to enhanced support and functionality for individuals with knee injuries or instability.

Despite the growing adoption of knee braces in rehabilitation protocols, current designs often fail to offer adequate comfort and optimized mechanical performance. Many designs overlook the importance of stress distribution and displacement control, leading to user discomfort, potential joint instability, and prolonged recovery times. There remains a significant gap in the development of a knee brace that not only meets mechanical demands but also enhances patient mobility and comfort during the recovery process

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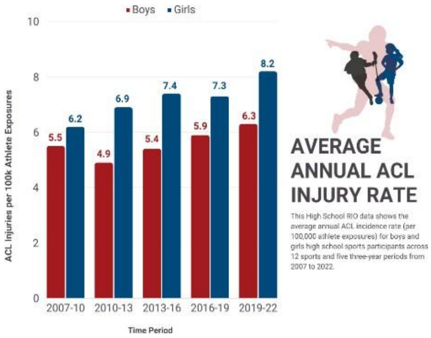

Fig. 1 The rate of ACL Injuries among youngster (Minjares, 2023).

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This research aims to enhance the structural design of a 3D-printed knee brace by investigating the influence of hole geometry and lower brace height on mechanical performance. The objectives are to design multiple variations of the knee brace, conduct Finite Element Analysis (FEA) to evaluate stress distribution and displacement, and determine the optimal design configuration that minimizes stress concentrations while improving load support.

ACL injuries account for a significant proportion of musculoskeletal injuries, especially among athletes involved in pivot-heavy sports. Rehabilitation strategies aim to restore mechanical function, reduce pain, and prevent long-term complications like osteoarthritis.

Conventional knee braces are commonly categorized into prophylactic, functional, and rehabilitative types. Functional braces aim to stabilize an injured knee, whereas rehabilitative braces restrict harmful motion post- surgery. Materials range from neoprene to aluminum alloys, yet many designs compromise between rigidity and comfort.

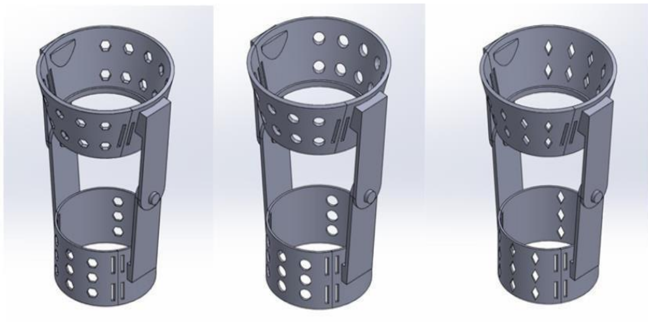
Recent advancements in additive manufacturing and finite element simulation have enabled patient-specific orthotic solutions. Studies demonstrate that 3D-printed braces can be tailored to distribute mechanical loads evenly, enhancing recovery outcomes.

Current literature often overlooks optimizing internal structural designs, such as hole geometries, and rarely analyzes variations in mechanical stability based on brace height adjustments. Existing knee orthosis designs for rehabilitation purposes have demonstrated a deficiency in providing personalized comfort to individuals with different knee injuries. This lack of customization often leads to discomfort, including symptoms such as aches, stiffness, irritation, and soreness (Rosenberg, 2019). Knee braces are commonly used in the management of various knee injuries and conditions to provide support, stability, and aid in the rehabilitation process. However, there is a lack of comprehensive evaluation of different knee brace designs using advanced computational methods. Finite element analysis offers a powerful tool to simulate and analyse the structural behaviour of knee braces under various loading conditions.

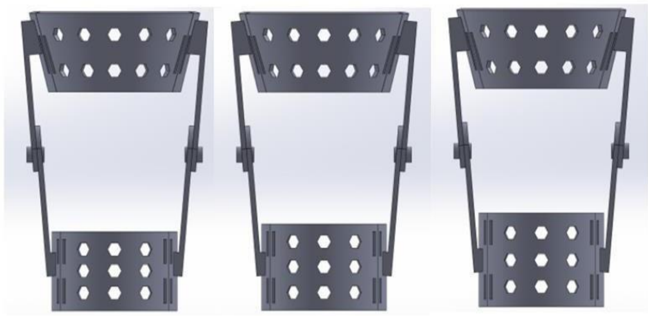
MATERIALS AND METHOD

Knee brace design

The knee brace was developed using SolidWorks software. The design consisted of two rigid shells, an upper and a lower part, interconnected through hinge mechanisms that allowed flexion movements while restricting undesirable rotational forces. The brace incorporated variations in internal hole geometries as shown in Fig. 2, specifically hexagonal, circular, and diamond shapes, to investigate their effects on structural optimization and mechanical performance.



(a)



(b)

Fig. 2 a) Different type of ventilation holes; b) Different length of the lower brace.

Material Selection

The material selected for the brace construction was Aluminum Alloy 7075, chosen for its superior strength- to-weight ratio and excellent corrosion-resistant properties. The mechanical properties used in the simulations included a Young's Modulus of 72,000 MPa, a Poisson's ratio of 0.33, and a density of 2810 kg/m³. These properties made Aluminum Alloy 7075 particularly suitable for lightweight orthopedic applications.

Finite Element Analysis (FEA) Setup

The finite element model was generated using SolidWorks Simulation software (Version 2023). SolidWorks Simulation provides an integrated environment combining computer-aided design and finite element analysis, making it highly efficient for rapid iterations. A Static Study module was used to evaluate the brace's structural performance under applied loads, as it is particularly suited for linear stress analysis.

Meshing was performed using second-order tetrahedral elements due to their higher accuracy when modeling complex curved geometries. An automatic meshing strategy was initially applied, followed by mesh refinement, resulting in an average element size of approximately 2 mm. Convergence was deemed achieved when variations in maximum stress values were less than 5% across refinements.

Boundary conditions were established with a fully fixed constraint at the femoral attachment, simulating a rigid fixation. Loads were applied on the tibial side: a posterior load for the 3-point bending simulation and a vertical compressive load for the compression test. The SolidWorks solver used direct sparse matrix solving techniques for computational efficiency. SolidWorks 2023 was selected because of its ease of use, its ability to simulate realistic mechanical loads, and its comprehensive meshing capabilities, which allowed accurate representation of small structural features critical to brace performance. The load values were set at 134 N for bending and 350 N for compression, with a support span of 300 mm used in the bending configuration.

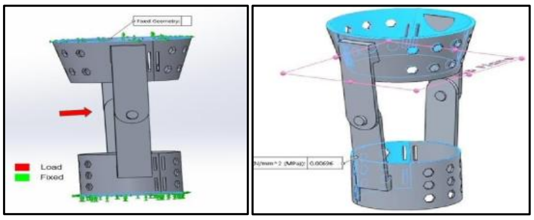
Mechanical Testing Procedures (3-Point Bending Test)

The 3-point bending test simulated anterior-posterior loading scenarios encountered during flexion and extension movements. A 134N load was applied centrally on the posterior aspect of the tibial brace shell. The test evaluated the brace's ability to resist bending forces and maintain structural integrity. Supports were positioned symmetrically, 300 mm apart, to replicate anatomical load distribution. Fig. 3 (a) shows the direction of forces applied.

Mechanical Testing Procedures (Compression Test)

The compression test simulated the effects of body weight on the knee brace during standing and walking activities. A compressive force equivalent to half of an average individual's body weight (multiplied by a factor of 10N for amplification) was applied vertically on the upper surface of the brace. This test assessed the structural stability and resistance to deformation under axial loading conditions.

Key outputs evaluated for both tests included maximum von Mises stress, total displacement, and stress distribution patterns. These metrics provided critical insight into the mechanical robustness and performance optimization of the knee brace designs. Fig. 3 (b) shows the direction of force applied.



(a) (b)

Fig. 3 (a) 3-Point Bending test (b) Compression Test

Validation Approach

To ensure reliability of the simulation outcomes, validation was performed by comparing simulation results with theoretical calculations based on classical mechanics. Additionally, simulation outputs were cross- checked against findings from previous literature on orthopedic brace mechanical performance. A maximum deviation of 10% between simulation and theoretical or reference values was considered acceptable.

Formula Used

The stress values are obtained from the Solidworks software. However, the basic pressure formula was used to calculate the pressure required for compression test.

$$Pressure = \frac{Force\ (N)}{Area\ (mm^2)}$$

RESULT AND DISCUSSION

Market Analysis

The orthopedic bracing market, particularly the knee brace segment, has experienced significant growth due to increasing incidences of sports injuries, aging populations, and a rising awareness of preventive care in musculoskeletal health. Current market offerings primarily focus on functional and rehabilitative knee braces, manufactured using traditional techniques and materials. However, challenges persist in balancing comfort, structural strength, and customization for patient-specific needs. Existing designs often fail to address load optimization, leading to discomfort and potential hindrance in patient mobility during rehabilitation. The trend towards lightweight, 3D-printed, and biomechanically optimized braces presents an opportunity to meet the evolving demands of patients and healthcare providers. The proposed design in this study targets these gaps by enhancing mechanical performance and user comfort.

3D Drawing

The knee brace design developed in SolidWorks incorporates two primary rigid shells connected through a hinge mechanism to facilitate flexion and controlled motion as shown in Fig. 4. The model includes variations in internal hole shapes such as hexagonal, circular, and diamond patterns. These design variations were generated to analyze their influence on stress distribution and load-carrying performance. The detailed 3D models formed the basis for subsequent finite element analysis and mechanical evaluation.

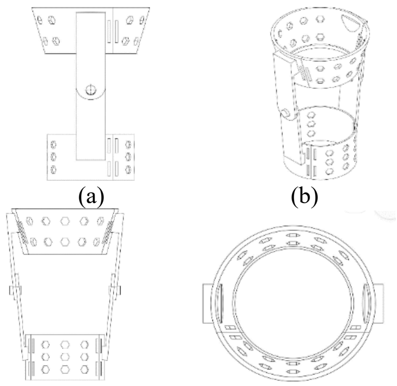


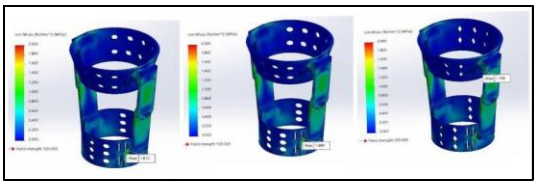
Fig. 4 (a) Side view (b) Isometric view (c) Front view (d) Top view

Study 1: The Analysis on the Shape of the Holes (3-Point Bending Test)

In the 3-point bending test, different hole geometries were evaluated to determine their influence on stress distribution and displacement as shown in Tab 1 and Fig. 5. The circular hole design showed the lowest maximum von Mises stress and achieved more uniform stress dispersion compared to hexagonal and diamond designs. The absence of sharp edges in the circular design minimized stress concentration, thereby enhancing the brace's durability under bending forces.

Tab. 1 Stress on knee braces

Shape of the holes	Maximum von Mises Stress (VMS) (MPa)
Design 1 (Hexagonal)	6.660
Design 2 (Circle)	6.625
Design 3 (Diamond)	6.789



(a) (b) (c)

Fig. 5 Stress on brace models (a) Hexagonal, (b) Circle, (c) Diamond

In the conducted 3-point bending test, it was observed that the highest stress (VMS) occurred at the connecting points of the side brace in the knee brace during bending. This phenomenon can be attributed to the design of the straight and rectangular hinge used to connect the upper and lower braces. The purpose of this hinge is to prevent hyperextension and allow a rotation range of 0° to 135°, aligning with the axis of rotation of the knee joint (Pouwels, 2016). This alignment ensures that the ligaments and muscles maintain their appropriate length patterns and helps avoid external stresses.

However, during the bending of the knee brace, tension is generated at the hinges. This tension may be a result of the hinges not being aligned precisely with the axis of rotation of the knee joint. Therefore, stress concentration occurs at the end of the brace hinges. The maximum stress distribution of the knee brace after applying pressure is summarized in Table 1. Among the designs, design 2 with circle holes exhibited the highest maximum stress value of 1.884 MPa, followed by design 1 with hexagonal holes at 1.812 MPa. Notably, design 3 with diamond-shaped holes demonstrated the lowest maximum stress value of 1.748 MPa.

Designing a knee brace that exceeds the material's yield strength, which is the highest stress a material can withstand before it fails in specific areas under applied force (Turiman, 2021) is essential for ensuring its safe use. Consequently, it is essential to prioritize safety during the design process. Patients are considered to be the safest with a design that has the lowest stress value, as has been repeatedly demonstrated by previous studies (Turiman, 2021).

In contrast to the previous research, in which the hexagonal shape exhibited the lowest stress of 1.438 MPa, the findings of the current study indicate that the diamond shape results in the lowest maximum stress. The difference in outcomes can be attributed to a number of factors, including the choice of material, minor variations in hole dimensions, and the overall design of the knee brace. These variables have an important effect on the load distribution and structural behavior of the knee brace, as well as the stress distribution throughout the brace (Zhang, 2017).

These findings highlight the importance of the considering material properties and design considerations to optimize knee brace performance and stress distribution. By selecting appropriate materials and incorporating intended design elements, knee braces can be made more effective and functional. This enhances their ability to provide optimal support, stability, and injury protection (Wilson, 1999).

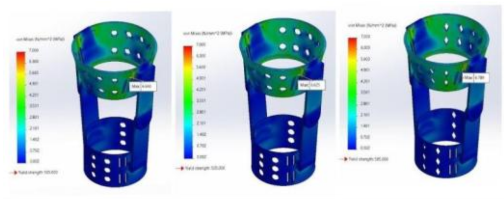
Consequently, based on the findings of Study 1, Design 3 with diamond-shaped holes exhibits the lowest maximal stress distribution, proving its suitability as the most advantageous design option for the knee brace. This study's findings provide practitioners, researchers, and manufacturers with valuable information that will aid in the design of knee braces that prioritize patient safety and overall efficacy.

Study 1: The Analysis on the Shape of the Holes (Compression Test)

Under compression loading, similar trends were observed as shown in Tab. 2 and Fig. 6. The circular hole design again demonstrated superior performance by reducing peak stress values and maintaining better load distribution across the structure. The hexagonal and diamond designs exhibited higher localized stress regions, making them less ideal under compressive conditions.

Table 2 Stress values on models

Shape of the holes	Maximum von Mises Stress (VMS) (MPa)
Design 1 (Hexagonal)	6.660
Design 2 (Circle)	6.625
Design 3 (Diamond)	6.789



(a) (b) (c)

Fig. 6 Stress on knee brace models (a) Hexagonal, (b) Circle, (c) Diamond

The compression test results for the 3D designs of the knee brace indicate variations in the maximum von Mises stress (VMS) presented in Table 2. Among the designs, the highest stress is observed at the upper brace, which is consistent across all three designs. Design 2, which features circle holes, exhibits the lowest maximum stress value of 6.625 MPa. Design 1, with hexagonal holes, follows closely with a maximum stress value of 6.660 MPa. On the other hand, Design 3, incorporating diamond holes, shows the highest maximum stress value of 6.789 MPa.

The compression force is the primary force acting on the surface of the knee brace. This force is applied vertically to the brace to simulate the weight-bearing load encountered during activities such as standing, walking, and sprinting. The purpose of the knee brace is to support and stabilize the knee joint by effectively distributing compressive force (Patel, 2009).

To determine the compression force, the patient's body weight is typically multiplied by a factor. Common methods include, for instance, multiplying the body weight by a factor of ten. This scaling factor takes the dynamic nature of activities into consideration and ensures that the brace can withstand the expected loads. As compression force is applied to the knee brace, the force is transmitted to the tissue beneath. The skin functions as a barrier between the brace and the knee joint's underlying tissues, ligaments, and bones. Effective force distribution is essential for preventing the formation of localized pressure points, which can result in distress or even injury (Zhang, 2017). Proper brace-to-skin interaction is crucial for achieving balanced force distribution and minimizing the risk of adverse effects.

In a previous study, a knee brace design with a circular shape demonstrated the lowest maximum stress of 2,297 MPa. In the present study, however, the stress distribution within the knee brace model produced different outcomes. The difference could be attributed to a number of factors, including the use of different analysis software and the choice of materials for the knee brace. The analysis software functions an essential role in determining stress distribution. Various software has different algorithms and methodologies, which can result in varying outcomes (Cvetković, 2012).

Consequently, it is essential to choose software that accurately simulates the knee brace's behavior and provides reliable stress analysis. Moreover, the material properties of the knee brace can also affect the distribution of stress. Mechanical properties, such as rigidity, elasticity, and strength, differ among materials. These characteristics influence how the brace interacts with the applied forces and how the structure distributes stress (Wilson, 1999). To assure optimal performance and stress distribution in the knee brace, the selection of materials should be carefully considered.

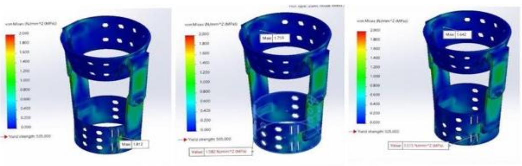
Consequently, based on the findings of Study 1, Design 2 with circular-shaped holes exhibits the lowest maximal stress distribution for compression test, proving its suitability as the most advantageous design option for the knee brace.

Study 2: The Analysis on the Height of the Lower Brace (3-Point Bending Test)

For varying lower brace heights, increasing the brace height from 10 cm to 12 cm resulted in reduced maximum stress and displacement during the 3-point bending simulation as shown in Tab. 3 and Fig. 7. The greater height improved overall structural rigidity and allowed for better load transfer through the brace, minimizing midspan deformations.

Tab. 3 Stress values on knee braces models

Variation in height of lower brace	Maximum von Mises Stress (VMS) (MPa)
Design 1 (10 cm)	1.812
Design 2 (11 cm)	1.582
Design 3 (12 cm)	1.515



(a) (b) (c)
Fig. 7 Stress on models (a) 10cm, (b) 11cm, (c) 12cm

In the 3-point bending test results presented in Table 3, the influence of the height of the lower brace on the von Mises stress of the knee brace is evident. Design 3, which has the highest height of 12 cm for the lower brace, exhibits the lowest stress value of 1.515 MPa. This suggests that a taller lower brace contributes to stress reduction and improved load distribution within the knee joint.

On the other hand, design 1, with the lowest height of 10 cm for the lower brace, demonstrates the highest stress value of 1.812 MPa. This indicates that a shorter lower brace may lead to higher stress concentrations and a more focused load distribution within the knee joint. In the previous study, the lower brace design with the same height had a maximum stress distribution of 1.483 MPa, while in this study, the design 3 exhibited a maximum stress distribution of 1.515 MPa (Turiman, 2021). The difference in maximum stress values between the studies is relatively small. This variation could be attributed to the use of different software for analysis and the potential challenge of evenly distributing stress throughout the knee brace model (Cvetković, 2012). These factors highlight the importance of software selection and ensuring proper stress distribution for accurate and consistent results.

The height of the lower brace plays a significant role in the functionality of the knee brace. A taller lower brace provides increased stability and support to the knee joint, limiting excessive movement and offering improved stability during bending and weight-bearing activities (Thacker, 2002). It helps distribute the applied load more evenly, minimizing stress concentrations and potential damage to the knee structures.

Conversely, a shorter lower brace allows for more freedom of movement and flexibility but may result in a higher concentration of stress in specific regions of the knee. Choosing the appropriate height for the lower brace requires considering the desired level of stability, range of motion, and comfort for the individual wearer (Thacker, 2002). Factors such as the patient's condition, activity level, and specific requirements should be considered during the design process (Zhang, 2018).

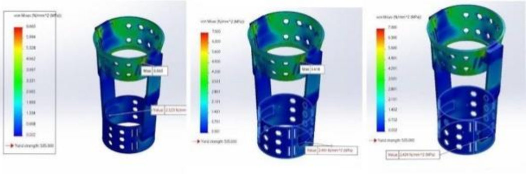
Overall, the height of the lower brace in a knee brace design has a direct impact on load distribution, stress patterns, and overall functionality. It is essential to find the right balance between stability and mobility to ensure optimal performance and support for the knee joint.

Study 2: The Analysis on the Height of the Lower Brace (Compression Test)

Similarly, in compression tests, the 12 cm lower brace height offered improved support by distributing axial loads more effectively compared to the 10 cm and 11 cm designs as shown in Tab. 4 and Fig. 8. The increased contact area and structural support from the extended lower section contributed to the observed enhancements in mechanical stability.

Tab. 4 Stress values on knee braces

Variation in height of lower brace	Maximum von Mises Stress (VMS) (MPa)
Design 1 (10 cm)	2.523
Design 2 (11 cm)	2.491
Design 3 (12 cm)	2.424



(a) (b) (c)

Fig. 8 Stress on models (a) 10cm, (b) 11cm, (c) 12cm

The influence of the height of the lower brace on the von Mises stress of the knee brace can be observed from the compression test results presented in Tab. 4. The stress values vary depending on the height of the lower brace, with Design 3 (12 cm height) exhibiting the lowest stress value of 2.424 MPa, and Design 1 (10 cm height) demonstrating the highest stress value of 2.523 MPa. In the previous study, the highest maximum stress distribution for the designs reached 5.075 MPa in the side brace. However, in the current study, the highest maximum stress observed in the lower brace was 2.523 MPa, which is still within an acceptable range as neither study exceeded the material's yield strength. While the values differ between the two studies, it is important to note that both remained within a safe stress range. This indicates that the knee brace designs in both studies were able to withstand the applied loads without surpassing the material's yield strength (Turiman, 2021).

During the compression test, the knee brace is subjected to a downward force that simulates the weight-bearing load experienced when standing or walking. The height of the lower brace, which extends below the knee joint, plays a crucial role in determining the functionality and performance of the brace (Thacker, 2002).

The knee's overall stability and support are influenced by the height of the lower brace. A taller lower brace provides additional support and restricts excessive movement, thereby enhancing the knee's stability during flexion or weight-bearing activities (Thacker, 2002). This additional stability can be especially advantageous for individuals with weak or injured knees, as it prevents potentially harmful motions and provides a sense of security. A shortened lower brace, on the other hand, permits greater mobility and flexibility, which can be advantageous for individuals who require a greater range of motion. It is essential to note, however, that a shorter lower brace may provide less stability than a taller one (Paolini, 2010).

Additionally, the load distribution and stress patterns within the knee joint are influenced by the height of the lower brace. A taller lower brace helps distribute the applied load across the joint more evenly, thereby minimizing stress concentration in specific areas. A taller lower brace can prevent localized stress points and reduce the risk of injury and discomfort by distributing the stress over a larger surface area (Paolini, 2010). This is especially essential for individuals who engage in activities, such as running or jumping, that place greater stress on the knee joint. In contrast, a shorter lower brace may result in a more concentrated load distribution, which may increase tension in particular regions of the knee (Dejour, 2009). This concentrated stress may cause discomfort, tissue injury, or worsen present knee conditions.

By analyzing the von Mises stress values for different heights of the lower brace in the compression test, we can gain insights into how the height affects the brace's performance. This information is crucial for designing knee braces that provide optimal support, stability, and stress distribution for individuals with specific needs.

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CONCLUSION

This study successfully demonstrated the influence of hole geometry and lower brace height on the mechanical performance of a rehabilitative knee brace intended for ACL injury recovery. A series of 3D models were designed and evaluated using Finite Element Analysis to simulate both 3-point bending and compression loading conditions. The simulation results revealed that the brace design incorporating circular hole geometry consistently produced the lowest maximum von Mises stress and the most uniform stress distribution, minimizing stress concentration zones.

In terms of structural reinforcement, the 12 cm lower brace height emerged as the most effective configuration, offering improved rigidity, reduced displacement, and enhanced axial load support compared to the 10 cm and 11 cm variants.

Therefore, the optimal knee brace design, based on the findings of this study, combines the circular hole pattern with a 12 cm lower brace height. This configuration achieves the best balance between structural integrity, comfort, and load distribution—making it the most suitable for rehabilitation use. Future work should include prototype fabrication, clinical testing, and integration of wearable sensors for real-time feedback and performance monitoring.

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