Parametric Design-Based Personalization Study of Zoned Knee Braces

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Abstract. This study proposes a zoned knee protector design methodology integrating personalized parametric approaches. Utilizing a comprehensive reverse engineering workflow, 3D morphological data of the human knee were acquired via the Einscan Pro 2X Series scanner. Two primary materials were selected based on functional requirements: Polymaker TPU 85A for the substrate and PLA+2.0 for zoned structural components. Through the Ntopology parametric design platform, the development of zoned lattice structures was implemented via five critical stages: boundary definition, stochastic point cloud distribution, mesh framework establishment, Boolean operations, and final model output – enabling the transformation from theoretical models to physical constructs. The 3D-printed prototypes underwent rigorous sports biomechanics simulation experiments. Kinematic and dynamic analyses confirmed that the designed knee protector achieves: personalized anatomical conformity, enhanced joint protection, and optimized biomechanical load distribution.

Keywords: Knee Protective Gear, Three-Dimensional Scanning, Personalized Design, 3D Printing Technology, Parametric Design

1 Introduction

As one of the most complex structures in the human lower limb, the knee joint plays a crucial role in coordinating movement, distributing loads, and absorbing shock during daily activities [1]. Related studies have demonstrated that knee joint protective gear can not only provide appropriate muscle compression and effectively limit the range of joint medial-lateral movement, but also promote local blood circulation and metabolic function, while significantly enhancing the joint area's resistance to external impact forces, thereby comprehensively improving exercise safety and rehabilitation outcomes [2-3]. Moreover, with the continuous growth in demand for sports protection and rehabilitation medicine, knee joint protective gear has become an important auxiliary device for injury prevention and mitigation [4]. POPA et al. [5] utilized three-dimensional modeling technology of the knee joint and 3D printing processes to manufacture knee

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pad sandwich elastomer structures, effectively addressing the issue of insufficient matching between traditional knee pads and human anatomical structures. Zhang Fanglan et al. [6] employed reverse engineering and three-dimensional scanning technology to obtain precise digitized models of human joints, thereby improving the design efficiency of customized ankle-foot orthoses. Zhao Jiaxin [7] utilized reverse engineering technology, NURBS surface reconstruction, and deviation analysis to obtain accurate surface morphological characteristics of the knee joint, and developed a nonlinear automated protective gear modeling program using Grasshopper. Ji Yuliang et al. [8] investigated the relationship between sports protective gear and sports biomechanics, providing theoretical foundations for the improvement of sports protective gear design. Guo Luqi [4] explored the kinematic protective mechanism of knee joint decompression protective gear by examining changes in knee joint kinematics before and after wearing the gear. Duan Jiejie and Song Xiaoxia [9] designed protective gear products that meet the specific functional requirements of different parts of the knee joint by adjusting the structural organization and material density of different regions within the protective gear. Wang Yutao et al. [10] constructed a zoned knee pad model that matches the thermal and moisture requirements of the knee joint by combining the morphological characteristics and hygrothermal distribution features of the human lower limb. However, current research on functional zoning, lattice structures, and variable stiffness aspects of protective gear remains limited. In response to the limitations of traditional protective gear design, this paper proposes a parametric design method for zoned variable-stiffness knee joint protective gear.

2 Multi-Zone Functional Brace Design

2.1 Knee Joint Shape Reconstruction

The personalized design of knee joint protective gear requires accurate acquisition of three-dimensional morphological data of the human knee joint. This study employed a complete reverse engineering workflow. A 24-year-old male subject with a BMI of 23.6 kg/m^2 was selected from the electromyographic experiment participants as the target for knee joint morphological data collection. Non-contact data acquisition was performed using an Einscan Pro 2X Series three-dimensional scanning device. During data collection, a semi-weight-bearing natural standing posture was adopted to obtain raw point cloud data at 0° knee joint flexion angle. The acquired raw point cloud data underwent in-depth optimization processing using Geomagic Studio software. The preprocessing workflow is illustrated in Figure 1, which primarily includes trimming redundant data, removing interfering features, model segmentation, surface smoothing, and global alignment. Based on this processed data, a knee brace shell model was constructed.

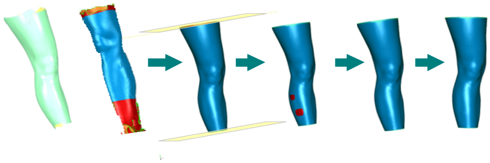

Fig. 1. Knee joint point cloud data preprocessing process

2.2 Knee Brace Design

Material Selection. Based on functional requirements and manufacturing process characteristics, this study selected two primary materials: Polymaker TPU 85A for the protective gear substrate component and PLA+2.0 for the zoned variable-stiffness structural component. TPU 85A exhibits excellent elongation at break properties, making it suitable as a substrate material to provide the necessary toughness and tear resistance. Meanwhile, PLA+2.0, owing to its higher tensile strength and flexural strength, is appropriate for fabricating zoned structures with varying stiffness characteristics. The material properties are presented in Table 1.

Table 1. Material Properties

Material	Density (g/cm³)	Tensile Strength (MPa)	Flexural Strength (MPa)	Elongation at Break (%)
TPU85A	1.15	22.4±2.7	/	564±35
PLA+2.0	1.23	58	73	3.6

Human Knee Joint Dimensions. The subject maintained a fixed posture with the lower leg perpendicular to the ground and the thigh positioned at 30° to the horizontal plane. Circumferential measurements were taken at three key positions: knee circumference at the horizontal level of the patellar center; upper leg circumference 14 cm above the patellar center; and lower leg circumference 12 cm below the patellar center. The measurement results were as follows: upper leg circumference 47 cm, knee circumference 37 cm, and lower leg circumference 41 cm.

Protective Gear Dimensions. Based on the knee joint dimensions, the knee brace size parameters were determined as follows: total length 30.5 cm, upper opening width 16.5 cm, lower opening width 14 cm, knee circumference width 13.5 cm, patellar protection area approximately 10 cm, support strut length 22 cm, and upper and lower opening extensions of 1 cm each. These dimensions correspond to a size M range.

The knee joint protective gear was divided into nine independent functional zones. As illustrated in Figure 2, the patellar region employs an open structure design to effectively accommodate and stabilize knee joint motion while preventing excessive displacement during movement. The lateral support regions incorporate rigid support struts to effectively limit knee joint valgus and varus movements and resist lateral stress forces. High activation regions feature a relatively flexible structure design to provide adequate range of motion. Low activation regions utilize high-density structures to provide sufficient external support force. Impact protection zones encompass areas containing bony structures of the knee joint and employ high-density designs to provide adequate protection.

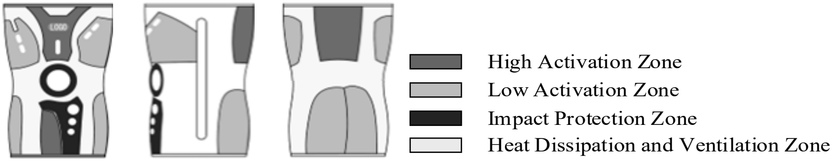

Fig. 2. Knee brace zoning

2.3 Parametric Brace Model Development

To achieve the transformation from theoretical model to physical structure, this study employed the Ntopology parametric design platform to construct zoned lattice structures. The lattice model construction workflow comprises five key steps: upper and lower boundary determination, random point cloud distribution generation, mesh framework establishment, Boolean operations, and final model output. Based on the zoned module construction workflow, a complete parametric model of the knee joint protective gear was developed, as shown in Figure 3.

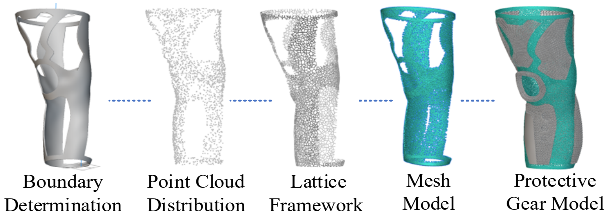

Fig. 3. Zonal module lattice structure construction workflow

3 Experimental Verification

Based on the protective gear zoning framework, experimental prototypes were obtained through FDM 3D lattice printing technology. Figure 4 illustrates three protective gear wearing conditions: prefabricated sleeve protector A, prefabricated compression protector B, and the proposed protector C. This study integrates motion capture systems with AnyBody biomechanical simulation software for analysis, comparing kinematic and dynamic parameter changes under different protective gear conditions to validate the effectiveness and rationality of the zoned variable-stiffness protective gear design.

The same individuals who participated in knee joint morphology data collection were selected as subjects for the motion capture experiments under four wearing conditions. Subjects were required to complete movement data collection tasks under four working conditions while wearing each of the four protective gear types sequentially.

Following the donning of each protector, a 3-minute adaptation period was allowed. Each working condition was tested for 5 sets, with a 5-minute rest period between consecutive movements.


(a) (b) (c)

Fig. 4. Wearing effect picture ((a) Gear A; (b) Gear B; (c) Gear C)

The knee flexion angle and knee joint moment curves are presented in Figure 5. The blue line represents the control group (no protector), red indicates Protector A, green denotes Protector B, and yellow corresponds to Protector C. From a phase relationship perspective, all protectors effectively reduced peak joint flexion. However, Protector C demonstrated superior restriction of flexion angles across all four working conditions, achieving an average reduction of 20°–25°significantly greater than Protectors A and B. Crucially, while substantially decreasing flexion angles, Protector C maintained optimal phase modulation balance, thereby enhancing the preservation of coordination between muscular and joint movements.

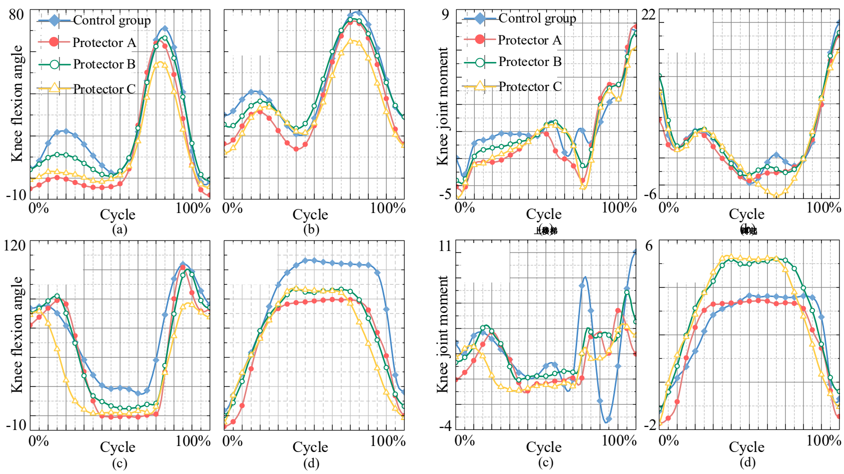

Fig. 5. Knee flexion angle and knee joint moment curves ((a) Normal gait; (b) Jogging (6 km/h); (c) Stair ascent; (d) Squatting down and up)

Regarding joint moment regulation, Protector C exhibited exceptional control capability throughout all working conditions. During high-moment tasks such as stair ascent, it significantly attenuated peak joint moments compared to conventional protectors. By providing differentiated mechanical support during critical motion phases, Protector C delivers important clinical benefits: reduced anterior cruciate ligament (ACL) loading, diminished anterior tibial translation forces, and optimized load distribution across joint structures.

4 Conclusions

This study integrated reverse engineering, parametric modeling, and zoned architectural principles to develop a novel knee protector design method that effectively meets the biomechanical demands of different regions. The parametric framework based on the Ntopology platform achieves personalized customization, while the dual-material strategy optimizes performance and comfort. Prototypes fabricated through additive manufacturing were validated via AnyBody simulation, confirming the effectiveness of the protector under four working conditions. Future research will evaluate the performance stability and usage effects of the protector through long-term tracking in practical applications, providing theoretical and technical support for personalized protective equipment.

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