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Influence of Patellar Implant Shape on Patellofemoral Contact Pressure Using Finite Element Analysis

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Purpose: This study focused on analyzing the contact pressure and area on different patellar component designs in total knee arthroplasty (TKA) to evaluate biomechanics related to the patellofemoral (PF) joint.

Materials and Methods: The patellar components studied included the dome design, modified dome design, and anatomical design implants. Using finite element analysis and mechanical testing, the pressure and area were evaluated. The first loading condition was simulated at flexion angles of 0°, 15°, 45°, 90°, 120°, and 150°. The second loading condition was simulated for a clinically relevant scenario, involving a 2-mm medial shift at a flexion angle of 45°.

Results: For both the modified dome and anatomical designs, the contact area and pressure increased with the flexion angle. The dome design reached its maximum contact area at a flexion angle of 120°. Among the designs, the anatomical design had the largest contact area and a lower contact pressure compared to the dome and modified dome designs. However, when a medial shift of 2 mm was simulated at a 45° flexion angle, which can occur clinically, the anatomical design showed edge contact, leading to higher contact pressure and reduced contact area. In contrast, the modified dome design demonstrated the lowest contact pressure and the greatest contact area under the same shifted conditions.

Conclusion: These findings suggest that the design of the patellar component significantly affects patellar biomechanics and stability. Specifically, the modified dome design showed improved biomechanical effects in clinically relevant scenarios. Therefore, patellar components with a modified dome design are expected to better manage PF joint pain and reduce complications in TKA.

Key Words: Total knee arthroplasty, patellar implant shape, patellofemoral contact, finite element analysis, biomechanics

INTRODUCTION

Total knee arthroplasty (TKA) is a recognized treatment for advanced knee joint arthritis, providing reliable pain relief and functional restoration.[1,2] However, despite these benefits, patients may still experience residual pain and suboptimal functional improvement.[3] Additionally, the longevity of implants can be compromised by various complications, such as joint instability, infection, loosening, and wear, which may develop in either the femorotibial or patellofemoral (PF) joint.[4] Complications related to the PF joint are some of the troublesome prognostic factors of TKA, while patellar resurfacing remains a subject of debate.[5,6] These findings have the potential to im-

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prove knee function, reduce pain, and prolong the lifespan of the artificial joint.[7] The main symptoms and signs in resurfaced knees include anterior knee pain, clunk syndrome, maltracking, crepitus, and fractures.[8-10] Furthermore, problems with the implants, such as wear, dislocation, and delamination, can occur. These complications are related to the stress on the PF joint, influenced by patellar component design, patient preoperative condition, and surgical techniques, including alignment, rotation, and fixation of the patella.[11,12]

A reduction in pressure has been achieved through numerous changes in the designs of the patella and trochlea shapes, as the design of the patellar component plays a crucial role in the mechanics of the PF joint.[13] The commonly used types of patellar component design configurations include dome, offset dome, modified dome, and anatomical designs.

The initial design of the patellar component was an anatomical design incorporated into a condylar-type TKA.[14] However, its long-term results were disappointing owing to suboptimal implant materials and a high risk of malalignment. To address this, the dome-shaped patella was developed to reduce the risk of malalignment.[15] The dome design of the patellar component intuitively eliminates a degree of freedom that the surgeon must consider during the alignment of the patellar component due to its coronal plane symmetry.

The recently developed modified dome design for the patellar component was created to alter the geometry of the PF joint and optimize patellar tracking compared to the dome design. However, there has not yet been a direct comparative study of the contact area and pressure among these three designs of patellar components.

Therefore, the present study aimed to analyze the contact area and pressure of three different designs of patellar components using computational methods. We evaluated flexion at 0°, 15°, 45°, 90°, 120°, and 150°, and also assessed a clinically relevant scenario by analyzing flexion at 45° with a medial shift of 2 mm. We hypothesized that the modified dome design of the patellar component would exhibit beneficial biomechanical effects in a clinically relevant environment.

MATERIALS AND METHODS

Different patellar component designs

A three-dimensional (3D) finite element (FE) model was developed for three different patellar component designs. Three common types of patellar implant designs were evaluated, as illustrated in Fig. 1.

The first design was a dome-shaped patellar component (Vanguard; Zimmer Biomet, Warsaw, IN, USA) that was circular and convex, optimized to maximize the contact area with the femoral component of the knee joint. This design allows for rotational freedom, accommodating a wide range of knee movements. The second design (BP KNEE; Endotec, Inc., Santa Fe Springs, CA, USA) was an anatomically shaped patellar component, which more closely replicates the natural form of the patella compared to the uniform dome shape. This design potentially reduces wear and enhances the overall joint function by providing a more natural feel and movement. The third design was a modified dome-shape patellar component (PNK KNEE; Skyve Co. Ltd, Seoul, South Korea), a variation of the traditional dome shape. It features a more gradual convex curvature to better fit the femoral trochlea, thus improving alignment and reducing peak stress concentration. This design typically includes a slightly flatter surface or other subtle modifications to enhance tracking and fit within the femoral groove. These adjustments aim to improve stability and minimize the risk of dislocation or misalignment.

Computational model

Three different patellar component designs were scanned using a non-contact 3D laser scanner (COMET VZ; Steinbichler Optotechnik GmbH, Neubeuern, Germany) with an accuracy of 50 μm. The scanned point data were converted into 3D models, and the scanning process was repeated until the dimensions of the 3D models exhibited geometric errors of less than 100 μm.

The 3D models of the three patellar component designs were created using SolidWorks software (version 2023 SP5.0; Dassault Systèmes, Yvelines Vélizy-Villacoublay, France), as shown in Fig. 2.

All components were patellar-type designs. The patella was

Fig. 1. Three design types of patellar implants: dome type, modified dome type, and anatomic type.

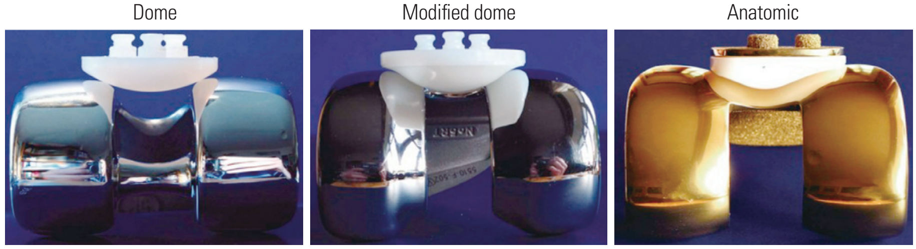

Fig. 2. Three TKR implants representing three different patella implant designs: dome shape, modified dome shape, and anatomic shape.

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positioned slightly medial and centrally in height, aligning with the trochlear component. The FE mesh models were generated using HyperMesh (version 8.0; Altair Engineering, Troy, MI, USA). The constructed FE model was used to simulate a PF test according to the American Society for Testing and Materials (ASTM) standard.[16,17] The convergence of the FE model was examined. Mesh convergence was determined when the maximum displacement on the patellar button fell within 95% of the values obtained from the next two finer mesh sizes. A mesh size of 1.0 mm for both the patellar and femoral components satisfied these criteria.

Material properties

Cobalt chrome alloy was used for the femoral components (Young's modulus E=195 GPa, Poisson's ratio ν=0.3).[18] Ultra-high-molecular-weight polyethylene (Young's modulus E=685 MPa, Poisson's ratio ν=0.47) was utilized for the patellar components.[18] All materials were considered as linear elastic, isotropic, and homogeneous.

Loading and boundary conditions

This FE investigation examined two types of loading conditions that matched those used in the experimental study, aimed at model validation and predicting the outcomes of clinically relevant scenarios.[19] For model validation, the same loading protocols as those applied in the experiments were simulated. The first loading condition was simulated at flexion angles of 0°, 15°, 45°, 90°, 120°, and 150°, which are identical to those used in PF testing. The load values for each flexion angle are shown in Table 1. The second loading condition was simulated for a clinically relevant scenario, involving a 2-mm medial shift at a flexion angle of 45°.[19]

Simulations were performed under static conditions owing to the high computational demands and time constraints of modeling the joint's ideal dynamic motion. Additionally, for FE model validation, the modified dome design was selected, and a mechanical test was conducted to assess the contact area of the PF component, as illustrated in Fig. 3. This test was performed in accordance with ASTM standards.[16,17]

RESULTS

Validation

To validate the FE model, the results were compared with experimental data. The experimental results showed contact areas of 19.6, 22.5, 65.6, and 95.2 mm^2 at flexion angles of 0°, 15°, 45°, and 90°, respectively. The FE model also showed respective contact areas of 20.2, 18.3, 60.1, and 88.3 mm^2 at the same flexion angles. This demonstrated good agreement between the experimental results and the FE model.

Table 1. Implant Loading Conditions for the Patellofemoral Contact Area

Inclination angle (°)	Load (n)
0	377
15	377
45	961
90	2195
120	3068
150	3068

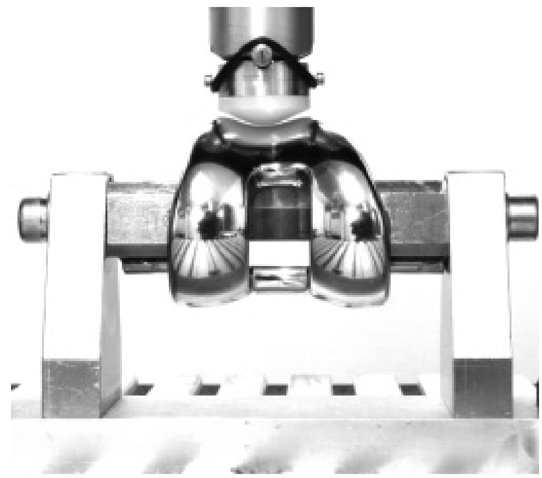

Fig. 3. Principle photograph of test setup used to measure patellofemoral pressure distribution and contact area.

Contact pressure and area

The contact pressure areas of the patellar component for the three different designs are shown in Fig. 4. For the modified dome and anatomical designs of the patellar component, both the contact area and pressure increased with the flexion angle. However, the dome design showed the greatest contact area at 120° of flexion.

The anatomical design of the patellar component exhibited a greater contact area and lower contact pressure compared to the other two designs at all flexion angles. In addition, the modified dome design demonstrated a greater contact area and lower contact pressure compared to the dome design at all flexion angles.

When the patellar component of the three different designs was shifted 2 mm medially, the contact area and pressure at a flexion angle of 45° are shown in Fig. 5. Unlike the other designs, the modified dome design exhibited the greatest contact area and the lowest contact pressure. Fig. 6 shows the contact pressure distribution at a flexion angle of 45° in both normal and clinically relevant conditions.

DISCUSSION

The most important finding of this study was that the contact pressure and area varied depending on the design of the pa-

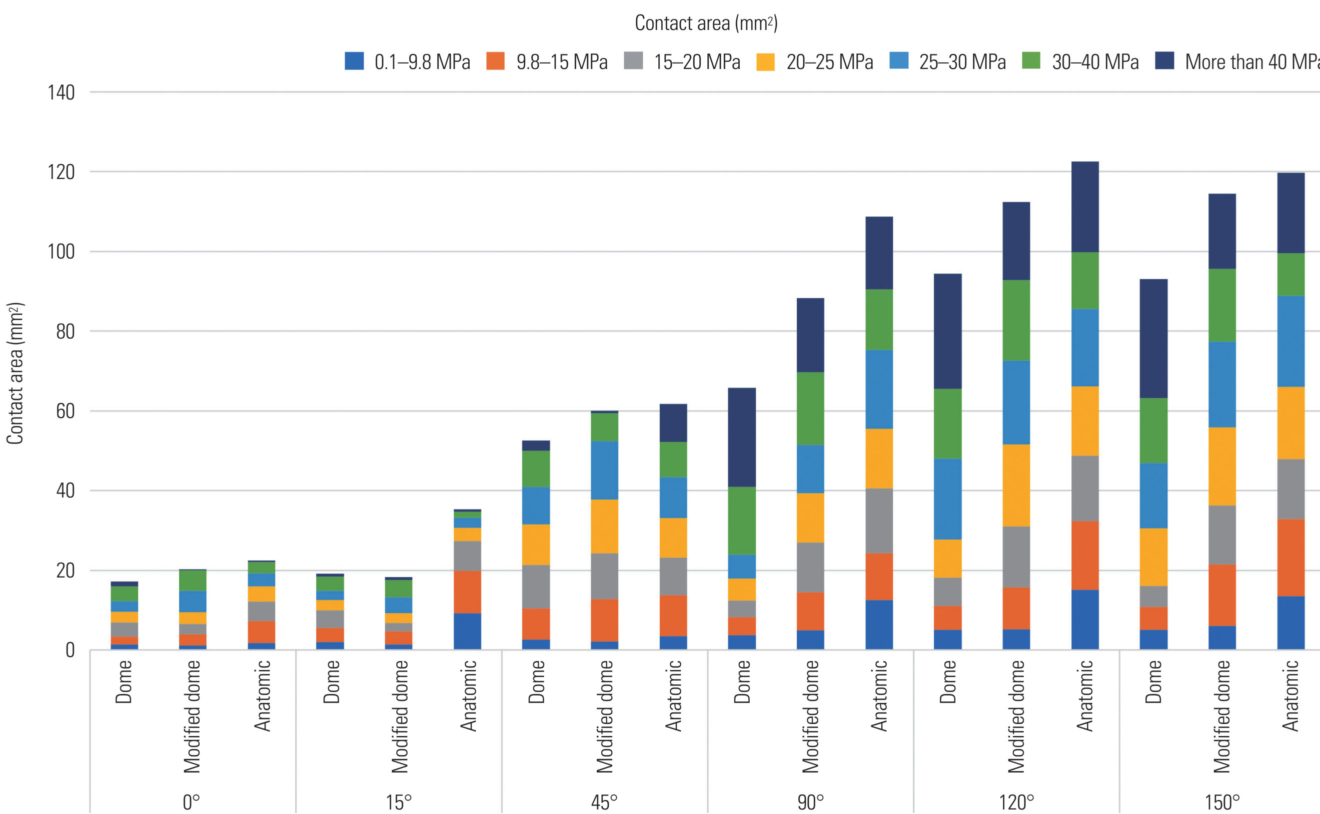

Fig. 4. Contact pressure areas of the patellar components for the three different designs with various flexion angles (0°, 15°, 45°, 90°, 120°, and 150°).

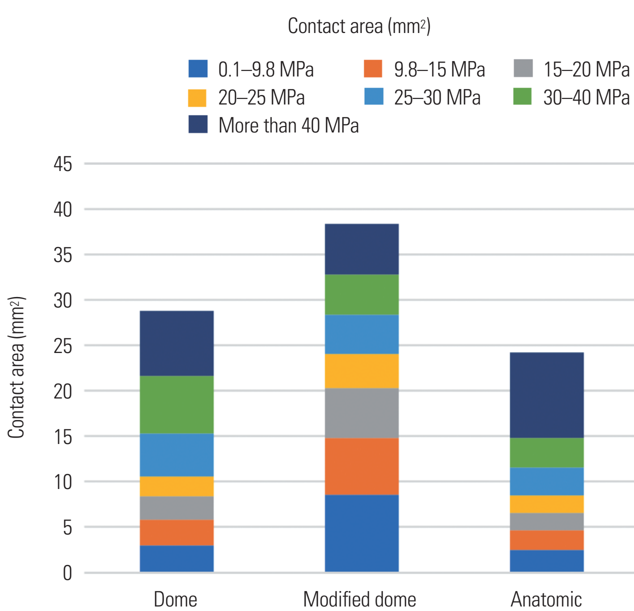

Fig. 5. Contact pressure areas of patellar components for the three different designs with 45° flexion angles at a 2 mm medially shifted position.

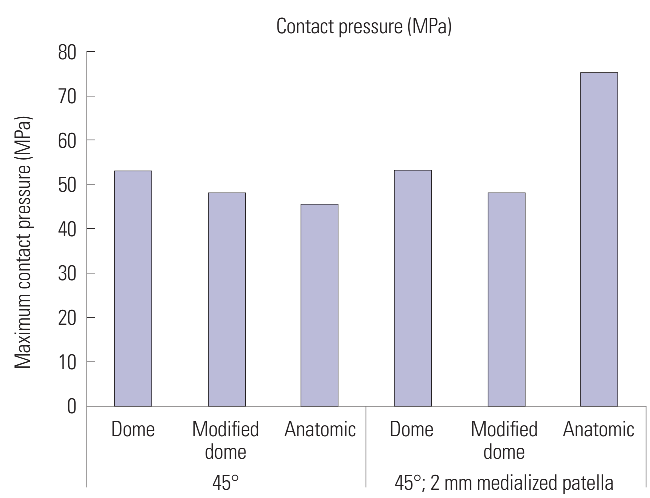

Fig. 6. The maximum contact pressure of the patellar components for the three different designs with 45° flexion angles in both normal and clinically relevant conditions.

tellar component. The anatomical design of the patellar component showed the best biomechanical effects at all flexion angles. However, in clinically relevant scenarios, the modified dome design of the patellar component exhibited the most favorable biomechanical effects. Therefore, our hypothesis was validated.

In TKA, the PF joint is crucial for determining the overall outcome. Complications in this joint can present as anterior knee pain; crepitus; restricted movement; instability; and issues related to the implant, such as wear and loosening.[8-10,16] The primary cause of these complications is known to be increased pressure on the PF joint. The contributing factors can be categorized into patient-related factors, surgical factors, and patellar

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component design factors. Patient-related factors include the preoperative alignment of the patella and femur, their shapes, and the preoperative range of motion.[11,12] Surgical factors encompass issues such as malalignment, improper positioning of the patellar component, and fixation problems. Among the component factors, the design of the patellar component is particularly important in enhancing patellar tracking and reducing pressure on the patella. The design of these components has seen significant advancements over time.

At present, patellar components are available in a variety of shapes and sizes, highlighting the ongoing debate over the optimal design.[20] The patellar component comes in two basic designs: domed and anatomical. Other designs are variations based on these two types, with recent developments referred to as modified dome designs.[21] Patellar components with the anatomical design are believed to more accurately replicate natural kinematics, offering a larger PF contact area and reducing the risk of subluxation.[21] Given their considerable asymmetry, these designs are more prone to malalignment and necessitate the use of specialized instruments and meticulous precision during surgery.[20] Patellar components with the dome design feature simple spherical contact geometries between the patella and femur, ensuring a consistent fit with the femoral trochlear groove across various planes.[21] This design is more tolerant during implantation, making it less prone to issues from rotational misalignment or minor positioning errors, as it reduces edge loading.[21] However, as flexion increases, the PF articulation shifts to a point contact, which results in higher stress and an increased risk of component wear.[7] Consequently, the dome design of the patella component has been revised to address these issues. The modified dome design was developed to enhance PF contact and lower contact stress, particularly at greater flexion angles. Additionally, the edges were reinforced to create a "sombrero"-like shape, which improves durability.[22] Since the design is fundamentally round, it reduces the risk of malrotation and malposition. These designs are now known as "patella-friendly shapes," as they have been engineered biomechanically to align the patella with the trochlea.[23,24]

Our results showed that, under flexion conditions, the contact area was greatest with the patellar component with the anatomical design, followed by that with the modified dome design, and then that with the dome design. In contrast, the contact pressure exhibited the opposite trend. Compared to the anatomical design, both the modified dome design and the dome design offer greater freedom of movement. The modified dome design provides a larger contact angle between the patella and femur compared to the dome shape, which helps prevent patellar subluxation. The modified dome design offers a contact area similar to the anatomically shaped patellar component, while maintaining a higher degree of movement freedom. It also has a larger contact area than the dome design and shows better performance at preventing patellar subluxation. Furthermore, the modified dome design provides more stable femur–patella contact during high flexion compared to the dome design.

Patellar components with the dome design are preferred for their tolerance, ability to reduce stress at the bone–cement interface, ease of alignment and tracking, and better conformity to the trochlea when deformed.[25] The dome-design patellar component was considered the optimal solution due to its adaptability to any groove shape and alignment.[26] Despite good clinical outcomes, cemented all-polyethylene dome-design patellar components often fail due to high contact stresses.[20,27] The modified dome design improves articulation at higher flexion angles by increasing the contact area and extends component life by more than 20 times compared to standard dome components.[20] An interesting finding was observed in clinically relevant scenarios. The patellar component with the modified dome design exhibited a higher contact area and lower contact pressure compared to the patellar component with the anatomical design. Recent studies of retrieved patellar components have also shown similar results. The patellar component with the modified dome design demonstrated significantly less damage compared to that with the dome design. Recent studies of retrieved patellar components have also shown similar results.[28] These results highlight that, while the patellar component with the anatomical design provides a high contact area when perfectly aligned, it shows a lower contact area and higher contact pressure when the component shifts medially by 2 mm, as seen in clinically relevant scenarios.

Therefore, balancing the acceptable level of conformity with considerations of patellar motion is important. Understanding the impact of the mechanical environment on the PF joint's behavior is crucial for developing knee replacement systems that ensure satisfactory function and long-term clinical success.[20]

The present study had two main limitations. First, simulations were performed under static conditions owing to the high computational demands and time constraints of modeling the joint's ideal dynamic motion. Additionally, the in vitro nature of the experiments failed to fully capture the complexities of real knee kinematics, which include not only extension and flexion, but also rotational movements across various angles.

Second, the simulations were limited to the implant alone. Future research should include studies involving bone and ligamentous tissues. Moreover, the actual PF contact stress is significantly affected by the strength of the quadriceps, a factor that was not thoroughly captured in our simulations. Browne, et al.[29] emphasized the role of the extensor moment arm in modifying PF forces after TKA, which directly influences the effectiveness of the quadriceps mechanism. Future research will focus on achieving a more precise simulation of the joint and analyzing its performance under cyclic loading to more accurately reflect these interactions and their effects on knee mechanics. However, to evaluate the characteristics of implant designs, simpler conditions, as used in the current study, may be more appropriate than complex scenarios.

In conclusion, our results demonstrated that the contact area and pressure vary depending on the design of the patellar component. In other words, differences in patellar component design affect patellar biomechanics. The differences in patellar component design may influence patellar stability. The patellar component with the modified dome design showed contact area and pressure similar to that with the anatomical design during flexion scenarios. In addition, the modified dome design exceeded the traditional dome design in contact area, improving patellar tracking and offering more stable contact in the PF joint during flexion. In particular, the modified dome design demonstrated enhanced biomechanical effects in clinically relevant scenarios compared to the other two designs. Consequently, the patellar component with the modified dome design is considered the most promising design for patellar components in knee arthroplasty.

AUTHOR CONTRIBUTIONS

Conceptualization: Kwan Kyu Park and Kyoung-Tak Kang. Data curation: Hun Sik Cho. Formal analysis: Hyuck Min Kwon. Funding acquisition: Seong-Mun Hwang. Investigation: Hyuck Min Kwon. Methodology: Hyoung-Taek Hong. Project administration: Kwan Kyu Park and Kyoung-Tak Kang. Resources: Kwan Kyu Park. Software: Hyoung-Taek Hong. Supervision: Yong-Gon Koh. Validation: Kyoung-Tak Kang. Visualization: Kyoung-Tak Kang. Writing—original draft: Hun Sik Cho. Writing—review & editing: Kwan Kyu Park and Kyoung-Tak Kang. Approval of final manuscript: all authors.

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