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Can making parametric finite element models of the knee that include anatomical details important for osteoarthritis improve the clinical effectiveness of treatment methods?

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ABSTRACT

Osteoarthritis (OA) is a degenerative condition that impacts synovial joints, particularly the knee joint, impairing patients' capacity to engage in regular physical activity. Regrettably, there is no remedy for this musculoskeletal condition. Currently, numerous researchers focus on developing ways to model individualized risks for the initiation and progression of osteoarthritis and assess the impact of various conservative preventive measures. Finite element analysis (FEA) is now known as a potential technique for the management of knee osteoarthritis. The FEA pipeline comprises three recognized phases: pre-processing, processing, and post- This study aims to introduce an innovative concept in the customization of knee prosthesis, considering the anatomical characteristics influencing osteoarthritis, to enhance treatment efficacy. We posited that anatomical parameters in simplified knee models can be adjusted so that the estimation of the tissue mechanical response from a parametric model matches that of a model with precise geometry. Consequently, we want to integrate simpler models with individualized modeling to provide successful treatment solutions that will help clinicians identify individuals at high risk of knee OA and provide more conservative treatments for patients.

Introduction

The knee is a synovial joint that transmits load and motion transfer between the distal femur and proximal tibia, aided by the lever function of the patella [1]. A slender coating of articular cartilage envelops the bone extremities, facilitating nearly frictionless interaction between the bones and diminishing impact pressures on the joints [2]. The crescent-shaped menisci, situated between the femur and tibia in both the lateral and medial compartments, diminish contact stresses on the articular cartilage [1]. Ligaments maintain the knee joint and limit excessive movements during various physical activities, whereas tendons convey muscular forces to bone structures [3]. All knee joint tissues function synergistically to preserve joint health; however, when the functionality of any knee component is compromised, such as by alterations in geometric parameters or trauma, the joint becomes susceptible to the onset of osteoarthritis (OA) [3].

Osteoarthritis is a degenerative condition that diminishes the mechanical characteristics of articular cartilage and bone [4]. Over 527 million individuals worldwide suffer from knee osteoarthritis [5]. Treatment of symptoms and surgical procedures renders osteoarthritis a costly disease for nations, with an economic burden of roughly 2 % of GDP [6]. The huge increase in the number of knee replacement surgeries, usually for severe osteoarthritis, in the past few years, especially among young people, is cause for alarm [7]. Therefore, it is crucial to implement efficient interventions that focus on enhancing comprehension, control, and mitigation of related risk factors [7]. The primary risk factors for the initiation and advancement of osteoarthritis include age, sex, genetic predisposition, obesity, joint misalignment, joint anatomy, and trauma [3,8]. Examining the risk factors influencing osteoarthritis is beneficial for clinical comprehension [9]. Studies have indicated that

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knees affected by osteoarthritis are likely to have similar morphological features [10,11]. It is possible that the size or volume of the condyles or the slope of the tibial plateau may influence the course of osteoarthritis and knee joint destruction. We hypothesized that these anatomical characteristics may play a role in the pathogenesis of knee osteoarthritis. After evaluating the current evidence, we designed a study to assess whether tibial plateau tilt (TPT), cam effect (CE), and tibial plateau coverage by femoral condyles (TPCFC) influence the contact forces, strain, and displacement generated at the articular surface of the tibial plateau in individuals. Gathering data and insights regarding the role of anatomical factors may be crucial for comprehending the pathogenesis or course of this prevalent disease. We hope that our hypothesis will stimulate further studies to confirm whether anatomical features play a greater role in the pathogenesis of knee osteoarthritis.

The hypothesis

Modifying the geometric attributes of the knee joint influences its biomechanical properties. Previous studies have shown that the TPT, CE, and TPCFC are greater in patients with knee osteoarthritis compared to those without symptoms [11,12]. We hypothesized that the shape of the medial and lateral condyles on the femoral side is associated with the incidence of osteoarthritis. Similarly, on the tibial side, the slope of the tibial plane is linked to the incidence of osteoarthritis. Additionally, there is a relationship between the coverage of the articular surface occupied by the femoral condyles in the tibial plane and the incidence of osteoarthritis. Using a knee model capable of modifying the knee joint geometry based on the optimal values of parameters such as TPT, CE, and TPCFC for individual subjects, we can evaluate the biomechanical responses of the knee affected by changes in these geometric parameters. Furthermore, we hypothesized that by developing a customized knee joint prosthesis based on the optimal values of the parameters α, a, b, c, LM, and HL biomechanical responses of the knee may be improved.

Evolution of the hypothesis

In the knees, where the cam effect increases, the inner condyle of the femur has a more oval shape. Consequently, increased slipperiness and ligament laxity are required for knee flexion movement. Consequently, a shear force is produced on the inner plateau of the tibia, accelerating the advancement of osteoarthritis in [11,13,14]. A study on amputated knees revealed that knees affected by osteoarthritis exhibited greater contact areas [15]. The flattening of the femoral condyles resulting from secondary osteoarthritis likely enhances coverage of the tibial plateau in knees affected by osteoarthritis [16]. Furthermore, when standing, the knee's range of motion is between 0 and 20 degrees of flexion. If the slope of the tibial plateau is 10 degrees, the sine of 10 degrees equal to 17.3 % of the body weight is converted into a shear force [17]. If the knee flexion is 10 degrees, it will be neutralized, and all the force of the body's weight will be converted into compressive forces. However, if the tilt of the tibial plateau increases beyond 10 degrees, it also increases the shear force, which can lead to the onset and progression of osteoarthritis in people's knees [11,18]. The main goal is to better understand how knee osteoarthritis develops and provide solutions to reduce its effects. There are promising computational techniques that attempt to take into account the geometric factors that affect osteoarthritis. Consequently, there is a clear need to develop clinical tools.

Finite element (FE) analysis is a computational method that addresses physics-based problems through the use of constitutive and governing equations. For three decades, FEA has served as a non-invasive method to investigate the influence of various biomechanical risk factors on knee joint tissues. The technique has aided researchers in comprehending the mechanisms of cartilage degeneration at the tissue level and the biomechanics of the knee joint under diverse loading circumstances [19–22]. An FEA is typically conducted in three phases: a pre-processing phase to build the model, a processing phase to solve the mathematical issue, and a post-processing phase to analyze the results and derive conclusions [23,24]. The primary limitation for clinical implementation of knee joint FE analyses is the time necessary to create precise subject-specific models, which include intricate three-dimensional (3D) geometries and feasible FE meshes, often requiring several working days [24,25]. Given the intricate geometry of the knee, the models incorporate complex interfaces, necessitating substantial time spent on preprocessing, processing, and postprocessing stages within the FE analysis. This makes them unsuitable for use in clinicals [23]. Conversely, the presence of intrinsic geometric diversity among individuals may add a level of uncertainty to the outcomes of models that rely on an individual. and diminish their reliability [24]. Consequently, this hypothesis seeks to fill the current gaps by evaluating the influence of anatomical features on the amount of strain and displacement generated at the articular surface of individuals by a parametric FE model of the knee joint that is capable of varying geometric factors. The development of personalized FE analyses based on geometric factors is crucial for assessing the causes of the onset and progression of knee osteoarthritis and for using optimal values of geometric parameters in the design of custom knee prostheses in the future. We hypothesize that by analyzing the biomechanical responses (strain, and deformation) of the knee joint of individuals with osteoarthritis, which are obtained using a personalized FE model with the ability to change the geometry of the knee joint in the anatomical factors TPT, CE, and TPCFC, we may create a new window for designing customized prostheses with the most appropriate values for knee joint replacement cases. If this hypothesis is carried out, we can determine what changes in each of the above geometric parameters lead to what changes in the values of strain, and deformation at the articular surfaces of the knees of individuals.

Hypothesis testing

To estimate the optimal values of TPT, CE, and TPCFC parameters for use in customized knee prostheses, we use the parametric FE model of the knee joint [26]. In the above parametric model, by changing each of the values related to the height and diameter of the femoral condyles, the amount of contact surface of the condyles with the articular surface of the tibial plateau and the slope of the tibial plateau, the amount of contact force, strain, and displacement created can be evaluated. And finally, the predicted optimal values for each of the factors can be used in the design of customized knee joint prostheses for individuals. The variables a, b, c, Lm, Hl, and α' shown in Fig. 1 represent the contact surfaces of the medial (a) and lateral (b) condyles of the femur, the articular surface of the tibial plateau (c), the maximum diameter of the medial femoral condyle (Lm), the height of the lateral femoral condyle (Hl), and the anterior slope of the tibial plateau (α'), respectively. Equations (1) to (3) show the role of each of the above geometric features in calculating the optimal values of the TPT, CE, and TPCFC parameters. Ultimately, by examining the impact of altering each geometric parameter α, a, b, c, LM, and HL on the biomechanical responses of the knee joint, it may facilitate the development of a novel approach to constructing tailored prostheses for individuals, utilizing the ideal values forecasted by our model.

$$\mathrm{TPT}(\alpha) = 90 - \acute{a} \tag{1}$$

$$\mathrm{CE} = L_M / H_L \tag{2}$$

$$\mathrm{TPCFC} = \frac{(\mathrm{a}+\mathrm{b})}{\mathrm{c}} * 100 \tag{3}$$

In the next step to simulate a knee joint prosthesis, we can create the overall geometry of the joint by reconstructing the CT scan of the bone structures and directly digitizing the soft tissue boundaries and ligament attachment sites in the individual using MIMICS software and simulate parametric models of the knee joint prosthesis based on six parameters

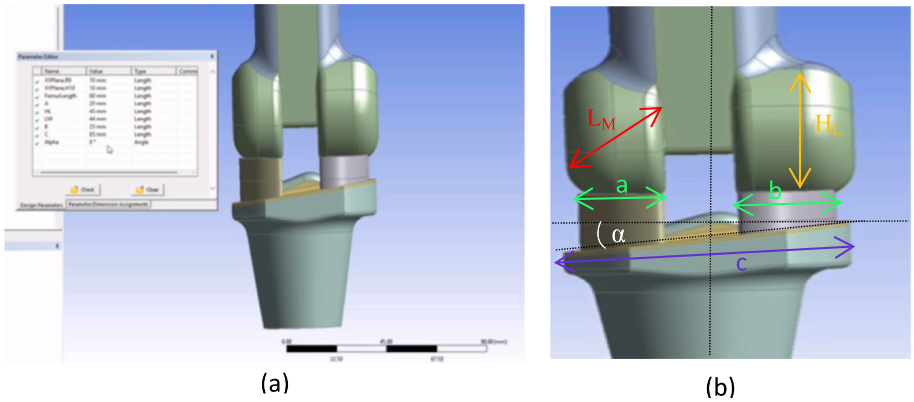

Fig. 1. A: View of the parametric knee model with the ability to customize the anatomical parameters α a, b, c, L_M, H_L and α′ in the ANSYS environment; **1.b**: Location of parameters in the parametric knee model.

α, ά, LM, HL, b, and c in ANSYS software. This hypothesis states that the development of knee joint prosthesis modelling will rely on the morphology of three bones (tibia, patella, and femur), articular cartilage layers, meniscus, and four ligaments (ACL, PCL, LCL, and MCL in TF) [27]. In addition, it includes the following geometric parameters, respectively: α, a, b, c, LM, and HL. A visual summary of the steps of modelling is shown in Fig. 2. Finally, by analyzing the effect of changing each of the geometric parameters α, a, b, c, LM, and HL on the biomechanical responses of the knee joint, a customized prosthesis can be created for individuals with the optimal values predicted by our model.

Implications

To validate the proposed hypothesis, we first evaluated the effect of the TPT, CE, and TPCFC parameters on the strain and displacement rates. The parameter ranges were divided into three categories: (L-TPT < 10.5, $10.5 \leq$ M-TPT < 12.5, H-TPT ≥ 12.5), (L-CE < 1.8, $1.8 \leq$ M-CE < 1.9, H-CE ≥ 1.9), and (L-TPCFC < 50.5, $50.5 \leq$ M-TPCFC < 52.5, H-TPCFC ≥ 52.5). This evaluation showed that the models specific to different geometries show different responses, which emphasizes the importance of considering different geometries. The mechanical responses observed with the models in the literature confirm the important effects of geometry [26]. Furthermore, we performed a comparison between the results obtained from FE models in both the control and OA groups (Fig. 3).

Fig. 3 illustrates the mean total displacement and peak strain in two cohorts, osteoarthritis and control, utilizing individualized values of TPT, CE, and TPCFC within the parametric FE model of the knee joint. The average total displacement across all three examined geometric parameters was shown to be lower in the OA group compared to the control group. Furthermore, the results indicated that the average maximum strain, predicted by the parametric model, was higher in the OA group across all three categories and for the three analyzed geometric parameters. Furthermore, the category M−TPCFC had the lowest amount of displacement compared to the other categories, and the H groups demonstrated the greatest level of strain compared to the other two groups. Consequently, based on the observed data, we anticipate that determining the ideal values of the three parameters TPT, CE, and TPCFC for individuals and the fabrication of knee prostheses, derived from the calculated optimal values, may be able to significantly enhance knee prostheses.

If our hypothesis is confirmed, it will have important implications for the treatment and management of OA. Early prevention through imaging studies and parametric simulation models may help individuals at risk for developing knee osteoarthritis. In addition, targeted rehabilitation programs aimed at strengthening the quadriceps and hamstrings may be effective in reducing the degree of osteoarthritis. Furthermore, designing customized prostheses with optimal geometric factors for individuals could provide better long-term treatment effects for patients who are candidates for knee replacement. Modifications to CE, TPCFC, and TPT may be able to reduce contact pressure at the tibial articular surface, thereby reducing knee strain and displacement.

Future research can prioritize validating our hypothesis by fabricating personalized knee prostheses tailored to individual patients' anatomical parameters. This validation process should involve comparing model predictions with results from cadaveric experiments to assess accuracy. Additionally, patient follow-ups after corrective muscle strengthening exercises will be crucial to evaluate the long-term effectiveness and functional improvements provided by these customized prostheses.

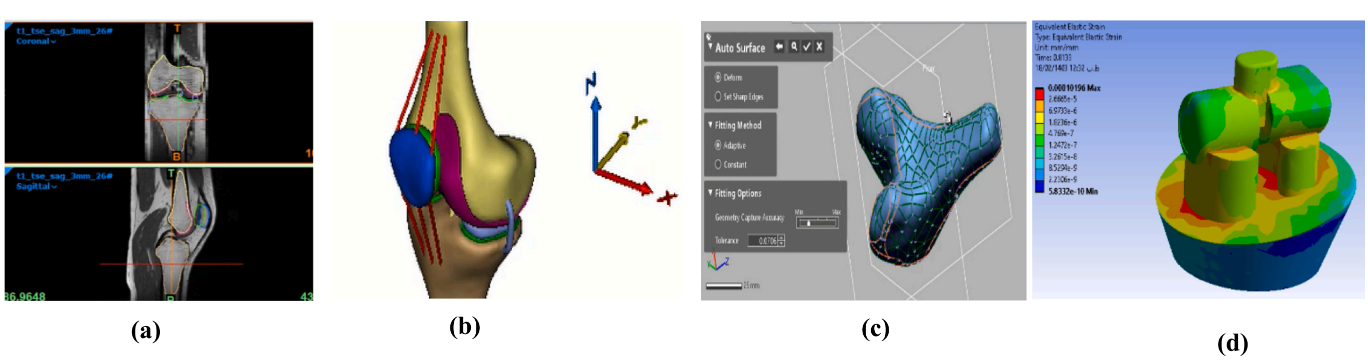

Fig. 2. Steps of custom FE modeling for a knee joint prosthesis. 2.a: X-ray image retrieval in Mimics software 2.b: Creation of a surface model of the knee joint 2.c: Design of the initial design using reverse engineering based on the geometry extracted from the X-ray images; 2.d: An example of strain calculated for the parametric FE model for the OA group.

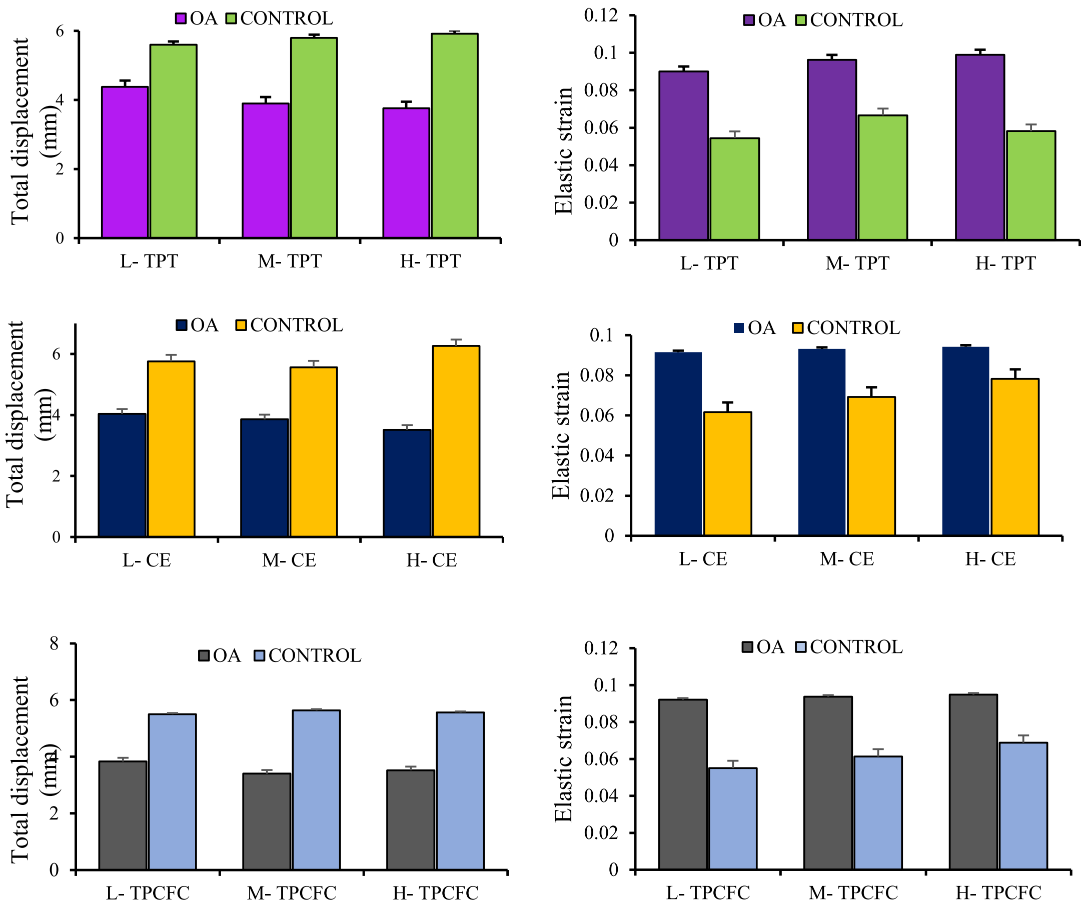

Fig. 3. Illustrates the increase in total deformation and elastic strain within customized geometric parameters for both groups. the parameter ranges were divided into three categories: (l-tpt $< 10.5, 10.5 \leq$ M$-$TPT < 12.5, H-TPT ≥ 12.5), (L-CE $< 1.8, 1.8 \leq$ M$-$CE < 1.9, H-CE ≥ 1.9), and (L-TPCFC $< 50.5, 50.5 \leq$ M$-$TPCFC $<$ 52.5, H-TPCFC ≥ 52.5).

Limitations of the hypothesis

This study primarily uses a combination of simple geometries to create a model suitable for investigating the role of relevant anatomical factors on the biomechanical responses of the knee, which is an unavoidable feature of parametric modelling. As a result, the influence of intricate geometry is overlooked, which, as expected, may modify the local biomechanical results. The second constraint stems from the presumption of consistent mechanical properties among numerous individuals. This unavoidable obstacle stems from the intricacy of directly acquiring the mechanical properties of stiff and soft tissues from X-ray images. Another constraint of our FE model is the neglect of active muscle forces and gait kinematics. This modelling technique currently seeks to analyze the biomechanical response to static loads. Integrating customized muscle forces into the model and accounting for variations in posture should be highlighted in future research.

Conclusion

In conclusion, we propose that the α, a, b, c, LM, and HL may be contributing factors in the development of osteoarthritis in individuals. This hypothesis is supported by existing research on the role of geometric factors in osteoarthritis and is consistent with biomechanical observations. Further research is needed to test this hypothesis and investigate potential mechanisms between the modification of anatomical parameters and the development of osteoarthritis. These insights could lead to the development of novel diagnostic and therapeutic strategies for OA.

In summary, this hypothesis presents the idea of creating personalized knee prostheses based on geometric parameters α, a, b, c, LM, and HL that could induce better biomechanical response in individuals undergoing clinical knee replacement interventions. We posit that, despite the simple geometry, these models will furnish doctors with critical insights regarding the impact of anatomical parameters that can be beneficial in the design of knee prostheses. Consequently, it can be hoped that knee replacement surgery will lead to better clinical outcomes.

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Consent to participate

Written Informed consent was obtained from all individual participants included in the study.

Consent to publish

The authors affirm that human research participants provided informed consent for publication of the images and data.

CRediT authorship contribution statement

Fatemeh Abdollahpour: Writing – original draft, Validation, Supervision, Software, Project administration, Investigation, Conceptualization. **Goldis Darbemamieh:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Mohammad Nikkhoo:** Writing – review & editing, Visualization, Software, Project administration, Methodology, Investigation, Conceptualization. **Kamran Hassani:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Sadegh Rahmati:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. It has local Approval by the Ethics Committee of University Islamic Azad University, Central Tehran branch. Approval number: C1403-0319-4.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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