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Original Research Article

Stress response of patellofemoral joint subjected to femoral retroversion with various patellar kinematics and flexions – An FEA study

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ABSTRACT

The purpose of this study is to observe the stress response of the patellofemoral joint associated with three patellar kinematics: shift, spin and tilt under femoral retroversion conditions. By assigning various flexions and different loads, the stresses were quantified in the bones, tendons, cartilages and cartilage–bone interface. Four different loads of 600, 657, 706 and 753 N were applied on 12 models representing each of the various kinematics of shifts, spins and tilts of the patella with femoral flexions of 30°, 60°, 90° and 120° which gave results for 48 analyses. The 'Q' angle of the femur bone was maintained at 14° with femoral retroversion of 21°. Based on the patellar kinematics, three different cases were modeled as (a) 5 mm shift 10° spin 4° tilt, (b) 10 mm shift 13° spin 8° tilt, and (c) 15 mm shift 16° spin 12° tilt. Medial shift, spin and tilt with femoral retroversion were limited in this study. The femoral displacement for 30° flexion at 600 N was found to be same in all the (a), (b), and (c) cases. Similarly, respective same displacements were achieved in all three cases when subjected to 60° flex at 657 N, 90° flex at 706 N and 120° flex at 753 N. From the simulated results it is inferred that femoral retroversion with case (b) kinematics susceptibly dominated by the cartilages causes patellofemoral joint pain, arthritis and instability due to the larger contact areas between the patella and femur bone at flexions 60° and 90°.

1. Introduction

The patellofemoral joint (PF joint) is gaining more attention in the field of orthopedic biomechanics due to such associated instabilities such as patellar maltracking and patellofemoral pain syndrome [1,2]. The reasons that dominate the causes and effects of the PF joint are due to the knee varus–valgus conditions, excessive 'Q' angles in both genders without any structural changes or by any significant pathological changes in the articular cartilage [3], femoral retroversion and ante-version with medial and lateral patellar kinematics such as

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patellar shifts, spins and tilts. Various literature studies have reported investigative methods on patellofemoral instability, pain and maltracking by considering only two factors of patellar movements i.e., patellar shift and spin or spin and tilt or tilt and shift. In some clinical cases, analytical and experimental methods were conducted with femoral retroversion and anteversion conditions, but patellar kinematic factors were not often considered. This paper reports a simulated approach on stress analysis of a three dimensional human PF joint under different loads for the given boundary conditions during various flexions by considering all the three patellar kinematics along with femoral retroversion and 'Q' angle at the same time. The study is limited to only femoral retroversion with medial shift, spin and tilt conditions since most of the literature studies shows cases related to out toe conditions. Moreover, adopting all the factors related to the PF joint and its associates may give a better understanding for the orthopedic surgeons and physicians in determining what factors contribute in assessing the biomechanics of the joint of a patient [4].

2. Materials and methods

CT scan machine ''SOMATOM Definition AS'' (Siemens, Germany) was used to acquire two dimensional sliced gray scale magnetic resonance images with each slice thickness of 1 mm from an untreated cadaver knee bones of approximately 30–35 years age, male, right leg consisting of femur, patella and tibia. The images were saved in DICOM (Digital Imaging and Communications in Medicine) format.

The 2D DICOM images were imported into MIMICS software package (Materialise's Interactive Medical Image Control System software) through which three dimensional hollow CAD models of each bone were generated with the assistance of several visualization tools such as segmentation, region growth, thresholding and wrapping technique. Apart from the visualization tools used, a volume mesh was performed to reduce the number of bad triangles in the 2D elements to obtain a finer and smooth model. The model was exported as . stl (stereolithography) file which was compatible to import into Altair's Hypermesh platform to perform stress analysis.

Initially, the femur, patella and tibia bone models when imported into the Hypermesh platform, they appeared to be in Cartesian coordinates. However, the volume mesh performed in the MIMICS consists of irregularly sized and shaped 2D elements. Since it is a 3D hollow model, the surface geometry of each bone model should be extracted in order to remesh the geometry so that the irregular 2D elements are more ordered. The surface geometry was achieved by generating a new mesh that consists of both triangle and quadrilateral 2D elements with an average size of 1.0 mm and a tolerance of 0.010. The meshing was performed with 2D quadrilateral (mixed) so that the entire geometry is captured and thus the elements resulted in more ordered and finer mesh. After the surfaces are generated they must be visually inspected to ensure whether there are no free edges or interpolation errors (abnormal curves in the surface topography) which hindrances the connectivity of the elements. These can be rectified by deleting the complex surfaces and manually developing a new surface using the built in functions of the Hypermesh software.

The head, trochanter and the shaft of femur were remeshed with 2D quadrilateral (mixed) elements. Since our area of interest was focused only at the PF joint, the epicondyle region of the femur bone was remeshed with triangular elements to provide better results during analysis. The patella bone was remeshed with triangular elements since the epicondyle region of the femur has to have connectedness without any complexity between the femur and patella bone associated with its cartilages. 2D quadrilateral elements were used to remesh the tibia bone.

Finally the 2D mixed quadrilateral (Triad and Quad) and the triangular elements were converted into tetramesh to obtain a 3D solid element for all the bones. After converting the bones into 3D solid models, the femur bone had 559,241 elements, the patella had 24,566 elements and the tibia bone had 432,807 elements. The 2D quadrilateral articular and patellar cartilages were meshed into 3D hexahedral mesh so that the tetrameshed femur bone interfaces with the hexahedral cartilage elements without any complexity, thus forming a cartilage–bone interface. The same process is carried out to attach the patella bone with the patellar cartilage. The hexahedral meshed articular and patellar cartilage elements were found to be 20,612 and 6243.

The quadriceps tendons, patellar tendons, medial and lateral retinaculum bundles were modeled as 1D element strings. The quadriceps tendons were represented by 22 strings with a spring stiffness of 1350 N/mm. The patellar tendons, medial and lateral retinaculum bundles were represented with 10 one-dimensional strings each, with a spring stiffness of 2000 N/mm for the patellar tendons [5].

3. Analysis

Hypermesh V11 software with Optistruct mode was used to perform Von misses stress analysis on the PF joint through which the response of the joint associated with its cartilages and tendons were observed during each loading conditions for the assigned boundary conditions at various flexions and patellar kinematics. In the previous PF joint literatures, simulation and experimental techniques were performed by determining the patellar kinematics either by shift–spin or spin–tilt or tilt–spin with femoral anteversion and retroversion conditions. An average range of 5–20 mm medial–lateral shift movements, spin ranging from 8–18°, tilt ranging 4–15° and femoral anteversion–retroversion angles ranging from 8–25° were adopted in all previous literature cases related to the PF joint. In our study, we have performed a simulated approach of analyzing the PF joint based on considering all the three patellar kinematics (shift–spin–tilt) at the same time during each flexions with various loads. A total number of 48 analyses were simulated by changing the patellar kinematics to medial: shift ranging from 5–15 mm, spinning range 10–16° and tilting range from 4–12° with femoral retroversion as 21° constantly and by maintaining femur 'Q' angle as 14° throughout the entire analysis.

All six degrees of freedom at the distal end of the femur bone were constrained. The other end was not constrained as

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