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Analyzing Patellar Response to Impact Loads: Enhancing Safety through Simulation

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Abstract

Accidents, particularly those affecting the lower body, frequently result in bone injuries, with the knee, encompassing the patella, being especially susceptible due to its exposed position. Patellar fractures, common in falls or accidents, cause significant pain and impairment. Situated at the front of the knee, the patella provides structural support and ensures proper knee function. Its vulnerability to damage from impacts, such as those in traffic accidents or sports-related falls, is well-documented, with athletes being particularly at risk due to the dynamic movements involved in sports activities.

To assess the impact of such loads on the patella, researchers have utilized advanced techniques like Finite Element Analysis (FEA). By employing CT scans and software like 3D Slicer and Ansys Space claim, a 3D model of the patella is generated and further developed into a Finite Element Model (FEM) using Ansys Workbench. FEA simulations allow researchers to understand the behavior of the patella under various loading conditions.

Studying the patella's response to impact loads via FEA provides invaluable insights into its structural integrity and susceptibility to fractures. This knowledge is instrumental in designing preventive measures and protective gear to mitigate injury risks in both everyday accidents and high-impact activities like sports.

In conclusion, analyzing the patella's response to impact loads is essential for enhancing safety and preventing fractures. Advanced techniques such as FEA and 3D modeling enable researchers to comprehend the mechanics of patellar injuries better, leading to more effective preventive strategies and interventions.

Index Terms: *Patella, CT scan, 3D Slicer, ANSYS Space claim, ANSYS Workbench*

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1. Introduction

The patella, or kneecap, stands out as the largest sesamoid bone in the human body, positioned snugly between the femur and tibia. It boasts a unique groove on the femur, acting as a track for its movement, while both neighboring bones are safeguarded by protective cartilage. Sesamoid bones are also found in hand and foot flexor muscle tendons, particularly in regions exposed to significant bending and friction stress.

Integral to the knee joint, the patella resides within the tendon of the quadriceps femoris muscle. Its primary function involves reducing friction over the femur's patellar surface during active lower leg extension, thus protecting both the quadriceps tendon and thigh bone cartilage. Additionally, sesamoid bones like the patella redirect muscle traction vectors at insertion points, enhancing muscle efficiency. Specifically, the patella significantly boosts quadriceps femoris efficacy during lower leg extension, improving its action by about 40%.

Bone fractures, commonly referred to as broken bones, affect numerous individuals due to sports injuries, automobile accidents, or falls. In the context of the patella, any injury is labeled as an acute patellar injury, marked by its sudden onset. Serving as a protective shield for the knee joint and its soft tissues, the patella is deeply embedded in the patellar and quadriceps tendons. These injuries often result from external objects colliding with the kneecap, high-impact pressure on the knee during speedy ground contact, traction injuries involving the patellar tendon under weight-bearing, or forceful quadriceps muscle contraction when the knee is in a valgus position, potentially displacing the patella. These various injury mechanisms underscore the patella's vulnerability and its crucial role in knee joint function.

Patellofemoral pain (PFP) is a common orthopedic complaint, contributing to 25%–40% of knee injuries (Liao et al., 2015). Activities such as squatting, running, and stair climbing exacerbate this pain, significantly limiting daily functioning for those affected (Fick et al., 2022). Despite extensive research, the exact mechanisms underlying PFP development remain unclear (Vannatta and Kernozek, (2015). However, a prevalent theory suggests that increased stress on the patellofemoral joint (PFJ) plays a central role (Salsich and Perman, 2007). Chronic overuse of this joint leads to elevated intraosseous pressures, resulting in pain, microfractures, heightened bone metabolism, and increased bone water content, all of which detrimentally affect the subchondral bone (Ho et al., 2014).

Studies indicate that individuals with PFP experience heightened PFJ stress during walking and running compared to those without pain (Farrokhi et al., 2011b; Liao et al., 2015). Given these associations, PFJ stress emerges as a crucial factor in evaluating patellofemoral load. Understanding PFJ stress not only aids in preventing injuries but also in assessing the effectiveness of PFP rehabilitation programs.

The analytical model stands as the predominant method for assessing patellofemoral joint stress (PFJS), relying on formulas derived from previous cadaver experiments. However, this classic model has notable limitations, such as its failure to incorporate synergistic muscle contraction and its focus solely on sagittal plane factors concerning PFJS (Bonacci et al., 2014; Atkins et al., 2019). In pursuit of greater accuracy, alternative methods have emerged, including musculoskeletal models, discrete element analysis (DEA), and finite element analysis (FEA). Nunes et al. conducted a systematic review of literature employing analytical models to evaluate PFJS, proposing potential improvements to the evaluation paradigm (Nunes et al., 2018). However, a notable limitation of this review is its narrow definition of PFJS assessment methods, overlooking musculoskeletal modeling, DEA, and FEA. Given advancements in PFJS evaluation technology and an increase in studies since the previous review, a fresh literature review is warranted to encompass these methodologies comprehensively.

These studies collectively contribute valuable insights into the biomechanics, clinical aspects, and structural properties of the patella bone, offering essential knowledge for medical practitioners, researchers, and engineers working in the field of orthopaedics and bone health.

2 ANALYSIS OF PATELLA:

The geometry of the Patella is created and it is meshed using tetrahedral mesh elements. 1323525 nodes and 774442 elements are created in the mesh. The boundary conditions are fixed-free. The loading and boundary conditions are as follows:

1. The medial articular facet and lateral articular facet of the patella are fixed.
2. Impact loads of 10 KN and 20 KN are applied in the anterior portion of the patella.

The patella with mesh and constraints are shown in Fig. 1.

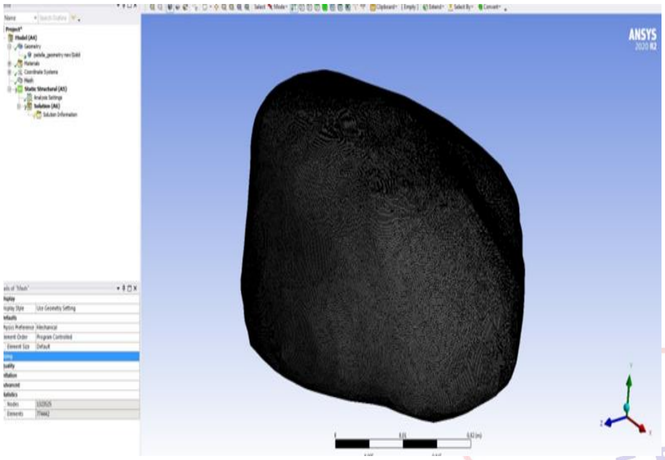

Fig-1: Patella with mesh and constraints

Constraints:

The patella is considered as a single seismoid bone without considering the joints and tissues, hence the medial articular facet and lateral articular facet of the patella are fixed.

The stresses and deformation for 10 KN and 15 KN are shown from Fig. 2 to Fig.5.

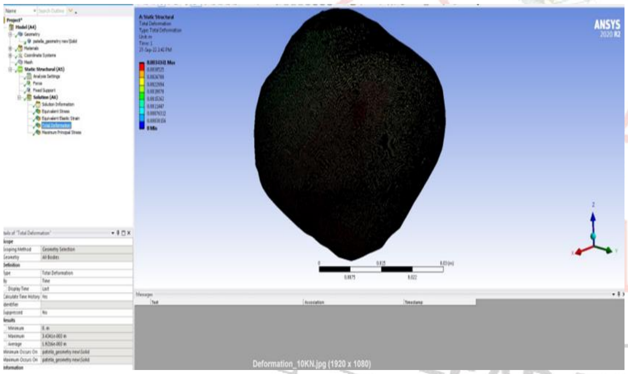

Fig-2: Displacement for 10 KN

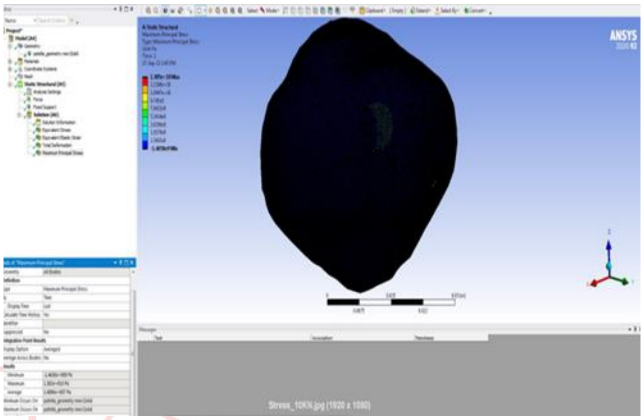

Fig-3: Displacement for 10 KN

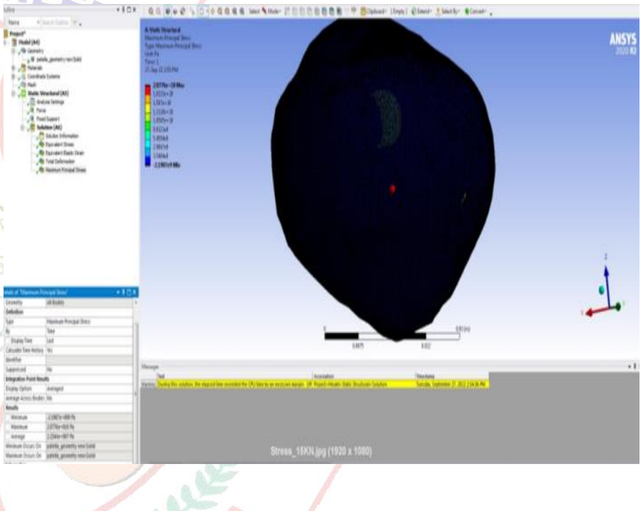

Fig-4: Stress for 15 KN

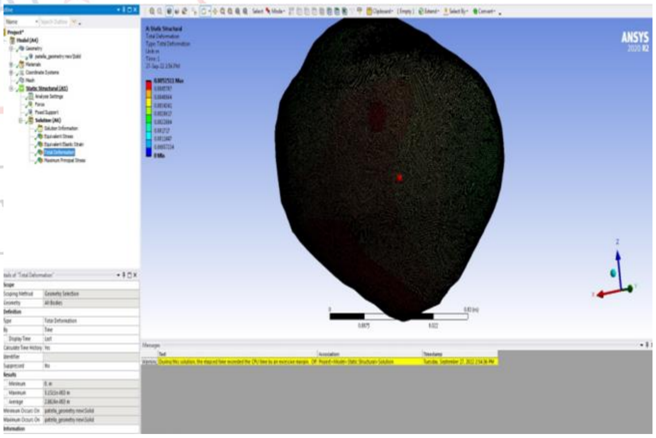

Fig-5: Displacement for 15 KN

The impact stress for the given loads is determined from the formula

$$\boldsymbol{\sigma_i=\sigma[1+[\surd 1 + 2h\delta]]}$$

Where **σi**= Impact stress; **h**=height; **δ**= static deflection; σ = static stress

1) σi for 10 KN

δ = 2.4 mm, **h** = 100 mm, **σ** = 13.85 MPa

σi = 140.993 MPa

2) **σi** for 15 KN

δ = 4.8 mm, **h** = 100 mm, **σ** = 20.77 MPa

σi = 156.43 MPa

Results of Patella subjected to static and impact load:

Stress and Displacement results are shown in Table 1

Sl. No.	Load (Newton's)	Displacement (mm)	Stress (MPa)
1	10000	3.05	13.85
2	15000	5.15	20.77
3	10000 (impact)	-	140.993
4	15000 (impact)	-	156.43

From the results of the analysis it is found that, the bone can withstand static load and stress induced as well within the Yield point, but the bone fractures at impact loads, because of high stresses which are higher than the yield strength of the bone. Hence fracture of patella takes place.

3. CONCLUSION

The primary goal of this research is to develop a comprehensive patella model based on CT images, facilitating stress analysis through the utilization of ANSYS. By subjecting the patella model to various forces, the study aims to analyze stress and displacement, providing valuable insights into the bone's behavior under different loading conditions.

The investigation delves into understanding the response of the patella bone to both static and impact loading scenarios, considering the prevalence of bone fractures resulting from sports injuries, automobile accidents, and falls. Among all bones in the human body, the patella is particularly susceptible to injuries, necessitating a thorough analysis under various loading conditions.

In the static loading phase, forces of 10 KN and 15 KN were applied to the patella, keeping in mind its yield strength of 89 MPa. The analysis outcomes revealed maximum stress levels of 13.85 MPa and 20.77 MPa, respectively, under these loads. Notably, during impact loading conditions, where fractures are more likely to occur, analytically calculated impact stresses reached values of 140 MPa and 156.43 MPa at the specified loads. Crucially, the study demonstrates that the impact stresses exceed the bone's yield strength, leading to fractures during impact loading. This is attributed to the elevated impact stresses generated during such loading conditions.

The practical implications of this research extend to aiding orthopedic doctors in the precise diagnosis of patella conditions. The findings offer valuable information for assessing the strength and resilience of the patella bone, contributing to enhanced medical understanding.

Future research endeavors involve experimental testing on real bones by applying diverse forces and subsequently comparing the results. This approach will provide a more comprehensive understanding of the patella's strength, informing medical professionals about the bone's performance under varying conditions. The outcomes of these future studies will likely offer additional insights and further refine our understanding of patellar mechanics.

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