Relation between First Metacarpal Head Morphology and First Metacarpophalangeal Joint Degenerative Joint Disease: A Computer Model

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ABSTRACT

Background: Degenerative Joint Disease (DJD) of the first Metacarpophalangeal (MCP) joint, can severely impair hand function due to pain, stiffness, and reduced range of motion. Anatomical variations in metacarpal head morphology may play a critical role in altering joint biomechanics and stress distribution, potentially accelerating cartilage wear and osteoarthritis progression.

Objective: This study aimed to evaluate the biomechanical impact of different first metacarpal head morphologies on stress distribution within the MCP joint under various positions using computer simulation.

Material and Methods: In this computer simulation study, three-dimensional models of the thumb MCP joint were reconstructed from Computed Tomography (CT) scans of healthy subjects. The models were adjusted to represent flat, biplanar, and convex metacarpal head morphologies and were simulated in three positions: neutral, 20° flexion, and 20° extension. Computer simulation was performed using Analysis System (ANSYS) to calculate von Mises stress distributions. Descriptive statistics and one-way Analysis of Variance (ANOVA) were applied to compare stress values between groups.

Results: The flat metacarpal head exhibited the highest stress concentrations, peaking at 138 MPa in 20° extension. Biplanar morphology showed moderate stresses, while the convex shape demonstrated the lowest stress, with a maximum of 58 MPa. The analysis confirmed significant differences between groups (P-value=0.039). Stress increased notably in flexion and extension positions compared to neutral across all morphologies.

Conclusion: Metacarpal head morphology and joint positioning significantly influence MCP joint biomechanics. Flat and biplanar shapes increase stress concentration, potentially elevating DJD risk. Convex morphology offers better stress dispersion, indicating a biomechanical advantage.

Keywords

First Metacarpophalangeal Joint; Degenerative Joint Disease; Metacarpal Head Morphology; Osteoarthritis; Biomechanics; Computer Simulation; Orthopaedics

Introduction

Degenerative Joint Disease (DJD), also known as Osteoarthritis (OA), is a progressive musculoskeletal disorder characterized by cartilage degradation, subchondral bone remodeling, synovial inflammation, and osteophyte formation [1]. While DJD predominantly affects weight-bearing joints, such as the knees and hips, it

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can also involve smaller joints of the hand, including the first Metacarpophalangeal (MCP) joint. The first MCP joint, located at the base of the thumb, plays a vital role in hand function, contributing to grip strength, fine motor control, and overall dexterity. When affected by DJD, patients often experience pain, stiffness, swelling, and reduced range of motion, leading to significant impairment in daily activities such as writing, grasping, and manipulating objects [1-3].

Although DJD of the first MCP joint is less common than osteoarthritis of the first Carpometacarpal (CMC) joint, it remains an important cause of disability, particularly among individuals engaged in repetitive hand-intensive activities, manual labor, or sports. The etiology of first MCP DJD is multifactorial, with contributing factors including aging, joint instability, previous trauma (such as fractures or ligament injuries), and mechanical stress [2-5]. However, emerging evidence suggests that the morphology of the metacarpal head itself may play a critical role in the development and progression of DJD. Variations in the shape of the metacarpal head, such as biplanar, flat, or convex configurations, may influence joint biomechanics, load distribution, and cartilage wear patterns, ultimately impacting disease susceptibility [6,7].

In this study, we aimed to investigate the role of metacarpal head morphology in first MCP DJD using a computer-based approach in Materialise Mimics, a powerful software for 3D reconstruction and analysis of anatomical structures from medical imaging data. This investigation will provide valuable insights into the structural determinants of first MCP DJD, potentially guiding future clinical strategies for early detection, personalized treatment approaches, and even surgical decision-making.

Material and Methods

Study Design

This computer simulation study used a randomly selected Computed Tomography (CT) scan of three young healthy cases, with no previous history of significant injury to the thumb, with no previous medical history in Chamran Hospital in Shiraz, Iran. Materialise Mimics Research version 21 software was used for the 3D design of the hand. The files were imported, evaluated, and modified, and a mask for the bony segment was created based on specific Hounsfield unit values.

The pre-design process focused on the metacarpal and proximal phalanx bones, excluding surrounding areas, and artifacts and noises were eliminated. Further refinement was done using 3-Matic Research version 13 software.

The final models were obtained after adjusting the MCP joint based on the morphology of the metacarpal head (flat, biplanar, and convex) and the position of the joint (extended, flexed, and neutral position) (Figure 1). The models were meshed using ANSYS R2 2020, with an average number of nodes and elements of 214354 and 223794, respectively. The mesh convergence study was conducted, and changes were made in the meshing process to ensure accurate modeling with a stress change below 1%.

The distal end of the metacarpal bone was fixed, and a force was applied from the top of the proximal phalanx. The two bones were connected using wires that replaced the Ulnar Collateral Ligament (UCL) and Radial Collateral Ligament (RCL) tendons with the same properties (Figure 2).

Once the models were designed, the physical properties of the materials were added (Table 1).

Statistical Analysis

To compare the stress distribution across different metacarpal head morphologies, descriptive statistics, including mean, standard deviation, minimum, maximum, and 95% confidence intervals were calculated. A one-way Analysis of Variance (ANOVA) was conducted to assess the significance of

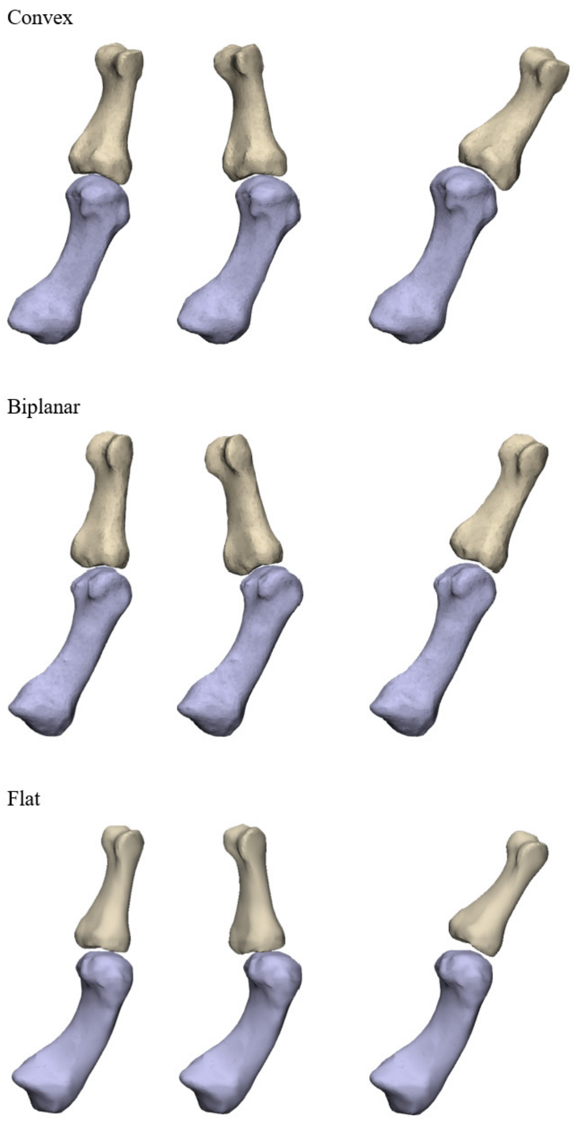

Figure 1: Design of the metacarpophalangeal joint of the thumb in neutral, flexion and extension position with flat biplanar and convex morphologies of the metacarpal head.

differences in von Mises stress values between the Flat, Biplanar, and Convex groups. A p-value of less than 0.05 was considered statistically significant. All statistical analyses were performed using Stata 17 MP (StataCorp LLC, College Station, TX, USA).

Ethical Considerations

The ethical principles outlined in the World Medical Association Declaration of Helsinki were strictly adhered to in the present study. Approval was obtained from the Shiraz University of Medical Sciences institutional ethics board.

Figure 2: Load application site

Table 1: Modulus of elasticity and Poisson's ratio for the materials used for modeling

Material	Modulus of elasticity (MPa)	Poisson's ratio
Bone	1.77×10^{10}	0.30
Synovial fluid	1×10^{7}	0.50
RCL & UCL	300	0.35

RCL: Radial Collateral Ligament, UCL: Ulnar Collateral Ligament

Results

Wear in the articular surfaces, especially in the MCP joint of the thumb, is an important factor in the development of osteoarthritis and bone loss. Examination of wear based on von Mises stress analysis can help predict areas prone to injury and provide treatment strategies (Figure 3). The analysis of von Mises stress distribution across different metacarpal head morphologies and joint positions revealed significant variations in stress concentration patterns, as visualized in Figures 3 and 4 and quantified in Tables 2 and 3.

The stress mapping results demonstrated

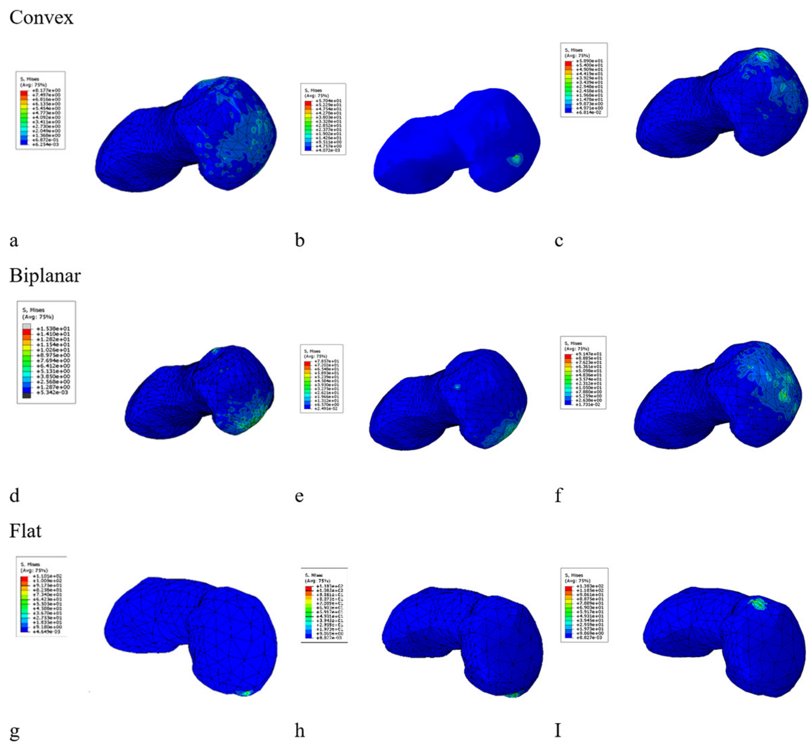

Figure 3: Pattern of von Mises stress distribution in the top of metacarpal bone.

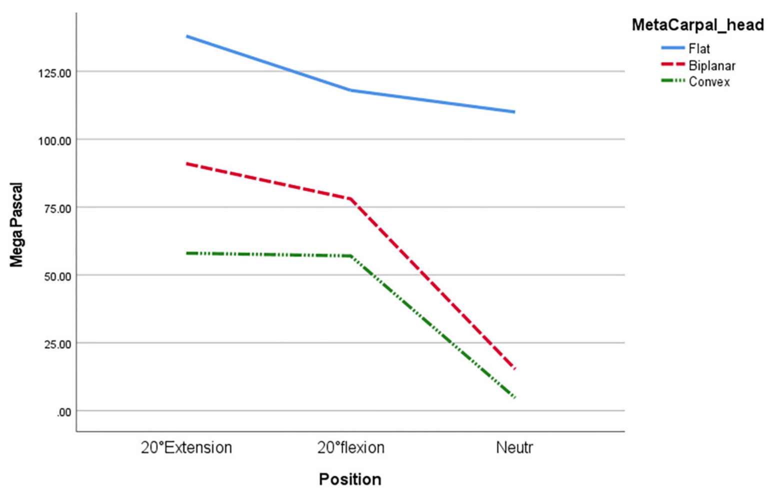

Figure 4: Distribution of forces in various morphologies and joint positions.

Table 2: Joint line stress in different positions

Position / Morphology of the Metacarpal Head	Flat	Bi planar	Convex
Neutral	110 MPa	15.3 MPa	4.7 MPa
20°flexion	118 MPa	78 MPa	57 MPa
20°Extension	138 MPa	91 MPa	58 MPa

Table 3: Analysis of Variance (ANOVA) comparison of differences among various morphologies and positions

Morphology	(n)	Mean	Standard deviation	95% Confidence Interval for Mean		Minimum stress	Maximum stress	*P*-value
				Lower Bound	Upper Bound			
Flat	3	122 MPa	14.4	86.2	157.8	110 MPa	138 MPa	*0.039
Biplanar	3	61.4 MPa	40.5	-39.1	162	15.3 MPa	91 MPa	
Convex	3	39.9 MPa	30.5	-35.8	115.6	4.7 MPa	58 MPa	
Total	9	74.4 MPa	45.3	39.6	109.3	4.7 MPa	138 MPa	

*According to the *P*-value, there is a significant difference between the groups.

that the flat metacarpal head morphology consistently exhibited the highest von Mises stress values in all tested positions. Specifically, in the neutral position, the peak stress reached 110 MPa, increasing to 118 MPa in 20° flexion, and peaking at 138 MPa in 20° extension (Table 2). This pattern suggests that the flat morphology inherently concentrates mechanical load, particularly under extension, potentially predisposing the joint to increased wear and degeneration.

In contrast, the biplanar morphology displayed moderate stress values, with von Mises stresses of 15.3 MPa in neutral, 78 MPa in flexion, and 91 MPa in extension. Although the biplanar configuration showed better load distribution than the flat morphology, the rising stress levels in flexion and extension still indicate susceptibility to localized stress accumulation, especially during dynamic thumb movements.

The convex morphology consistently demonstrated the most favorable stress distribution. Von Mises stress values were 4.7 MPa in neutral, 57 MPa in flexion, and 58 MPa in extension, reflecting a more uniform load transmission and reduced peak stress across positions (Table 2). This highlights the biomechanical advantage of the convex shape in minimizing joint stress during functional movements.

The visual stress distribution patterns (Figure 4) further corroborated these findings. Notably, the flat morphology exhibited extensive stress concentration regions, particularly on the radial side of the metacarpal head, across all positions. The biplanar morphology showed focal areas of stress increase, predominantly in flexion and extension, whereas the convex configuration maintained a relatively dispersed and low-stress profile.

The ANOVA statistical analysis confirmed significant differences in stress distribution among the three morphologies (*P*-value=0.039) (Table 3). The flat morphology had the highest mean stress of 122 MPa (SD 14.4), followed by the biplanar with 61.4 MPa (SD 40.5), and the convex with 39.9 MPa (SD 30.5). The maximum recorded stress across all configurations was 138 MPa in the flat morphology during extension, while the lowest was 4.7 MPa in the convex morphology at neutral positioning.

Discussion

The findings of this study highlight the critical role of metacarpal head morphology in influencing joint stress distribution within the first MCP joint. Our results indicate that the flat metacarpal head exhibited the highest peak stress (measured in megapascals), followed by the biplanar and convex morphologies. These observations suggest that even small variations in metacarpal head shape can markedly alter force transmission across the joint, which in turn may play a key role in the onset and progression of DJD.

The elevated stress observed in the flat metacarpal head configuration may be attributed to a less effective distribution of mechanical loads. Unlike the convex morphology, which allows for a more uniform stress dispersion due to its curved articular surface, the flat morphology may result in localized stress concentrations. These areas of increased pressure could accelerate cartilage wear and subchondral bone changes, predisposing individuals with this morphology to a higher risk of DJD. The biplanar metacarpal head, which exhibited intermediate stress levels, may represent a transitional morphology with moderate load distribution efficiency, while the convex shape demonstrated the most favorable biomechanical properties in reducing peak joint stress [6].

In addition to morphological differences, our analysis also revealed that joint position significantly influences stress distribution within the first MCP joint. The highest peak stress was recorded in 20-degree extension, followed by 20-degree flexion, with the lowest stress occurring in the neutral position. This suggests that joint loading patterns are not only dependent on metacarpal head shape but also on dynamic positioning during functional movements. The increased stress in extension may be linked to altered joint contact mechanics, where the articular surfaces experience a greater force concentration, particularly in load-bearing activities that involve thumb extension, such as gripping or pinching. Conversely, the neutral position appears to allow for more optimal force distribution, potentially reducing the risk of degenerative changes over time.

Our findings provide a potential biomechanical explanation for the observed patterns of DJD in hyperextended MCP joints in cases of CMC DJD and flexed MCP joints in Rheumatoid Arthritis (RA). The increased stress distribution in MCP hyperextension, as demonstrated by our results, suggests that individuals with CMC DJD, who often compensate by adopting a hyperextended MCP posture to maintain grip strength, may be predisposed to secondary MCP DJD due to excessive joint loading [8]. This compensatory mechanism, commonly seen in thumb collapse deformities, leads to chronic stress concentration, cartilage breakdown, and subsequent degenerative changes over time. Conversely, in RA, where chronic inflammation leads to ligamentous instability and volar plate laxity, the MCP joint often assumes a flexed posture due to progressive joint deformity [9-11]. Our findings demonstrate that stress levels are also elevated in MCP flexion, which could contribute to the characteristic erosive and degenerative changes seen in RA patients with MCP involvement. The increased mechanical loading in both hyperextended and flexed positions supports the notion that altered joint biomechanics play a crucial role in disease progression. This finding highlights the importance of early intervention, joint stabilization strategies, and therapeutic approaches to reduce excessive stress in these vulnerable joint positions.

The clinical implications of our findings suggest that metacarpal head morphology and MCP joint positioning play a crucial role in the development and progression of DJD, highlighting the importance of early identification and targeted treatment strategies to minimize joint deterioration. Given that flat and biplanar metacarpal heads are associated with higher peak stress, patients with these anatomical variations may be at greater risk for early-onset DJD, particularly if they engage in activities that involve repetitive thumb extension or flexion. Understanding these biomechanical factors can help guide both conservative and surgical treatment approaches. Non-surgical management typically includes activity modification, splinting to maintain Neutral Joint Positioning, Nonsteroidal Anti-Inflammatory Drugs (NSAIDs) for pain relief, and physical therapy to strengthen surrounding musculature and reduce joint strain. Intra-articular corticosteroid injections may provide temporary relief, though repeated use can lead to cartilage degradation and tendon weakening. For advanced cases where conservative treatment fails, surgical options such as arthrodesis, arthroplasty, or joint resurfacing may be considered, with implant selection potentially influenced by metacarpal head morphology to optimize load distribution. However, these surgical interventions carry risks, such as implant loosening, non-union, and loss of thumb mobility, which must be weighed against their potential benefits [12-16]. By integrating our findings into clinical decision-making, healthcare providers can develop personalized treatment plans to preserve hand function while minimizing complications associated with excessive joint stress.

It is important to acknowledge certain limitations. The study was conducted in a computer-based simulation using Materialise Mimics, and while this provides precise morphological and stress analysis, in vivo factors, such as soft tissue interactions, ligamentous support, and neuromuscular control were not accounted for. Future research should incorporate finite element analysis and cadaveric studies to further validate these findings in a physiological context. Additionally, longitudinal clinical studies could assess whether individuals with specific metacarpal head morphologies are indeed at a higher risk for DJD, corroborating computational data with real-world epidemiological trends.

Conclusion

In summary, our study demonstrates that metacarpal head morphology and joint positioning significantly influence stress distribution in the first MCP joint. The flat metacarpal head exhibited the highest peak stress, followed by biplanar and convex morphologies, with peak stress occurring in 20-degree extension, followed by 20-degree flexion and neutral positioning. These insights emphasize the importance of anatomical variations in DJD development and highlight potential areas for targeted clinical intervention. Future research integrating computational modeling with clinical, and cadaveric validation will be crucial in refining our understanding of first MCP DJD and optimizing patient care.

Acknowledgment

During the preparation of this work, the authors used ChatGPT in order to improve the readability and language of the work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Authors' Contribution

H. Namazi conceived the idea. The introduction of the paper was written by S. Behzadi. S. Behzadi and S. Heidari gathered the images and the related literature, and also helped with the writing of the related works. The method implementation was carried out by S. Behzadi and S. Heidari. Results and Analysis were carried out by S. Behzadi and S. Heidari. The research work was proofread and supervised by H. Namazi. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The ethical principles outlined in The World Medical Association Declaration of Helsinki were strictly adhered to in the present study. Approval was obtained from the

Shiraz University of Medical Sciences institutional ethics board (Code: IR.SUMS.MED.REC.1403.129).

Informed Consent

The ethical board of Shiraz University of Medical Sciences waived the requirement for obtaining informed consent due to the nature of this study.

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Conflict of Interest

None

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