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Review Article

Finite Element Analysis of the Wrist Joint: A Review

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Abstract

Introduction: Hand function is influenced by various diseases and trauma. Finite Element Analysis (FEA) is a method used to evaluate the impact of these conditions on the joint contact forces of wrist bones. This review aims to assess the feasibility of using FEA to determine the effects of diseases, trauma, and surgical interventions on wrist joint biomechanics.

Method: A search was conducted in several databases, including Google Scholar, ISI Web of Knowledge, Ebsco, Scopus, and PubMed. The primary keywords used in this review were 'finite element analysis' and 'finite element model', combined with 'wrist joint'.

Results: There were seven studies on using FEA for the wrist joint. Three of these studies evaluated the efficiency of various surgical procedures on wrist joint stress. The remaining four studies determined the joint contact forces in various diseases.

Conclusion: The results of the available studies on using FEA for the wrist joint confirm the high feasibility of this approach in determining the effects of various diseases or surgical interventions on wrist joint contact forces. It appears that various conditions, such as fractures, stroke, and rheumatoid arthritis, increase joint contact forces.

Keywords: Finite element analysis, modeling, stress, Wrist joint

Introduction

Hands are organs used daily for grasping, holding, manipulating, and moving objects. Undoubtedly, our performance relies on the integrity of hand functions. Various factors, including diseases, injuries, and congenital disorders, influence the hand's performance. Furthermore, numerical biomechanical parameters, such as the hand's position during activities and the loads applied to it, also influence the incidence of injuries [1]. The wrist joint, an important part of the hand complex, consists of eight small bones [2]. The orientation and movement of these bones determine the wrist's range of motion. One of the most common diseases affecting wrist function is rheumatoid arthritis, which impacts articular surfaces, ligaments, and the joint capsule, leading to considerable pain, loss of function, and joint deformities [3, 4]. Kienböck's disease, classified as osteonecrosis of the lunate bone [5], is another condition that affects the wrist. Although the etiology of this disease is not well understood, it is often attributed to trauma [6-8] and is more frequently seen in labor-intensive individuals and young people [6]. Available studies suggest that the loads applied to the bones increase the incidence of joint osteoarthritis [9]. Therefore, it is crucial to determine the loads applied to the wrist structure to reduce the incidence of joint osteoarthritis, especially Kienböck's disease. If the loads applied to the wrist bones decrease, the incidence of degenerative joint diseases will simultaneously decrease.

Various approaches have been used to determine the loads applied to the wrist complex, including the use of transducers, sensors (strain gauges), and Finite Element Analysis (FEA) [7, 10]. Studies using transducers and sensors have mostly been conducted on cadavers. In contrast, FEA is based on a three-dimensional (3D) model of the components, produced using X-ray, MRI, and CT scan images. This approach has been utilized in biomechanics since 1978. It consists of several procedures that influence the accuracy of the approach. The creation of a 3D model of the bones, the application of supportive structures, the assignment of material properties, and the configuration of boundary conditions and applied loads are parameters that influence the accuracy of the outputs [10]. The outputs of the finite element analysis of the wrist joint can be used to improve the available designs of artificial wrist joints and fingers and to determine the efficiency of various treatment approaches, including surgery and conservative treatment. Given the importance of using FEA in determining the loads applied to the wrist complex, it is crucial to review the available studies to understand the various approaches used for FEA of the wrist joint complex. The main aim of this review was to determine the feasibility of FEA in determining the loads applied to the wrist complex and to assess the efficiency of this approach in predicting the outcomes of various treatment approaches. It also aimed to provide a database regarding the procedures for conducting FEA of the wrist and the mechanical properties of the wrist structure.

Methods

Firstly, it should be emphasized that this is not a systematic review or meta-analysis. A search was conducted in databases such as Google Scholar, PubMed, Scopus, Ebsco, Embase, and ISI Web of Knowledge, covering a period from 1950 to 2018. Keywords such as 'Finite Element Analysis' and 'Finite Element Model' were combined with 'wrist joint'. More specifically, the 'Finite Element Model' and 'analysis' were used with 'Kienböck's disease', 'arthritis', and 'wrist surgical procedure'. The first criterion for paper selection was based on the research question of interest. Studies focusing on using FEA for designing wrist implants were excluded from the final list. An attempt was made to categorize the available studies based on the aims of this review. In each study, an effort was made to classify the method based on the model used, the mechanical properties assigned to the model, the modeling of ligamentous structures, the magnitude of applied loads, and the parameters reported.

Results

There were seven studies on using FEA for the wrist joint. Three of these papers focused on the efficiency of various surgical procedures or the impact of fractures on wrist joint stress. The remaining four studies used FEA to determine joint contact force (joint pressure) in cases of rheumatoid arthritis (one study), stroke (one study), and various wrist positions (two studies). Table 1 summarizes the methods and results of the studies conducted on FEA of the wrist. Tables 2 and 3 summarize the mechanical properties of the components used in these models.

Table 1: The method and outputs of the studies done on FEA of wrist joint.

Reference	Aim of the study	Subjects	Outputs
13)	To determine the loads applied on the wrist after scaphoid fracture.	A Healthy subject	Scaphoid bone seems to play a significant role in wrist to transmit the loads. FEA model may prove to be a highly useful tool for understanding of OA mechanisms. The loads transmitted through Scaphoid increase in wrist fracture.
11)	To determine the association between joint loading, kinematics and stress distributed on bones in normal healthy condition.	CT Scan images of the wrist joint of a cadaver were used in this study.	Due to comparison between the outputs of this approach with the use of transducer, there seems to be a good agreement between the outputs.
15)	The aim of this study was to determine the effects of various cutting of radius on stress developed in Lunate bone.	CT scan images of a normal subject was used in this study. Radius bone was cut at 0, 5, 10, 15 degrees to stimulate the effects of the operation.	The output of effectiveness of stress reduction with radius cutting angle also depends on initial morphology of carpal bone. The stress reduction achieved increased with angle.
16)	To evaluate the feasibility of FEA to determine severity of fractures follow the loads.	Radius bone of a cadaver was used in this study. Moreover, a Model was developed based on images of this bone.	It seems that the model developed based on FEM is a good representation of distal radius, which can predict the pre fracture and crack impact response well. It can predict the location and severity of fractures.
14)	To determine the effects of hand grip in the subjects with stroke.	A model of a normal subject was used but was modified to include the characteristics of stroke subjects.	The stroke subject model reported a higher contact pressure especially for MC1 trapezium. Wrist extension decreased the joint contact force.
10)	To determine the stress distribution of wrist bones in the subjects with rheumatoid arthritis.	CT scan images of normal subjects were used in this study.	The stress distributed in the wrist complex of the subjects with RA differed from that of normal subjects. The stress in radius, scaphoid, and capitolunate articulation differed significantly from normal subjects and correlated with clinical finding.
12)	To evaluate the difference between the stress of wrist bones in neutral and functional positions.	CT Scan images of 6 normal subjects (females) were used in this study.	The role of radio-scaphoid fossa to transmit the loads in neutral position seems to be more than radio-lunate fossa. In contrast in the functional position the role of radio-lunate fossa is more important.

Table 2: The procedure used in the research done on FEA model of wrist joint.

Reference	Model used	Bone mineral density	Loads applied	Boundary condition
10)	CT Scan images of normal subjects was used. But it was changed to be used for stroke subjects. Synovial proliferation, cartilage destruction, and ligamentous laxity were considered.	Young modulus of elasticity of 18 G-Pascal used for cortical bone and 100 M-Pascal for cancellous bone. Poison ratio: 0.2-0.25 Ligament: linear spring element, stiffness 40-350 N/mm.	Static griping force with resultant compression force of 0.73 M-Pascal applied upon the digits.	Distal end of radius and ulna.
12)	6 models developed based on AP and lateral CT-Scan images of normal females' subjects in neutral and extended wrist positions.	Young modulus of elasticity = No information Ligaments: Were modeled as compression spring with linear stiffness of 22.5 N/mm.	A total force of 140 N force was applied on 5 metacarpals in vertical direction.	Distal end of radius and ulna.
13)	A model of the wrist was developed based on the geometry obtained from X-ray (AP plane) of a healthy pronated wrist. Different types of fractures were simulated in this study.	Young modulus of elasticity: 18 G-Pascal. Ligament: was modeled with young modulus of elasticity of 50 M-Pascal.	A force of 100 N was applied to the structure.	No information.
15)	CT Scan images of a normal subject was used. Moreover, Lunate bone was tilted to simulate the condition of Kinebock disease.	Young modulus of elasticity: 18 G-Pascal Poison ratio: 0.2 Young modulus of elasticity of cartilage: 10 M-Pascal Poison ratio: 0.49	Force of 40N and 60 N were applied on top of Scaphoid and Lunate, respectively.	Distal end of radius and ulna.
16)	A FEA model of radius was developed from a cadaver. Moreover, some strain gauges were attached on radius bone to check the correlation between strain gauge and FEA model.	Young modulus of elasticity: 25.1 G-Pascal Poison ratio: 0.3 Young modulus of cancellous bone: 1.8 G-Pascal	No information	End of radius
14)	CT scan images of a healthy volunteer was used.	Young modulus of elasticity of 16.5 G-Pascal and 100 M-Pascal were used for cortical bone and cancellous bone, respectively. Poison ratio: 0.2-0.25 Ligament: were modeled as spring element with stiffness between 40-350N/mm.	Static grip force with resultant compression force of 7.33 M-Pascal applied upon digits	Proximal end of the distal of radius and ulna.
11)	FEA model was derived from cryomicrotome sections of a cadaver wrist. Moreover some strain gauges were attached on lunate to check the force applied on it.	Young modulus of elasticity of 13.8 G-Pascal and 2800 M-Pascal were used for cortical bone and cancellous bone, respectively. Poison ratio: 0.3 Ligament: were modeled as spring element.	Force of 100N were applied across radiocarpal bones.	The proximal end of radius was fixed.

Table 3: The ligaments used to attached the wrist bones and their stiffness (adapted from Bajuri et al [10])

Ligament	Connection 1	Connection 2	Mechanical stiffness (N/mm)
Capitohamate	Capitate	Hamate	325
Capitotrapezial	Capitate	Trapezium	300
Dorsal carpometacarpal	Capitate	4MC medial	300
Dorsal carpometacarpal	Capitate	4MC medial	300
Dorsal carpometacarpal	Capitate	3MC medial	300
Dorsal carpometacarpal	Capitate	3MC medial	300
Dorsal carpometacarpal	Trapezoid	2MC medial	100
Dorsal carpometacarpal	Trapezoid	2MC medial	50
Dorsal carpometacarpal	Trapezium	2MC medial	48
Dorsal carpometacarpal	Hamate	4MC	300
Dorsal carpometacarpal	Hamate	5MC	300
Dorsal intercarpal	Hamate	Capitate	325
Dorsal intercarpal	Capitate	Trapezoid	300
Dorsal intercarpal	Hamate	Triquetrum	300
Dorsal intercarpal	Hamate	Lunate	150
Dorsal intercarpal	Capitate	Lunate	150
Dorsal intercarpal	Capitate	Scaphoid	150
Dorsal intercarpal	Scaphoid	Trapezium	150
Dorsal intercarpal	Trapezoid	Trapezium	110
Dorsal intercarpal	Trapezium and Trapezoid	Triquetrum	128
Dorsal lunotriquetral	Lunate	Triquetrum	350
Dorsal 2MC1MC	2MC	1MC	100
Dorsal 3MC2MC	3MC	2MC	100
Dorsal 4MC3MC	4MC	3MC	100
Dorsal 5MC4MC	5MC	4MC	100
Dorsal scapholunate	Lunate	Scaphoid	230
Dorsal trapeziometacarpal carpometacarpal	Trapezium	1MC lateral	100
Palmar carpometacarpal	Capitate	3MC	100
Palmar carpometacarpal	Capitate	2MC	100
Palmar carpometacarpal	Capitate	4MC	100
Palmar carpometacarpal	Trapezium	3MC	88
Palmar carpometacarpal	Trapezium	2MC	57
Palmar carpometacarpal	Hamate	5MC	100
Palmar carpometacarpal	Hamate	3MC	100
Palmar carpometacarpal	Pisiform	5MC	100
Palmar 1MC2MC	1MC	2MC	100
Palmar 2MC3MC	2MC	3MC	100
Palmar 3MC4MC	3MC	4MC	100
Palmar 4MC5MC	4MC	5MC	100
Palmar trapeziometacarpal	Trapezium	1MC	24
Pisohamate	Hamate	Pisiform	100
Radial arcuate	Capitate	Scaphoid	40
Radiodorsal trapeziometacarpal	Trapezium	1MC medial	78
Scaphotrapezial	Scaphoid	Trapezium	150
Scaphotriquetrum	Scaphoid	Triquetrum	128
Ulnar arcuate	Capitate	Triquetrum	40
Volar lunotriquetral	Lunate	Triquetrum	350

Discussion

Undoubtedly, the loads applied to the wrist joint complex increase the incidence of wrist injuries and osteoarthritis. One significant disease that affects hand function is Kienböck's disease, which has a high incidence, especially among labor-intensive workers. Finite Element Analysis (FEA) is one of the methods used to determine joint loading and assess the efficiency of various approaches to reduce the loads applied to the wrist joint complex. The primary aim of this review was to determine the feasibility of FEA based on available studies.

The first question posed here is about the accuracy of the output of wrist FEA in determining the loads applied to the wrist joint complex. Only one study compared the outputs of wrist FEA with the outputs of transducers attached to cadaver bones [11]. The material properties of the FEA model varied between 13.86 G-Pascal (for cortical bone) and 345 M-Pascal (for cancellous bone). A load of 100 N was applied to the Lunate and Scaphoid. The pressure applied to the scaphoid fossa was 4.6 M-Pascal, which confirmed a good agreement between the outputs of the transducers attached to the bone and FEA. The results of this study also confirmed that FEA produced a model that could be used to establish a guideline for treating intra-articular fractures. No other study directly determined the association between the outputs of FEA and strain gauges or transducers. However, there appears to be a good agreement between the outputs of FEA and clinical findings.

The second question posed here is whether there is any difference in the joint contact pressure of the wrist joint between normal individuals and those with various diseases. There were four studies on this topic. In a study conducted by Bajuri et al., the stress applied to the wrist bones in subjects with Rheumatoid Arthritis (RA) was compared with that in normal subjects [10]. The findings of this study showed that the stress concentration was relatively higher in the RA model compared to healthy subjects. The RA model had a higher stress concentration at the styloid process (47 M-Pascal) than healthy subjects (39 M-Pascal). The results also confirmed a higher stress transmitted through the RA model's radius than normal subjects. The impact of wrist position on the load distribution of the wrist bones was also evaluated in research conducted by Genda et al. The wrist model was created based on CT scan images of normal subjects [12]. The results of this study confirmed the effects of wrist position on the percentage of loads transmitted through the scaphoid and lunate bones. In a functional position, there was no significant change in the force transition ratio; however, in a natural position, the force transmitted through the scaphoid fossa was greater than that of the lunate fossa [12].

The difference in the forces applied to the scaphoid in various types of scaphoid fractures was also studied by Ledoux et al. This study showed that the radio-scaphoid interface force varied between 0.442- 0.5513 M-Pascal under normal conditions [13]. The results indicated that the force applied to the scaphoid increased significantly, especially in fracture type 4. Another study evaluated the difference between the loads applied to the wrist joints of stroke patients and normal subjects based on CT scan images of a normal subject [14]. The properties of the model were adjusted according to BMD, cartilage thickness, and muscle spasticity. The output of this study showed that the stroke model represented a higher contact pressure than normal. However, performing activities in extension and displacement of the wrist decreased the loads applied to the wrist of stroke subjects less than that of normal subjects. As mentioned earlier, the results of the studies confirmed that FEA is a feasible approach to determining joint contact forces (pressure) of wrist bones in various activities [14]. This approach can be used to determine the effects of various surgical procedures and therapeutic approaches. It can be concluded that the pressure applied to the wrist bones increases in some diseases, such as rheumatoid arthritis and stroke, as well as in wrist complex fractures. However, the available studies on this topic are limited.

Another aim of this study was to produce a database regarding the FEA of the wrist. It should be emphasized that FEA consists of several steps, including [14]:

1. Creating a 3D model of the hand and wrist structure
2. Applying material properties
3. Applying loads or force configuration
4. Setting boundary conditions
5. Modeling supportive ligaments and joint cartilage

Table 1 summarizes the methods of the available studies regarding the stages above. It should be emphasized that although the effects of some diseases, such as rheumatoid arthritis, stroke, and fractures, have been studied, most of these studies were conducted on models developed based on CT scan images obtained from normal subjects. Furthermore, material properties were mostly obtained from cadaveric studies. In most available studies, the ligaments were modeled as spring elements with stiffness varying based on the ligament locations (Table 3). The main limitations of the available studies may be related to the selection of subjects, material properties, and modeling approaches. The results of the studies conducted on FEA of the wrist confirmed that this approach has sufficient feasibility to determine the difference in load sharing of the wrist complex in various diseases and may be used to predict the outcomes of treatment approaches. However, some limitations may influence the outputs of FEA of the wrist joint. It is recommended that FEA be used to determine the efficiency of various treatment approaches; however, the models should be developed based on CT scan images of subjects with the same pathology. It is also recommended that the mechanical properties applied to the wrist joint complex should be based on the approach recommended in 3D software.

There are limited studies on FEA of the wrist joint complex. However, the outputs of the available studies confirmed the feasibility of using FEA to determine the efficiency of various treatment approaches. It is recommended that the limitations of previous research be considered in future studies.

Conclusion

The results of the available studies on using FEA for the wrist joint confirm the high feasibility of this approach in determining the effects of various diseases or surgical interventions on wrist joint contact forces. It appears that various conditions, such as fractures, stroke, and rheumatoid arthritis, increase joint contact forces.

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Conflict of Interest Disclosures

None to declare.

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Authors' Contributions

Abolghasem Fallahzadeh Abarghuei researched literature and conceived the study. Both authors were involved in Conception, design and data collection. Mohammad Taghi Karimi performed the Analysis and interpretation and wrote the first draft of the manuscript. Both authors reviewed and edited the manuscript and approved the final version.

Ethical Statement

Not applicable.

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