

Finite Element Modeling of the Human Wrist: A Review

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Abstract

Keywords

- ▶ biomechanics
- ▶ finite element analysis
- ▶ finite element method
- ▶ model
- ▶ wrist

Background Understanding wrist biomechanics is important to appreciate and treat the wrist joint. Numerical methods, specifically, finite element method (FEM), have been used to overcome experimental methods' limitations. Due to the complexity of the wrist and difficulty in modeling, there is heterogeneity and lack of consistent methodology in the published studies, challenging our ability to incorporate information gleaned from the various studies.

Questions/Purposes This study summarizes the use of FEM to study the wrist in the last decade.

Methods We included studies published from 2012 to 2022 from databases: EBSCO, Research4Life, ScienceDirect, and Scopus. Twenty-two studies were included.

Results FEM used to study wrist in general, pathology, and treatment include diverse topics and are difficult to compare directly. Most studies evaluate normal wrist mechanics, all modeling the bones, with fewer studies including cartilage and ligamentous structures in the model. The dynamic effect of the tendons on wrist mechanics is rarely accounted for.

Conclusion Due to the complexity of wrist mechanics, the current literature remains incomplete. Considering published strategies and modeling techniques may aid in the development of more comprehensive and improved wrist model fidelity.

The wrist is one of the most complex human joints due to its involved biomechanics and anatomical configuration. It participates in most human functional activities and is thus exposed to many chronic, inflammatory, and traumatic conditions.^{1–4} Despite its importance, wrist biomechanics are not completely understood, and many wrist disorders and their treatment remain unexplored.

Biomechanical wrist modeling is challenging due to the complex interaction between bones, soft tissue, and the irregular and variable geometry of the joint. In fact, some authors regard the wrist as the most complex mechanical joint system in the human body.² The complexity of the wrist makes analytical methods suboptimal for the study of wrist

biomechanics. In addition, although experimental methods have been used extensively for data collection in many human joints, the expensive equipment needed for this task and the natural limitations of in vivo and ex vivo testing pose a challenge for the study of the wrist. Consequently, many authors have opted for numerical methods to overcome these limitations.

The finite element method (FEM) is a powerful tool due to its ability to analyze complex cases using different element formulations that can adapt to irregular topologies, allowing one to account for individual patient differences in wrist geometry. This method can also account for variations due to factors such as age, gender, and disease stage development.⁵

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FEM can simulate this joint in many functional tasks and even consider the effects of pathology and treatment to predict its behavior.

This methodology can provide a prediction of stress distribution and has the ability to predict problematic contact surfaces and wear, guiding researchers and clinicians to choose an optimal orientation for implants, and to improve elements in the design phase.⁶⁻⁸

The FEM is a numerical method used to solve differential equations that represent a mathematical model.⁹ A general FEM process is divided into three steps: (1) preprocessing or model preparation, (2) solution, and (3) postprocessing. Most authors discuss the preprocessing step in detail as most problems arise here. The definition of the model is done in the preprocessing step and depends entirely on the assumptions made to represent physical phenomena. The geometry is modeled using computer-aided design software or acquired from another process. In the case of the wrist, the geometry is commonly obtained from three-dimensional (3D) imaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI) scans. The constitutive laws used to represent the physical phenomena are chosen and the associated material properties are obtained from mechanical testing or from existing literature. The domain or geometry is discretized or meshed. Meshing is a fundamental step that divides a complex geometry into many simpler geometries called elements which are constructed using nodes.¹⁰ Controlling different aspects of the mesh is crucial to obtain accurate results.⁹ Two fundamental concepts are element type and element order. The element type is a denomination given to a specific arrangement of nodes, for example, a triangle is constructed with three nodes (two-dimensional [2D]) and a tetrahedral with four nodes (3D). The element order is associated with a specific element type. A first-order element only has nodes at the vertices of an element type, whereas a second-order element can have one additional node between two vertices allowing the element to adapt better to curved geometries.

Finally, the studied task or action, including forces and normal wrist range of motion, is represented by loads (initial condition) or boundary conditions that are applied to specific parts of the geometry. It is important to note that these tasks of the preprocessing steps are not necessarily done in the presented order as this is software dependent.

The solution step uses the defined model with all parameters and is mostly handled internally by the chosen FEM software. The final step, postprocessing, differs considerably depending on the way results are to be presented and if the next iterations of the same model are needed.

In addition to the typical protocol, two additional steps are frequently considered: validation and verification. Verification is related to appropriately solving the equations that represent a physical phenomenon, while validation is related to how accurately a model predicts real/in vivo behavior.¹¹ Verification is done throughout the model setup using features such as energy check and mesh verification, but it is normally not reported in the studies.⁹ Validation can take many forms, but literature comparison is usually utilized for

wrist FEM. A model is always validated to assure its results are consistent with real wrist behavior or at least with previous similar models.

FEM has been used successfully in other human joints and parts.^{12,13} The hip, for example, has been modeled extensively using FEM to predict the mechanical response of adjacent bones, resulting in advances in implant materials and geometry construction.¹⁴ The wrist has been studied using FEM, but since the field is still relatively new and complex, the studies are not homogenous using differing methods and evaluating diverse topics apparently unrelated. Organizing the available information is crucial for understanding contemporary interests and identifying common modeling techniques that can be used for future models. More specifically, this field lies at the interface of basic and clinical science and a summary may benefit both the wrist clinician and the wrist researcher.

This review aims to summarize the advances in FEM wrist biomechanics during the last decade. Essential simulation parameters and modeling techniques are recognized and categorized, so these results can be used as a foundation for future enhanced FEM models. Several key findings of each work may be used to increase the complexity of newer models, improve the accuracy of results, and most importantly, avoid shortcomings encountered in the literature.

Materials and Methods

Search and Categorization

The studies analyzed were selected based on content and publication year. The time frame for the collected studies was from 2012 to 2022. The searched databases included: EBSCO, Research4Life, ScienceDirect, and Scopus. Within EBSCO, we used: Academic Search Complete, Computers & Applied Sciences Complete, Engineering Source, and MEDLINE Complete. Every search used one keyword from the Computational modeling category (Finite Element Method, Finite Element Analysis, FEM, FEA) AND the Human Anatomic Part (Wrist, Carpus). Multiple combinations were used to gather all information. Only studies published in English were considered, and studies involving only animal specimens were excluded. Certain concepts related to wrist biomechanics used the same initials as FEA or FEM and thus were part of initial searches in some databases.

The included studies were organized into two categories based on the condition of the human wrist and the study's primary theme: healthy specimens/a normal wrist and simulated cases/pathology.

Results

A total of 43 studies meeting the search criteria were found. Twenty-two studies were included in the review. Three studies included the radius, using finite element (FE) techniques, 4 were partial-wrist models simulating treatment, and 15 used whole-wrist models to study the wrist. Among these 15 studies modeling a whole wrist, there were 11 normal wrist models, 3 pathology models, and 6 treatment

models (there are more wrist models than the total number of whole-wrist studies [15] because some studies include both healthy and treatment models).

The studies use 3D models with two exceptions: one 2D¹⁵ model and one pseudo-3D model,¹⁶ that is, 2D geometry, which is then extruded. Unless otherwise stated, for the following sections in this review, all models referred to are 3D.

Region of Interest

One aspect of constructing a wrist model is which areas should be included to accurately represent the behavior of the wrist. Defining the region of interest has been divided into two categories: partial-wrist models and whole-wrist models. Partial-wrist models are used to simulate specific conditions and areas of the wrist. Since smaller wrist sections are simulated, authors can choose more complex constitutive laws to represent features such as anisotropy in soft tissues. However, as each published model studies a distinct problem,^{15,17-19} comparing partial-wrist models may not be possible as opposed to comparing whole-wrist models.

Complete or whole wrists correspond to the definition of the wrist joint and include elements of the distal radius and ulna, carpal bones, and the carpometacarpal joints.

Modeling

There are two main techniques to construct whole-wrist models depending on the considered constitutive laws and the desired complexity of the final simulation. Due to significantly increased computational power, two important wrist modeling branches commonly used are shown in ►Fig. 1: branch (A) elastic models and branch (B) hyperelastic models. An additional modeling technique of (branch "C") quantitative computed tomography (QCT)-FE models

has been included in the figure for completeness because some upper limb models predict sections of the wrist.

Choosing the appropriate constitutive laws allows the model to represent the behavior of the simulated geometry, these constitutive laws describe the relationship between two quantities: stress and strain (related to deformation). A material is called elastic if no permanent deformation is caused after stress is applied to a body and it returns to its original state. If the elastic region presents a linear relationship between stress and strain, then the material is called linear elastic; if the relationship is nonlinear, the material is nonlinear elastic. The elastic region is typically limited to small deformations. In contrast, hyperelastic materials present extremely large elastic deformation and thus cannot be described appropriately by standard elastic constitutive laws.

Elastic or hyperelastic wrist models can also be isotropic, that is, physical properties are the same in all directions, and homogeneous, that is, physical properties are identical at each point of a body. Some models are neither isotropic nor homogeneous, but they are the exception rather than the rule.

Elastic models (branch "A": in ►Fig. 1) often use linear elastic isotropic constitutive laws. A model used nonlinear elastic constitutive laws by considering nonhomogeneous bone material properties.²⁰ Soft tissues such as cartilage and ligament have been modeled using hyperelastic constitutive laws. However, the majority of simulated structures have been bony and modeled using elastic properties. Consequently, these models are called "elastic models" in this work. In general, elastic models, whether linear or nonlinear, enable the creation of dependable simulations with validation data that are readily available and do not require excessive computational resources.^{1,2,7,21-24}

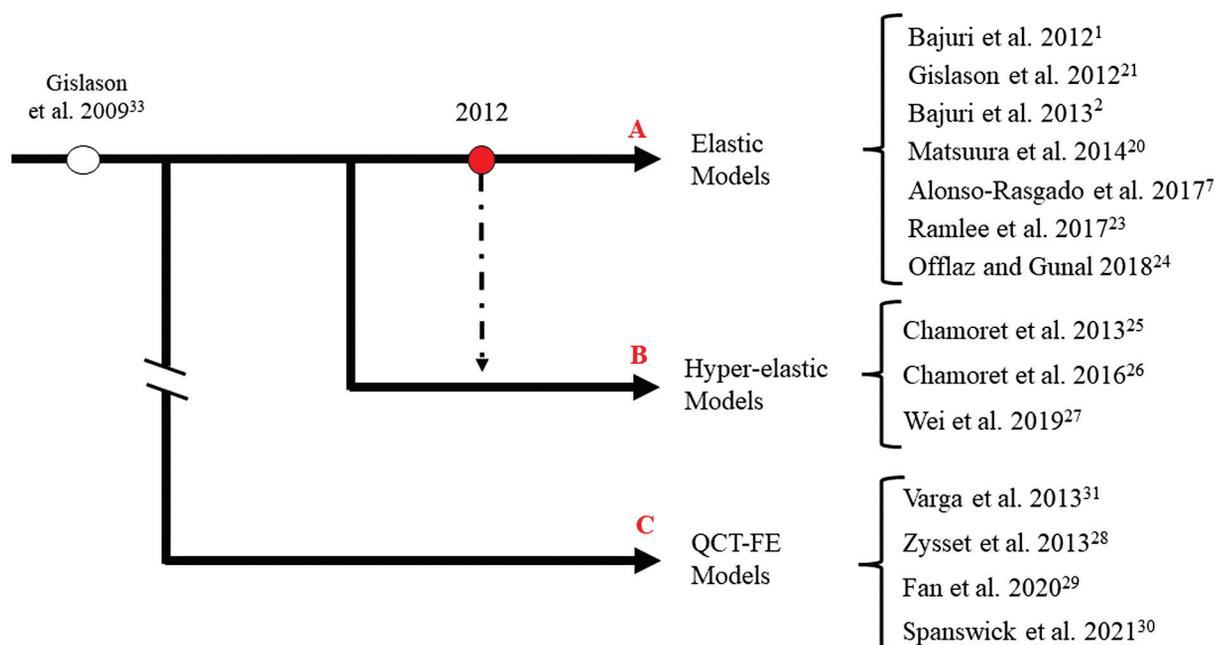


Fig. 1 Studies including elastic, hyperelastic, and quantitative computed tomography finite element models.

Table 1 Models with normal bone mechanical properties

Study	Element type	Cortical bone		Cancellous bone	
		E (MPa)	ν (-)	E (MPa)	ν (-)
Gislason et al (2009) ³³	Second-order tetrahedral	18,000	0.2	100	0.25
Gislason et al (2010) ¹²	Linear first-order tetrahedral	18,000	0.2	100	0.25
Bajuri et al (2012) ¹	Linear first-order tetrahedral	18,000	0.2	100	0.25
Gislason et al (2012) ²¹	Linear first-order tetrahedral	18,000	0.2	100	0.25
Bajuri et al (2013) ²	Linear first-order tetrahedral	18,000	0.2	100	0.25
Chamoret et al (2013) ^{a,25}	Linear first-order tetrahedral	10,000	0.22	-	-
Chamoret et al (2016) ^{a,26}	Linear first-order brick	15,000	0.2	-	-
Alonso Rasgado et al (2017) ⁷	Linear first-order tetrahedral	18,000	0.2	100	0.25
Ramlee et al (2018) ²³	Linear first-order tetrahedral	16,650	0.2	100	0.25
Oflaz and Gunal (2018) ²⁴	Not mentioned	10,000	0.22	500	0.3
Wei et al (2020) ^{a,27}	Linear first-order tetrahedral	17,000	0.3	-	-

Notes: All studies listed here used linear elastic isotropic materials. Linear first-order tetrahedral: tetrahedral-shaped element with nodes at each vertex (total 4); second-order tetrahedral: tetrahedral-shaped element with nodes at each vertex and edges midpoints (total 10); linear first-order brick: brick-shaped element with nodes at each vertex (total 8).

^aDid not consider cancellous bone in the model. E, Young's Modulus; ν , Poisson's ratio.

Hyperelastic models (branch "B" in ►Fig. 1) are often called hand models and they aim to overcome the limitations imposed by using elastic isotropic material properties in wrist sections with a high nonlinear response, especially soft tissue such as the skin or muscles.²⁵⁻²⁷

QCT-FE models (branch "C" in ►Fig. 1) can represent geometry more accurately with high-resolution imaging. In the wrist, it is particularly useful for distinguishing trabecular from cortical bone and for identifying cartilage. This technique is included in this section because μ FE and μ CT scanning, specific cases of QCT-FE, have lately been used to study distal radius fractures^{20,28-30} and to construct partial-wrist models of carpal bones with highly detailed cartilage surfaces.^{31,32}

It is possible that the trend of creating hyperelastic models may eventually aid techniques such as QCT-FE to model other nonelastic features. The creation of hyperelastic models demonstrates that new FEM modeling techniques aim to create improved biofidelic models to predict the behavior of the wrist.

Models can be further classified into normal wrists and pathology and treatment. Building a model of the normal wrist is the first step toward evaluating any pathology.

Meshing

Tetrahedrals and bricks are the preferred options in most literature due to their adaptability to irregular geometries and overall decent results without exceedingly high computational cost. First-order elements are used in most studies with just one exception.³³ A comparison among healthy models is shown in ►Table 1. A fine mesh, that is, a mesh with more elements/high element density, is desirable despite of element order, but this can increase the simulation time considerably. A proper balance must be found between these two features to assure the model's quality without

excessive computational cost. An inverse relationship exists between the element order and the mesh density. Fine meshes are often used to compensate lower order elements.^{9,34} However, during the last decade, first-order elements have been heavily favored, as shown in ►Table 1.

Pre- and Postprocessing: Simulated Action and Analysis Type

Preprocessing includes the definition of the type of tasks as well as the meshing technique and analysis. Since the wrist participates in a multitude of varied tasks that can be performed in different ways, the location of load application as well as the analysis in these studies varies greatly. This makes any comparison difficult if not impossible. ►Table 2 shows that gripping or prehension is the most common simulated task. Most FEM studies perform static and quasi-static analysis, where stress and displacement are the expected variables of the simulation. The loads are applied in the form of force or pressure.

Postprocessing analysis also varies among the different studies. When choosing static or quasi-static analysis, most studies use von Mises stress and displacement variables. ►Tables 2 and 3 summarize the methodology.

Contact Modeling

Contact is another important aspect of the simulation that is normally modeled after all the remaining geometries are already configured. Contact modeling represents what happens to the constructed geometries when one or several of the defined anatomical parts interact with one another. There are mainly two types of contact modeling techniques for the wrist: anatomic or internal contact and external contact.

Anatomic contact simulates the interaction among internal subsets of the wrist, such as bony structure and cartilage,

Table 2 Normal models preprocessing and studied task

Study	Simulated task	Preprocessing software (imaging, meshing)
Gislason et al (2009) ³³	Maximal hand grip	Mimics, Abaqus
Gislason et al (2010) ¹²	Gripping task	Mimics, Abaqus
Bajuri et al (2012) ¹	Hand grip	Amira, Marc.mentat
Gislason et al (2012) ²¹	Gripping task	Mimics, Abaqus
Bajuri et al (2013) ²	Static hand grip	Amira, Marc.mentat
Chamoret et al (2013) ²⁵	Hand and deformable object contact	Scan2Mesh, Hypermesh
Matsuura et al (2014) ²⁰	Evaluate distal radius strength	Mechanical Finder
Chamoret et al (2016) ²⁶	Prehension of deformable object	Scan2Mesh, Hypermesh
Alonso Rasgado et al (2017) ⁷	Ulnar deviated clenched fist posture	ScanIP, Abaqus
Ramlee et al (2018) ²³	Hand grip	Mimics, Amira, Marc.mentat
Oflaz and Gunal (2018) ²⁴	Maximum gripping force/grasping task	Mimics
Wei et al (2020) ²⁷	Grasping test (cylindrical grasping spherical grasping, precision grasping)	Mimics, CREO

by creating contact interfaces that allow relative bone movements or defining frictional surfaces.^{26,35,36} Most normal models used frictional or frictionless surface-to-surface anatomic contact modeling and tie constraints to prevent relative movement.^{7,12,26,27,33} Another study used deformable-to-deformable contact,¹ but this could be another way of referring to surface-to-surface contact as names and algorithms differ considerably between software programs. Another study used a different technique called the bipotential method,²⁵ but since it is a dynamic analysis, it is not comparable to other static analyses, which is the case for most studies of the wrist. Other models did not specify if contact was considered.^{1,24}

External contact represents hard contact and impenetrability, which is useful when simulating the grasping of external objects.²⁷ This is also why external contact is only

included in hand models that simulate the interaction between soft tissues, such as the skin, and external objects.^{26,27}

Contact definition is closely related to the type of analysis used, that is, static or dynamic, and more importantly, to the software used. It is usually configured at the end of the preprocessing step when the geometry of all anatomical parts is defined. However, the modeling techniques and algorithms used are not explained thoroughly in most models, making it difficult to quantify the variability of this feature.

Modeling of Tissue

The mechanics of the wrist relies on the concerted action of multiple tissue structures including static soft tissue, such as ligamentous structures, and cartilage, bony structure, as well

Table 3 Normal models simulation and expected variables

Study	FEM software	Analysis type	Postprocessing variables
Gislason et al (2009) ³³	Abaqus	Static/quasi-static	von Mises stress, forces, reaction forces
Gislason et al (2010) ¹²	Abaqus Explicit	Quasi-static	von Mises stress
Bajuri et al (2012) ¹	Marc.mentat	Static ^a	von Mises stress, displacement
Gislason et al. (2012) ²¹	Abaqus Explicit	Quasi-static	von Mises stress
Bajuri et al (2013) ²	Marc.mentat	Static ^a	Stress distribution, strain
Chamoret et al (2013) ²⁵	Not mentioned	Dynamic	von Mises stress
Matsuura et al (2014) ²⁰	Mechanical Finder	Static/quasi-static	Stress, force
Chamoret et al (2016) ²⁶	Altair Radioss (Explicit)	Quasi-static	von Mises stress, contact pressure
Alonso Rasgado et al (2017) ⁷	Abaqus	Static	Gap, angle, force
Ramlee et al (2018) ²³	Marc.mentat	Static	von Mises stress, force
Oflaz and Gunal (2018) ²⁴	ANSYS	Static ^a	von Mises stress
Wei et al (2020) ²⁷	Abaqus	Quasi-static	Contact area, contact pressure

^aNot explicitly mentioned.

as the dynamic effect of the muscles through their tendinous insertions. Modeling the wrist with all features is almost impossible due to the complexity/variability of structure and including the soft tissue and its properties but also due to variation between distinct subjects and between wrists of the same individual.

The following tissues are addressed in the reviewed publications: bones, ligaments, and cartilage. Bones are the only tissue modeled in all publications. Tendons are not always included, but when considered, they are modeled similarly to ligaments which may not reflect true mechanics.^{2,7,12,27,33} Because of this, tendons act as stabilizers when they are considered in a model.³ Skin is included in a few models but its mechanical significance is questionable.^{26,27} Each anatomical part must be modeled as a different material because of considerable differences in its mechanical properties.

Bone Modeling

The bone is a stiff connective tissue that supports body parts and is the mechanical basis for movement.^{37,38} Bone is often simplified into a macroscopic solid and modeled using elastic isotropic constitutive laws. In most simulations, bone is divided into two different types: cortical/compact bone and cancellous/trabecular bone. Other features of bones such as porosity and volume are not considered in these models. Since only elastic mechanical properties are considered, Young's modulus and Poisson's ratio are the fundamental material properties included. However, some authors do not consider material properties as homogeneous. An exam-

ple is one study that considered variable bone mineral density by correlating Hounsfield units (HU) at each element.²⁰

In the context of elastic models used to simulate healthy whole-wrist models, multiple authors adopt a modeling technique that accounts for both cortical and cancellous bones.^{1,2,7,21–27} However, in the hyperelastic models, all bony structures are typically simulated using only cortical bone material properties.^{25–27}

A comparison of the values used among several healthy wrist models is shown in ►Table 1. Note that the model with nonhomogeneous bone material properties is omitted.

Cartilage Modeling

Although bones can be easily segmented from imaging procedures such as CT scans or MRIs, the same cannot be done for cartilage. Close values of HU for similar densities make recognizing cartilage from bones difficult. Since CT and MRI scans are commonly used for model development, a problem arises when dealing with soft tissues adjacent to bones. Therefore, cartilage is often constructed later using FEM software capabilities rather than image segmentation.¹²

A hyperelastic model is preferred in modeling cartilage because this is a semirigid connective tissue considerably more flexible than bone. Linear elastic materials do not accurately predict the actual behavior of this tissue because of the presence of large deformations.³¹

A comparison is shown in ►Table 4. Some studies use the hyperelastic model of Mooney–Rivlin as a constitutive law

Table 4 Normal models' cartilage material properties

Study	Constitutive law	Modeling technique
Gislason et al (2009) ³³	Linear elastic isotropic	Masking technique on CT slicing using Boolean operators with second-order tetrahedral elements
Gislason et al (2010) ¹²	Hyperelastic (Mooney–Rivlin)	Extruded from the bone surface by identifying articulating surfaces with six-node wedge elements
Bajuri et al (2012) ¹	Hyperelastic (Mooney–Rivlin)	Extruded from bone surface
Gislason et al (2012) ²¹	Hyperelastic (Mooney–Rivlin)	Extruded from the bone surface by identifying articulating surfaces with six-node wedge elements
Bajuri et al (2012) ¹	Hyperelastic (Mooney–Rivlin)	Extruded from bone surface
Chamoret et al (2013) ^{a,25}	–	–
Matsuura et al (2014) ²⁰	Linear elastic isotropic	Areas of cartilage were set among bones using linear first-order tetrahedral elements
Chamoret et al (2016) ^{a,26}	–	–
Alonso Rasgado et al (2017) ⁷	Hyperelastic (Mooney–Rivlin)	Extruded from the bone surface by identifying articulating surfaces with six-node wedge elements
Ramlee et al (2018) ²³	Hyper-elastic (Mooney–Rivlin)	Extruded from articulating surfaces
Oflaz and Gunal (2018) ²⁴	Linear elastic isotropic	Incorporated as external borders of bones
Wei et al (2020) ^{a,27}	–	–

Abbreviation: CT, computed tomography.

Notes: Linear first-order tetrahedral: tetrahedral-shaped element with nodes at each vertex (total 4); second-order tetrahedral: tetrahedral-shaped element with nodes at each vertex and edges midpoints (total 10); and six-node wedge element: wedge-shaped element with nodes at each vertex and edges midpoints (total 6).

^aDid not include cartilage in the model.

instead of a linear elastic isotropic one. The same computational techniques of surface extrusion and hyperelasticity are used by all studies with only one exception.³³ In contrast, hand models do not consider cartilage.^{25–27}

Ligament Modeling

Ligaments constitute an important component of wrist mechanics providing mechanical stability.³⁹ They have hyperelastic behavior⁴⁰ and operate only in tension.⁴¹ A common technique is to model ligaments as springs to simulate their flexibility as semirigid tissue. There are two predominant modeling techniques commonly used: linear and nonlinear springs. The advantage of linear springs is simplicity as their parameter values are often reported in the literature. For nonlinear springs, stiffness values must be calculated and this represents additional steps in a simulation. Most studies with linear springs use a stiffness range of 4 to 350 N/mm.^{1,2,7,27} When linear springs are selected for a model and no stiffness is reported in databases, models normally use values of neighboring ligaments or their average. Since the anatomy of the ligaments and their physical properties are largely unknown and likely vary between individual wrists, the choice of which ligaments to use depends entirely on the researcher. Like cartilage, ligaments have similar densities to adjacent tissues making the process of image segmentation difficult and unreliable. Therefore, each ligament must be created manually, joining origin and insertion points which again are taken from limited previous works or databases. These stated variations cause significant differences in the constitutive laws used, the number of springs, and their position in each model. Some models use a higher number of linear springs to compensate for a more straightforward constitutive law,^{1,2} while others do the opposite with nonlinear springs.^{21,22} Using few spring elements in a node basis can result in highly localized stress concentrations in the origin and insertion points.³³

According to some authors, ligaments are crucial in providing stability to the simulation and for yielding coherent results.²⁷ However, some models did not consider liga-

ments and were still validated.²⁶ The use of contact modeling assumes the bones are held together and therefore can assume ligament integrity. This allows for modeling without the need to add unknown/unreliable ligament variables.

Wrist Conditions and Their Treatment Models

As opposed to the study of normal wrist mechanics, multiple studies have used FEM to evaluate pathology. Most works only describe a disease or condition of interest, without simulating it which can be problematic since features such as bone geometry modification and changes in material properties are never considered in the simulation. Furthermore, the area of interest is so varied that there is no possibility of comparison between studies.

The commonly simulated conditions are rheumatoid arthritis (RA) and carpal instability.

Rheumatoid Arthritis

RA is mechanically characterized by cartilage destruction and ligamentous laxity.^{13,22} Most studies in treatment for RA. Not simulating the disease constitutes a major limitation of several models whose goal is to simulate affected wrists. An exception in the study by Bajuri et al¹ includes RA features modeled as: reducing the elastic modulus of 33% for cortical bones and 66% for cancellous bones; removing the entire articular cartilage and allowing gaps to be closed if a load is applied; and reducing the number of spring elements to one. The second model proposed by Bajuri et al² is based on their first model and includes even more features to simulate several characteristics of a RA wrist, which is specified as a type with modification of bony geometry to simulate loss of carpal height; translation and rotation of bones to simulate dislocation of carpal bones, hand scoliosis, and reduction of contact between lunate and radius; and bone erosion.²

Carpal Instability

It is challenging to define carpal instability because it is a multifactorial phenomenon. Carpal instability is an injury of

Table 5 Arthroplasty and arthrodesis models

Study	Simulated anatomy	Disease addressed	Treatment	Sample characteristics
Bajuri et al (2012) ¹	Whole wrist	Rheumatoid arthritis	TWA with ReMotion implant	1 in vivo healthy 53-year-old man's wrist
Gíslason et al (2012) ²¹	Whole wrist	Degenerative and inflammatory wrist diseases	Partial-wrist arthrodesis	1 in vivo healthy young man's wrist
Bicen et al (2015) ¹⁶	Whole wrist (2D)	Several wrist diseases	Limited carpal fusions: STT, FCF, CH	1 in vivo healthy 24-year-old man's wrist
Gíslason et al (2017) ²²	Whole wrist	Rheumatoid arthritis	TWA with universal 2 implant	1 ex vivo healthy wrist
Faudot et al (2021) ⁸	Whole wrist	Wrist arthritis	Surgical constructs for wrist four-corner arthrodesis via dorsal and radial approaches	1 ex vivo fractured 35-year-old man's wrist

Abbreviations: 2D, two dimensional; TWA, total wrist arthroplasty; STT, scaphotrapezialtrapezoidal (fusion); CH, capitohamate (fusion); FCF, four corner fusion.

Table 6 Ligament-related models

Study	Simulated anatomy	Pathology	Treatment or objective	Sample characteristics
Alonso Rasgado et al (2017) ⁷	Whole wrist	Scapholunate instability	Tenodesis techniques: Corella, SLAM, MBT	1 in vivo healthy 63-y-old woman's wrist
Perevoshchikova et al (2021) ¹⁸	Scapholunate ligament and adjacent carpals	Rupture of scapholunate interosseus ligament	Performance of additively manufactured scaffolds for scapholunate ligament	Scaffold own design, no information about carpal bones
Yamazaki et al (2021) ¹⁹	TFCC and adjacent bones	TFCC injury	Stress distribution of the TFCC by rotation movements	1 ex vivo pathological 80-y-old man's wrist

Abbreviation: TFCC, triangular fibrocartilage complex; SLAM, scapholunate axis method; MBT, modified Brunelli tenodesis.

the wrist that induces carpal misalignment and is often caused by soft tissue with or without bony injuries.^{7,42}

Alonso Rasgado et al simulated several tenodesis techniques for the treatment of scapholunate (SL) instability using three models: intact ligament (healthy), SL instability virtual sectioning, and three tendon graft reconstruction techniques. The wrist affected by SL instability is simulated by totally removing the SL ligament, so there is no connection.

► **Table 5** summarizes the studies using FEM for arthroplasty and arthrodesis, as they constitute common topics in wrist FE models. ► **Table 6** presents studies focusing on ligaments, including one healthy and one treatment model.

Discussion

The complexity of wrist mechanics coupled with heterogeneous methods and approaches to FEM makes any attempt at standardization and consensus regarding FEM methodology virtually impossible at this time. The use of novel disciplines such as machine learning and big data may prove useful in the future of human wrist biomechanics to overcome these problems.⁴³

Image segmentation, material properties, contact modeling, validation, and verification are common challenges when constructing a model of the wrist using FEM. Image segmentation presents similar problems in most models since thresholding cannot be done automatically from CT scans. Many components such as soft tissues are modeled manually or not at all. In addition, image segmentation is not always thoroughly explained in the articles, making it difficult to identify an optimal technique.

Regarding contact modeling, although it is conceptually similar in most models, a significant issue stems from the software and different contact algorithms used. Furthermore, contact is not always explained adequately, and the utilized parameters are not always presented. In any future model, contact modeling must be carefully detailed just like other modeling parameters to understand and quantify this feature's variability.

Some form of validation is included in every study to show that the obtained results are coherent and that the model is useful to predict true behavior of the wrist. This is normally

done using previous works in the form of literature validation using numerical or experimental results. A clear difficulty of this approach is that the mechanics or treatment modalities being studied often differ from those described in published FEM studies, and thus, validation is often limited to similar existing models or just normal wrist models.

Regarding pathology and treatment, the limitation is that many models do not consider the effects of the pathology on the initial normal wrist model. Some features due to the disease development such as the reduction of material properties, geometry modification, and bone movement could alter the results considerably. The effects of considering these features should be investigated.

Elastic models have consolidated during the last decade, laying a solid foundation for bone modeling using simpler constitutive laws. Despite the difficulties, FEM allows for study of wrist mechanics and how they are affected by pathology and treatment. The future for wrist modeling using FEM seems promising because of newer hyperrealistic models that aim to predict wrist behavior more accurately. Utilization of hyperelastic models including soft tissue components will likely increase allowing for a better understanding of wrist mechanics.

Conclusion

FEM has been extensively used during the last decade to study the human wrist. It is an effective numerical tool for predicting the mechanical behavior of the wrist under different loading conditions circumventing the need for in vivo studies that are difficult and often costly to perform. A FE model's quality depends on several factors distributed over a typical FEM pipeline as well as verification and validation steps. Due to the heterogeneity of normal anatomy, mechanics, tasks, pathology, treatment examined, and variability of computational methods used for FEM simulations, comparing studies done during the last decade remains a difficult task. Future approaches may utilize already established models but every addition to the body of literature is helpful in what ultimately may become a big-data approach to understanding wrist biomechanics.

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Conflict of Interest

None declared.

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