Mechanical and functional assessment of the wrist affected by rheumatoid arthritis: A finite element analysis

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A B S T R A C T

Understanding the pathomechanics involved in rheumatoid arthritis (RA) of the wrist provides valuable information, which will invariably allow various therapeutic possibilities to be explored. The computational modelling of this disease permits the appropriate simulation to be conducted seamlessly. A study that underpins the fundamental concept that produces the biomechanical changes in a rheumatoid wrist was thus conducted through the use of finite element method. The RA model was constructed from computed tomography datasets, taking into account three major characteristics: synovial proliferation, cartilage destruction and ligamentous laxity. As control, a healthy wrist joint model was developed in parallel and compared. Cartilage was modelled based on the shape of the articulation while the ligaments were modelled with linear spring elements. A load-controlled analysis was performed simulating physiological hand grip loading conditions. The results demonstrated that the diseased model produced abnormal wrist extension and stress distribution as compared to the healthy wrist model. Due to the weakening of the ligaments, destruction of the cartilage and lower bone density, the altered biomechanical stresses were particularly evident at the radioscaphoid and capitulate articulations which correlate to clinical findings. These results demonstrate the robust finding of the developed RA wrist model, which accurately predicted the pathological process.

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1. Introduction

One of the most common skeletal diseases that affect the wrist joint is rheumatoid arthritis (RA) [1]. This disease causes inflammation of the synovial joints, resulting in significant pain, loss of function and ultimately resulting in structural deformity [2–4]. RA is a life-long disease which, like most other chronic autoimmune conditions, results in progressive tissue damage [2].

It has been previously described that three specific processes are involved in the pathophysiological development of rheumatoid disease. These include cartilage degradation, synovial proliferation and ligamentous laxity [2,5]. Cartilage degradation occurs due to effects of inflammatory cytokine, lysosomal enzymes released from polymorphonuclear cells and free radicals. This in turn will result in loss of cartilage, which may also result in the inhibition of new cartilage production [5]. Over time, bony erosion due to synovial proliferation may cause sharp bony edges which predisposes to tendon rupture [2,6]. Both processes contribute to ligamentous laxity by stretching the radioscaphocapitate ligament. This condition may also be associated with ulnar translation and carpal supination. Occurring concurrently, these changes will lead to biomechanical imbalances that ultimately result in visible deformity of the wrist [7,8].

Understanding the pathomechanics and the changes resulting from the disease progression is therefore important, as treatment outcomes may be related to methods which restore biomechanical integrity [2]. The use of finite element analysis has been demonstrated to be a reliable tool for investigative purpose [9–18] and may be appropriate to determine the changes involved in RA. This method has also been widely employed due to its ability to simulate load distribution and deformation patterns which, cannot be reliably achieved using any other methods [19–21]. Based on our literature survey, there has been no report on the use of finite element method to analyse the RA of the wrist joint.

In the present study, two 3-dimensional finite element models were constructed to simulate healthy and disease RA wrist models. These models were then analysed using computational software for their range of motion and stress distribution. The data obtained will provide sufficient information to determine the biomechanical changes as the result of the disease process.
2. Materials and methods

2.1. Defining the geometry

The geometry of the finite element model was obtained from 3-dimensional construction of computed tomography images from healthy wrist joint. Wrist joints with macroscopic or pathological changes were excluded from this study. Scans were performed for the whole left upper limb in a healthy volunteer. Images were captured with the wrist in extension (33.1°) and deviated (17.34° ulnar) positions, measured relative to the anatomically based radial coordinate system [22]. The CT images of the wrist joint, ranging from the distal end of the left forearm bone – radius and ulna – to the proximal third of the metacarpals were captured. The total length of the scans was 74.62 mm with a resolution of 0.98 mm in plane and a slice thickness of 1.5 mm. The images were exported into Amira 4.1 (Visage Imaging, United States) software for further analyses. Segmentation process was carried out on each slice of the CT dataset. This technique was performed in order to extract the bony topographic surface area on each slice. The interaction between bones was then investigated for each constructed image. This is crucial due to the numerous articulations which exist in the wrist joint. Boolean operations were performed in order to check for any intersecting bodies between the bones. When any overlapping was observed, modifications were made to the computational equation by subtracting each body using Boolean method. In order to check the operations with a high degree of consistency, mask was recalculated from the 3-dimensional objects so that the location and shape of the particular bone could be validated. The model was then converted into finite element mesh using triangular surface elements. Due to the relatively low resolution image of the CT datasets, an automatic smoothing procedure was utilised to remove sharp edges from the extrapolated images of the bone geometry. The ratio of twice the radius of the inscribed circle to the radius of the ascribed circle of the triangle was used as the parameter to determine the mesh quality [19,23]. The value for the quality threshold was set to 0.4 to produce high quality surface mesh [19] with an average element size of 0.4 mm. This resulted in an accurate geometric description of the bone geometry, checked and confirmed by comparing the model with an anatomy software [24]. Boolean operations were performed in order to identify intersecting bodies. Marc.Mentat (MSC.Software, Santa Ana, CA) software was used to convert the completed model to 3D solid linear first order tetrahedral elements with a total of 541,770 elements and 127,755 nodes.

Cartilage layers in the articulations between the solid geometry were modelled based on the available articulations. In order to estimate the distribution area of the cartilage, thorough observations were carried out on the CT images throughout the complex articulation of the joint. The region of the cartilage was then estimated through manual segmentation process and their corresponding 3D model was then constructed. Boolean operations were performed on the constructed bones and cartilages in order to get the profile of the associated surfaces. To create the cartilage structure, these articulation surfaces were extruded from the bone surfaces [23]. The thickness of the cartilage was assumed to be half of the minimum distance between the two smoothed surfaces of each articulation [24]. This technique was used for all articulations.

Fig. 1. Finite element model of the wrist joint showing the cartilage elements at the articulations between bones.
within the metacarpals, carpals and for the radiocarpal articulation. This resulted in a good geometrical representation and material distribution of the cartilage (Fig. 1).

2.2. Modelling of the wrist affected by rheumatoid arthritis

Previous clinical reports have thoroughly outlined the clinical symptoms of the wrist affected by RA. The three main factors, which play an important role during the pathological process of the wrist, were identified as synovial proliferation, cartilage destruction and ligamentous laxity [2,3,5]. The RA model in this study was therefore reconstructed based on these three identified criteria. Since synovial proliferation can cause disruption to the loading behaviour, the bones that are being stress-shielded tend to have osteoporotic characteristics. This was confirmed by Young et al. [25] who reported that osteoporotic fracture was also one of the complications of RA. The relatively low densities of RA bone were therefore simulated by reducing the elastic modulus of the bones: 33% for the cortical bone and 66% for the cancellous bone [21,26–31]. As reported in previous studies [4,25,32–34], the pathomechanics of RA caused permanent articular cartilage damage. This condition was simulated by removing the entire articular cartilage from the bones, allowing the interfacial gaps to be closed naturally once load is applied. The third major RA characteristic that was modelled, i.e. ligamentous laxity, is very subjective to individual cases. The present study therefore simulated the worst-case scenario by reducing the number of spring elements into one simulating the ligaments while maintaining its stiffness value, mimicking the severely torn and stretched ligaments [2,35,36]. The simulated RA wrist was then converted into solid tetrahedral mesh which produced an FE model consisting of the same numbers of elements and nodes as the healthy model.

2.3. Tissue properties modelling

Simulated bones were modelled using linear isotropic material with elastic modulus of 18 GPa for the cortical bone, 100 MPa for the cancellous [19,37,38] and Poisson's ratio values of 0.2 for the cortical bone and 0.25 for the cancellous bone [19]. Large deformation behaviour of the cartilage was modelled using hyper-elastic material properties [38]. Mooney–Rivlin modelling was used to perform the hyper-elastic behaviour with coefficients of $C_{01} = 0.41$ MPa and $C_{02} = 0.2$ MPa.
C_{10} = 4.1 \text{ MPa}[39]. These corresponding values have been successfully used to model the behaviour of the articular cartilage as proven in a computational study done by Gislason et al. [19].

Ligamentous constraints were modelled using linear spring elements [40]. The position of the ligaments was estimated based on previously published anatomical studies [19,41–44]. The stiffness parameter of the respective ligaments was varied from 40 to 350 N/mm. For ligaments without established material parameters, it was assumed that the properties of the neighbouring ligaments would apply [45]. Parallel multiple springs were applied in order to simulate the distribution of the origin and insertion of the ligaments [19,45].

2.4. Specification of loading conditions

The load calculated from the previous study was used to derive the loading applied at the individual metacarpals [19]. Loading simulating static gripping force with resultant compression pressure of 0.73 MPa in magnitude, distributed over the 5 digits, was applied on
the metacarpals. A summary of the applied loads and the placement of the loading are shown in Fig. 2.

3. Results

3.1. Wrist extension

The contour plots of displacements (Fig. 3) showed that the RA wrist was able to achieve larger wrist extension to that of a healthy wrist with values of 9.99° and 0.98°, respectively.

3.2. Bone stress distribution

Stress plots at the wrist bones revealed that the stresses were distributed over a relatively greater surface area in the healthy model compared to the RA model. However, in both models the stresses were concentrated radially (Fig. 4).

To determine the load transfer in the radius, the contour plots for stress distribution was generated for both the cortical and cancellous segments (Fig. 5). It appears that the thin cortical shell undergoes higher amounts of mean stress (1.1 MPa) compared to the more softer cancellous bone (0.01 MPa). In the cortical bone of the radius, it was observed that there was a difference in the

Fig. 4. Von Mises stress plots for (a) the healthy and (b) RA model.
stress distribution between the healthy and RA model based on the superior view. It appears that stress concentration was relatively higher in the RA model compared to the healthy model. The AP view also showed that the RA model had a higher stress concentration at the styloid process (47 MPa) compared to the healthy model (39 MPa).

A stress distribution measure for each element was performed. For the RA model, elements from the capitolunate joint experienced...
large stress magnitudes between 61 and 505 MPa (Fig. 6a). Another joint that showed high magnitudes of stress was the radioscaphoid joint (50–58 MPa). The load transmitted through the radius and ulna was analysed by calculating the total stress ratio between the radius and ulna for both models (Fig. 6b). In the healthy model, 89.5% of stresses were transmitted through the radius while only 10.5% were transmitted through the ulna. However, higher stresses were transmitted through the radius in the RA model (94.5%) than the healthy model.

4. Discussion

The present study reports a three dimensional simulation of RA wrist created from the CT images of a healthy individual using finite element method. As far as the authors of this paper are aware, this is the only study that has developed a virtual analysis of simulated RA model of the wrist joint using finite element method. The present study reports a three dimensional simulation of RA wrist and compared to the healthy wrist. The detailed understanding of the pathomechanics involved in the diseased joint provides a useful insight which could lead to useful clinical applications.

An assessment was made on the model quality based on surface element to confirm accuracy of the developed model. The ratio of twice the radius of the inscribed circle to the radius of the ascribed circle of the triangle for 90% of the elements was greater than 0.80 (where unity represents an equilateral triangle), thus substantiate the accuracy of the models.

The RA model simulated in this study is comparable to a grade IV rheumatoid arthritic joint observed in clinical conditions, considering that complete ligament disruption, permanent bony displacement and carpal dislocation were incorporated within the programming [3]. Obvious differences in the wrist extension were observed for both FE models of the healthy and RA model under the simulated hand grip condition. The load-controlled simulation showed excessive motion for the RA model due to the lost of physiological constraint from the ligaments. The laxity within the ligamentous structure reduces the stabilisers of the wrist thus leading to relatively free motion of the bones. This together with the presence of weakened ligaments results in unstable wrist motion leading to possible joint dislocation. The results of this study appear
to correspond to previous clinical reports [3,32,46]. Additionally, the static condition simulated in this study mimicked the real routine static radiographic examination of patients with grade IV RA wrist.

It was observed in this study that high stress concentration was generated at the radiocarpal and capitulonate joints, which is also known to occur in RA wrists [32]. Previous clinical studies [47−49] reported that these joints are critical joints in deteriorated wrists with pathophysiological characteristic of intra-articular fracture. Radiocarpal joint which is the most important articulation of the carpal complex [32], is easily subjected to dislocation as well as degenerative conditions [3,47]. Being the most mobile carpus, the scaphoid with its elliptic facet is easily misaligned within the distal radius facet as the result of abnormal joint motion. The increased ability for the wrist to undergo extension further compounds the problem. This results in the ulnar rotation of the scaphoid while displacing it palmarly. Clinically, this condition has also been described [3]. The critical condition of the capitulonate joint in rheumatoid wrist has also been reported in previous clinical study where the lunate sustained a relatively higher load compared to the scaphoid, thus resulted in imbalance load transfer [47]. Our findings in this study has successfully showed similar outcome.

The model of the wrist required several constraints in order to achieve convergence, one of which involved constraining the motion of the carpometacarpal joint. This is crucial considering that the absence of this constraint leads to excessive translations of the bones [19,50]. Furthermore, the actual physiology of the joint shows that the carpometacarpal joint is relatively immobile as compared to other joints. Linear properties of the ligaments as assigned in this study were found to be sufficient as the outcomes are comparable to that of the previous clinical trial reports. It is, however recommended for future study to use non-linear viscoelastic properties of the ligament to closely mimic the actual behaviour of ligaments [45].

Despite the robust findings and developed model of the present study, several aspects can be further improved to develop a superior RA wrist model. Although we have simulated all the main characteristics of an RA wrist, the pathophysiological characteristics have not been taken into account. This includes specific shape changes of individual carpal bones as well as their deteriorated material properties. This was done to ensure generality of our study rather than investigating a very specific RA case. The simulated RA model in this study also consisted of interfacial gaps between the RA bones with a thickness ranging from 0.1 to 1.5 mm. This was done to allow the gaps to close naturally under the applied load and it was acceptable as the movements of the bones after loading were similar to the rheumatic wrist. An analysis without interfacial gaps could be done in the future to mimic the real condition of RA bone [3]. To approximate functional wrist motion in real time, kinematics study could be incorporated into the simulation thereby providing wider physiological loading conditions with the use of more sophisticated modelling tools and designs. A more precise representation of the wrist model can be obtained with a higher resolution CT scan. Despite the shortcomings of the present model, the multi-articulation analysis in this study provided an appropriate and near accurate model of the RA wrist which in turn offer better understanding of the disease process. This may lead to useful clinical applications, such as the design and development of implants either to fully or partially replace the diseased joint.

5. Conclusions

Using three major pathological characteristics of RA, the present study successfully simulated the rheumatoid wrist through the use of finite element model. Using the hand grip function simulation, the RA wrist produced more extension and altered biomechanics, which lead to high stress areas within the wrist joint, most notably at the radiocarpal and capitulonate articulations. These findings appear to correspond to reported clinical conditions making the developed model valid for use in future studies.

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Conflict of interest statement

None.

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