OPTIMUM DESIGN OF AN ARTIFICIAL WRIST IMPLANT

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Abstract: This paper describes the anatomy and biomechanics of the normal wrist, proposes the requirements for ideal wrist prosthesis and suggests an optimum design solution with the aid of FEA techniques.

1. The wrist

The wrist is a complex joint made up of the eight carpal bones, the radius and the ulna. The carpal bones, or carpals, can be divided into two rows: proximal and distal (Fig 1). The proximal row is formed by the scaphoid, lunate, triquetrum and pisiform. The trapezium, trapezoid, capitate and hamate form the distal row [1 and 2].

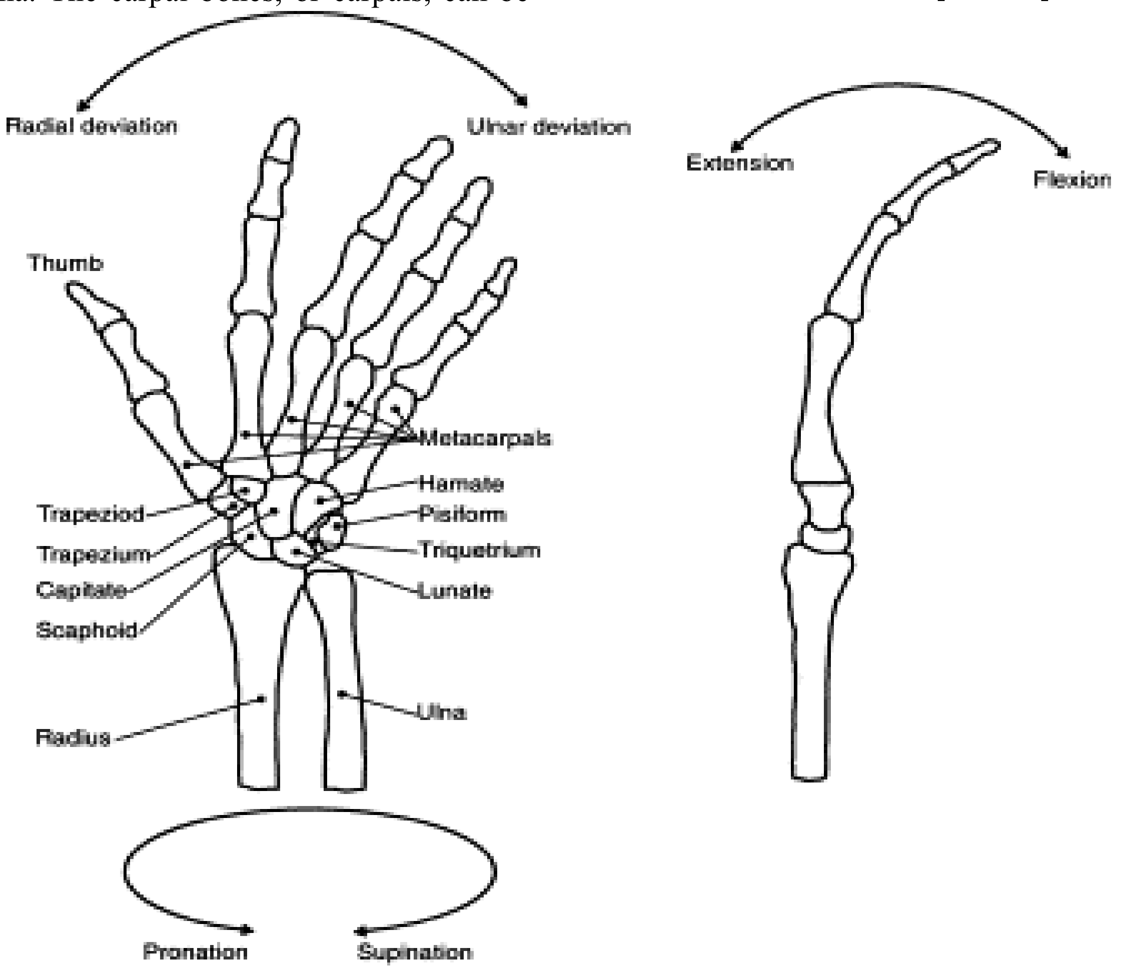


Fig. 1. Bony anatomy of the normal wrist, also showing the movements of the wrist: flexion/extension, radial/ulnar deviation and pronation/supination (occurring principally between the distal radius and ulna, although 2–12° occurs between the radius and the carpals at extremes of forearm rotation [3]).

The main joint of the wrist is the radio-carpal joint, which is a synovial articulation formed by the distal end of the radius and the scaphoid, lunate and triquetrum bones. The distal ulna makes contact with the proximal carpal bones through the interposed triangular fibrocartilage complex [2].
Ligaments connect the carpal bones to each other and also connect the carpal bones to the radius, ulna and to the metacarpals distally. The wrist joint is covered anteriorly (front) by the flexor tendons and dorsally by the extensor tendons [2].

1.1. Wrist Motion

The radio-carpal joint together with the mid-carpal joint (articulation between the proximal and distal carpal rows) enable the complex movements of the wrist. The main movements (Fig. 1) of the wrist are flexion and extension, and radial and ulnar deviation [2]. The centre of rotation for flexion/extension and radial/ulnar deviation is located in the head of the capitate [4]. Most rotation occurs between the distal radius and ulna (pronation and supination, Fig. 1), although subtle degrees of rotation take place between the carpal bones and the radius [3]. Combinations of these movements can enable other types of motion such as circumduction motion, which is an elliptical motion in which the hand starts in radial deviation, moves down into flexion, over into ulnar deviation and up into extension [5].
A normal range of motion for healthy wrist joints is 76° for flexion, 75° for extension, 22° for radial deviation and 36° for ulnar deviation [6]. However, a full range of motion is not required to undertake the simple activities of daily living and it has been shown that even a few degrees of wrist movement will increase the reach of the fingers by approximately 5–6 cm [7]. A number of authors have investigated the functional range of motion for the wrist during a variety of everyday activities, such as those required for personal hygiene or for culinary tasks. Brumfield and Champoux [8] describe the optimum functional range of motion for the wrist necessary to accomplish most daily activities as from 10° of flexion to 35° of extension. Palmer et al. [3] determined the functional range of motion for the wrist as 5° of flexion, 30° of extension, 10° of radial deviation and 15° of ulnar deviation. Ryu et al. [9] showed that 40° of extension, 40° of flexion, 28° of ulnar deviation and 12° of radial deviation were adequate to undertake a variety of everyday activities. Nelson [10] used splints to limit motion, and showed that activities of daily living could be completed with 5° of flexion, 6° of extension, 7° of radial deviation and 6° of ulnar deviation.
Although it has been suggested by several authors [2 and 11] that no rotation occurs between the carpal bones and the radius, this concept has been disproved. Palmer et al. [3] showed that there was indeed a small amount of rotation between the carpals and the distal radius of between 2 and 12°, confirming that the wrist has three degrees of freedom.

1.2. Wrist Forces

Most studies that have investigated the forces acting through the wrist have concentrated upon the normal wrist. Ketchum et al. [12] got their subjects to exert maximum effort of their wrists in extension within a test rig, and determined the total force along the extensor muscles to be 586 N. Amis [13] suggests that the muscles in the wrist can impose forces that are greater than body weight across the wrist in strenuous activities. Youm and Flatt [14] suggested that the wrist joint should maintain 200 N of force during ordinary daily activities. Forces of 118 to 143 N have been applied to the wrist in a variety of studies [15-19], and confirm that the forces passing through the wrist under normal physiological loading conditions are much less than the forces that occur during strenuous activities.

2.0 Design requirements for an ideal wrist implant

The main design requirements of a wrist implant are to [7 and 8]: (1) relieve pain; (2) be stable; (3) provide a functional range of motion; and (4) correct deformity. The most important of these areas that need to be addressed in the design of a successful implant for the treatment of advanced rheumatoid wrist are: (1) range of motion; (2) materials; and (3) fixation.

The vast majority of current and past designs of wrist implant have attempted to recreate the natural joint to enable a wide range of motion. It has often been assumed that the wrist has two degrees of freedom (flexion/extension and radial/ulnar deviation) [2 and 11], but a third degree of freedom (a small amount of rotation) does occur [3]. It has been suggested that if wrist implants do not allow for the three degrees of freedom they can be expected to loosen and/or fail over time [3].

It has been suggested that in the normal wrist, the centre of rotation for flexion/extension and radial/ulnar deviation is located in the head of the capitate [4]. Taking this into consideration all artificial wrist implants have been designed so that the centre of rotation for the implant is in the same location as the normal wrist joint, i.e in the capitate or where the capitate was before bone resection. In addition, the axis of rotation in the normal wrist is not fixed but varies as the wrist moves, through gliding of the proximal carpal row upon the distal radius. Also, the eight bones forming the carpus do not move as one unit, and a considerable amount of movement occurs between the proximal and distal rows of the carpus in addition to the movement taking place between the proximal carpal bones and the distal radius [5, 20 and 21].

3.0 Wrist implant Designs

Recent designs of wrist joint prostheses have followed a superficially similar design philosophy. Closer examination of competing designs shows that a variety of concepts are in use in the market. These fall into conforming and non-conforming designs, with either toroidal or elliptical articulating surfaces.

The design of a new wrist joint prosthesis stipulates the need for two key design features – unimpeded pronation/supination axial rotation between the distal and proximal parts of the design, and that the design must follow the anatomical centres of rotation for the natural wrist [22]. Specifying axial conformity reduces the chance of loosening through levering and torsional loading between the distal and proximal components, since the design can take a position of lowest energy. All soft tissues are retained except the dorsal capsule and intrinsic ligaments of the carpus in the way of the excisions made in positioning and locating the implant. Retaining the soft tissues ensures that the design is intrinsically stable [23]. There have been many different design of wrist implants but the popular wrist joints are Universal and Biaxial. More description of the joints is given below.

3.1. Universal total wrist (UTW)

The Universal Total Wrist System (KMI Inc, CA, USA) was developed by Menon [24 and 25] and is shown in Fig. 2. The metacarpal component (made from titanium) has a plate with a central stem that is cemented into the third metacarpal. Two titanium screws are also inserted through the plate and into the carpal bones. A polyethylene bearing surface is then slid onto the carpal plate. The radial component (cobalt chrome alloy) consists of a concave surface, which articulates against the polyethylene surface, and a stem which is cemented into the medullary canal of the radius.

Fig. 2. Universal total wrist implant

Menon [24] reported that the most common complication with this implant was dislocation, with loosening of the radial component also seen to occur.

3.2. Biaxial

The biaxial implant [26 and 27] (Biax™, Depuy International Ltd, Leeds, UK) has a metal (cobalt chrome alloy) metacarpal component with an ellipsoidal shaped head articulating against a polyethylene bearing surface attached to the metal radial component, as shown in Fig. 3. The shape of the bearing surfaces is to duplicate the flexion-extension and radial-ulnar deviation of the natural wrist. The long stem of the metacarpal component is inserted into the third metacarpal, but there is also a small stud that fits into the trapezoid bone for additional stability and fixation. Cement is used to fix the metacarpal and radial stems into position. The proximal surfaces of the implant also have a porous coating for enhanced stress distribution at the cement fixation interface.

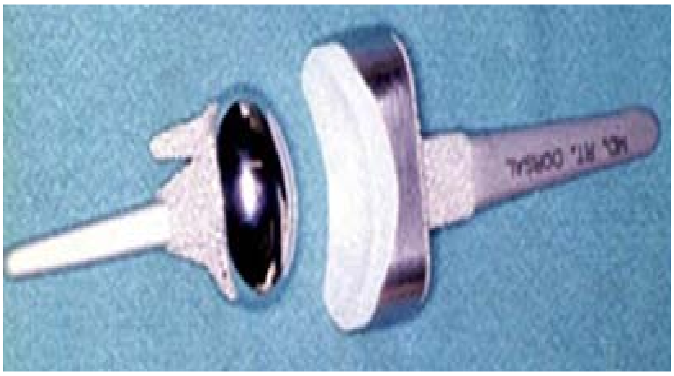


Fig. 3. Biaxial total wrist implant

Complications involving the biaxial wrist implant are: distal component loosening [27], dislocation [28] and perforation of the distal stem through the metacarpals [29].

4. UEL/OsteoTec design optimisation

In the new design of UEL/OsteoTec prosthesis (shown in Fig 4), the radii of curvature of the carpal tray and UHMWPE match in the RUD plane, but in the FEM plane, the radii of curvature increase by 1mm in the radial tray from a conforming curvature of 10mm (medium_r10(conforming) in Fig 5), up to a non conforming difference in curvature of 3mm in the FEM plane (medium_r13 in Fig 5). The best performing medium_r13 UEL/OsteoTec Design was selected for comparative analysis.

Fig 4 UEL/OsteoTec wrist prosthesis

Fig 5 shows the averaged and linear element results for Peak von Mises stress for the UEL/OsteoTec, DePuy and KMI designs up to an ellapsed time of 0.5 seconds. This point is half way through the analysis with the defined motion of the rigid bodies giving an overall extension of 30 degrees and an ulnar deviation of 7.5 degrees. Fig 6 shows the FEA analysis, highlighting the meshing feature.

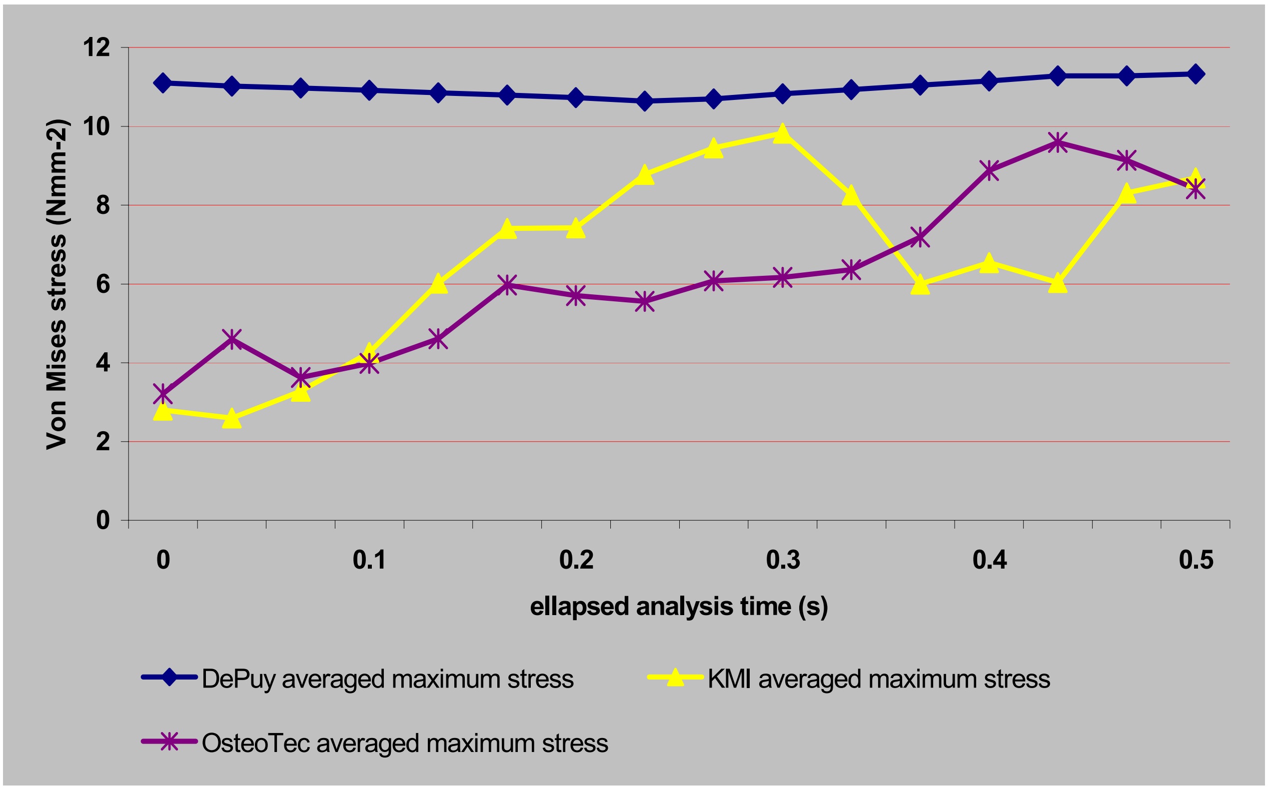
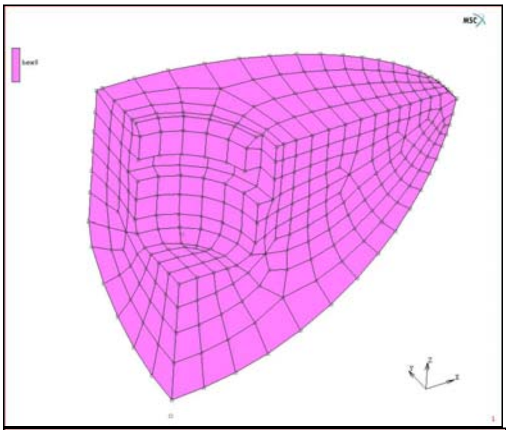
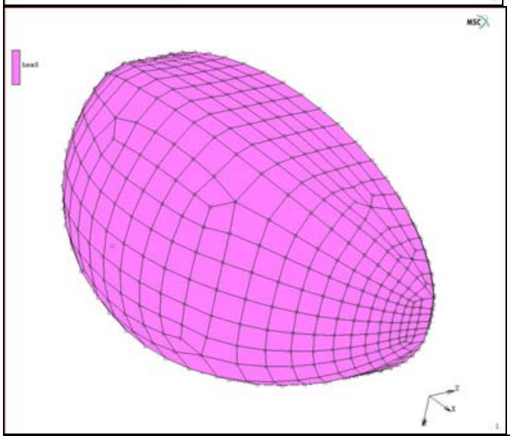


Fig 5 Peak averaged Von Mises stress for Deput, KMI and UEL/OsteoTec designs



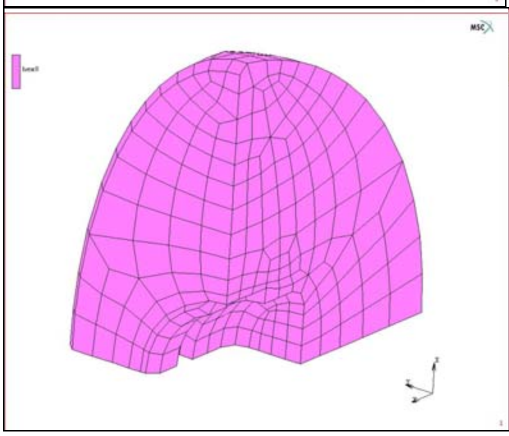
A quarter of the mesh bounded by the rigid bodies. The mesh is designed to incorporate the change from a cylindrical arrangement around the hole to a tapering cubic arrangement of elements at the extremities of the component. As such it contains numerous transition areas between the elements, both to allow efficient element usage, and also to follow the geometry of the UHMWPE component in the best possible way. All of the UEL/OsteoTec models follow a similar pattern of mesh generation.



Left. The completed medium implant mesh, showing uniform elements

Below Left. Large implant quarter mesh showing element transition approaches implemented

Below Right. Entire large implant mesh



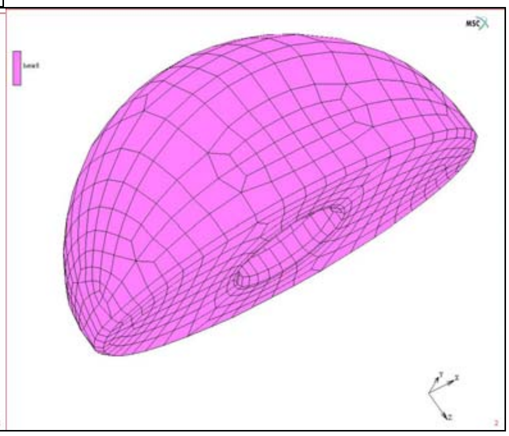


Fig 6 FEA analysis of the articulating surfaces of the UEL/ OsteoTec wrist prosthesis

It is important to realise that the analytical results obtained where the loading is constant over the range of motion is for comparison of the stress distribution patterns and values between the differing tray geometries of each size. However, grip strength varies with angular displacement and the loading bearing capacity of the natural wrist also varies depending on angular displacement. Maximum grip strength and load bearing capacity of the wrist occur simultaneously with maximum conformity of the articulating surfaces of the wrist – and in the UEL/OsteoTec wrist prosthesis this is nearest to, or at, the designed neutral position when the stress distribution through the articulating surfaces of the UHMWPE is lowest also. Hence the prosthesis design has the greatest load capacity at the position that is most likely to supply the greatest loads through the prosthesis. The new design also has a designed neutral position that incorporates a dorsally angled tray component giving 10 degrees extension, and an orientation of the tray 10 degrees ulnarly.

The ability of the prosthesis to contend with high loading at large angular displacements is not as important compared to its ability to contend with high loads in an anatomically appropriate position (i.e. a neutral wrist position), yet the new design is able to maintain an improved distribution of load over the UHMWPE component which will reduce wear over time.

6.0 Conclusions

From the analytical work, it is clear that in terms of consistent stress reduction, non conforming articulating surfaces in the UEL/OsteoTec wrist joint prosthesis give an overall reduction in Von Mises stress through a range of motion that encompasses daily living tasks under practical loading conditions. The work also shows that a wrist prosthesis design that closely replicates the described kinematics of the wrist, and incorporates many design features desirable for successful implantation can still be functionally competitive.

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