Finite element study of a wrist prosthesis

Mohammad Mianroodi[1], Siham Touchal[1*]

1. ICube laboratory, University of Strasbourg, CNRS, France

***Corresponding author:** Tel: +33 368 852957 Fax: +33 752372795
Address: Laboratoire ICube, 115, 4rue Boussingault, 67000 Strasbourg, CNRS, France
E-mail: touchal@unistra.fr
Received; 30/07/2017 revised; 30/08/2017 accepted; 5/11/2017

Abstract

Joint replacement surgery in the wrist is less common than other replacement, but can be an option if you have painful arthritis that does not respond to other treatments.
In wrist joint replacement surgery, the damaged parts of the wrist bones are removed and replaced with artificial components, called a wrist prosthesis. If the cartilage is worn away or damaged by injury, infection, or disease, the bones themselves will rub against each other, wearing out the ends of the bones. This causes a painful, arthritic condition. Osteoarthritis, the most common form of arthritis, results from a gradual wearing away of the cartilage covering on bones. Rheumatoid arthritis is a chronic inflammatory disease of the joints that results in pain, stiffness and swelling. Rheumatoid arthritis usually affects several joints on both the right and left sides of the body. Both forms of arthritis may affect the strength of the fingers and hand, making it difficult to grip or pinch.

Keywords: Wrist prosthesis, Joint replacement, Pain, Finite element method, Rheumatoid arthritis

Introduction

The typical candidate for wrist replacement surgery has severe arthritis but does not need to use the wrist to meet heavy demands in daily use. The primary reasons for wrist replacement surgery are to relieve pain and to maintain function in the wrist and hand. Wrist replacement surgery may help retain or recover wrist movements. It may also improve the ability to perform daily living activities, especially if there is arthritis in the elbow and shoulder. During any total joint replacement, the worn-out ends of the bones are removed and replaced by an artificial joint (prosthesis).There are several generation of wrist prosthesis developed until now but each one had a movement limit or other problem. Therefore, Argomedical® design new generation of wrist prosthesis. In this report I investigate mechanical behavior of this new prosthesis with finite element method by using ABAQUS software. second principal strain ε_2, which is minor in the plane of the sheet metals.

History of wrist arthroplasty

The first total wrist arthroplasty was performed by Gluck (1) in 1890 for a 19 year old with Tuberculosis infection of the wrist (Figure 1). After experimenting with many materials, he came up with this case a failure due to development of a chronic sinus. Interest in total wrist arthroplasty was renewed when Swanson introduced a flexible hinged silicone implant in 1967 (2).

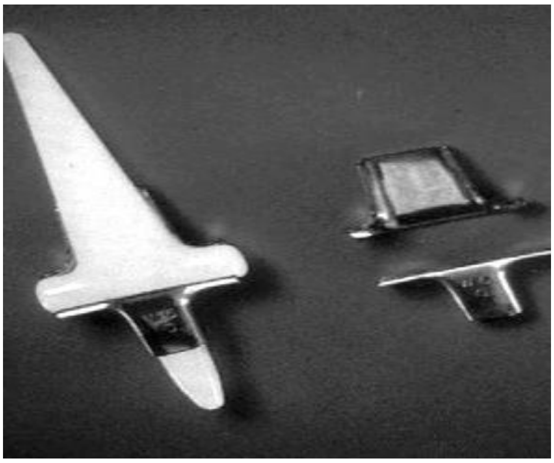


Figure 1. First generation of total wrist arthroplasty.

However, unlike more modern implants, it was designed to function more as an interposition articulated spacer than a true replacement. Many problems became apparent. Reactive synovitis with resulting pain, swelling and progressive osteolysis was extremely common within 3 years of implantation. The results of this prosthesis show 60% of person used this kind of implants had problem of movements and 35% of this person had problem of rapture. The main problem of this generation was failure and rupture of materials and the limitation of movements (1). Second generation implants were the first true replacements (Figure 2). They had polyethylene bearings and metal (3, 4). This generation was built in 1970s. It was unconstrained and permitted motion in all planes because of polyester ball and socket design with rotation centered on the position of the capitates head. Fixation in bone was, like Gluck's, with uncemented malleable metallic forks. The most common problem of these types of prosthesis was instability and prosthesis loosening. The 33% of patients were used this type of prosthesis had problem with loosening (5).

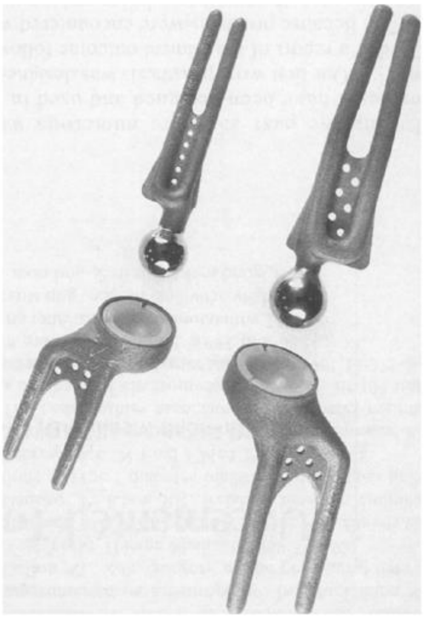


Figure 2. Second generation of total wrist arthroplasty.

Materials and methods

For third generation, there were many prostheses grouped third (Figure 3) (6). They are similar to current prostheses with stems and an elliptical polyethylene component. The third generation has been improved. For 5 years, only 26% reported problem of this prosthesis. The third generation with metal on polyethylene are now available (7).

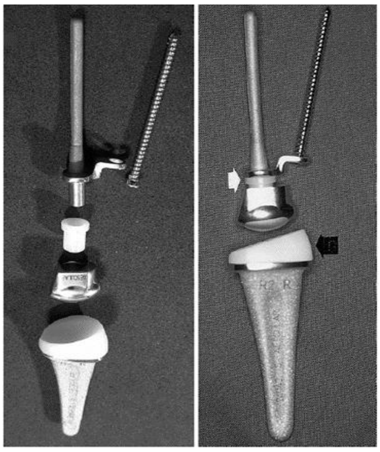


Figure 3. Third generation of total wrist arthroplasty.

Size of radius bon

In this case, we have experimental results. Linear geometric dependencies of the distal human radius investigated by choosing 2groups of people in Germany (B) and Austria (A) (Table 1). For each groups measured the maximum and minimum size of radius bone. They had been selected with 2 conditions: 1) Standard lower arms lengths and 2) Aged between 20-70 years.

Table 1. Radius length and width (8).

	Length (A) mm	Width (A) mm	Length (B) mm	Width (B) mm
Min	20.60	2.35	19.50	2.40
1st Qu	23.19	2.89	21.80	3.20
Median	24.57	3.05	23.20	3.20
Mean	24.65	3.10	23.17	3.40
3rd Qu	25.98	3.30	28.80	4.60
Max	28.80	3.80	28.80	4.60

In this research for group A, we have 51 female and 49 male and the average age of this group is 37.88 years old, and for group B, we have 76 female and 59 male. The average age of this group is 76.14 years old.

Material properties

One of the most important things in finite element problem is materials properties. In this project, we have 2 different part: 1) Bone and 2) Titanium (TiAl6V4).

Material properties of bones

We have 2 different parts of bone. First part is cortical bone and the second part is medullar bone. You can see the material properties in table 2**.**

Material properties of titanium (TiAl6V4)

TiAl6V4 is a high strength Titanium alloy providing a very good strength to density ratio (9). Compared to other Titanium alloys bar and flat products are readily available. Also under wet conditions the TiAl6V4 shows excellent fatigue strength and resistance against crack initiation and crack propagation. TiAl6V4 ELI (Extra-Low-Interstitial) is available for surgical implant applications. The table 3 shows the contents of this alloy.

One of the most important property of this alloy is poor shear strength for the bones and nit riding and oxidizing can improve the surface wear properties of this alloy**.**

Table 2. Material properties of bones by Rho (10).

Bone Type	Young's Modulus (MPa)	Poisson's Ratio	Density (g/cm^3)	Ultimate tensile (MPa)
Cortical	16000-19000	0.25	2000	150
Medullar	1500-1700	0.3	1500	20

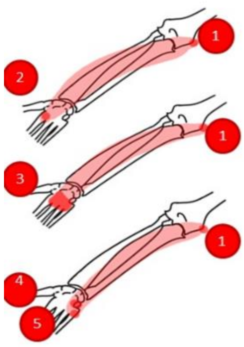
Table 3. Content of titanium alloy.

Component	Wt. %
Al	5.5
Fe	0.25
O	0.25
Ti	90
V	4

Forces

Forces that can be generated by the upper limb have been measured by orthopedic surgeons, ergonomists, and occupational and physical therapists (11). Wrist flexion and extension forces measured externally at the hand are a combination of forces acting between the forearm and hand, generated by exertions of agonistic and antagonistic muscle groups both within the hand (intrinsic) and the forearm (extrinsic) and by wrist dedicated (carpi) muscles. Many factors influence the magnitude of force that can be generated, including: type of pretension, digits involved, digital posture, wrist posture, arm posture, overall body posture, subject age, gender, hand tested, anthropometric dimensions, direction of force exertion, instructions to the subjects, day (12) (Figure 4).

There results between the biggest values within 3s exertion forces. There was no significant difference between the mean and peak force for either flexion or extension. Forces generated in flexion and extension were utilized in further analyses. Females were able to exert less force than males in all wrist positions, and you can see it in Table 4.



Flexor Carpi Radialis	Medial epicondyle (1)	2nd metacarpian (2)
Palmaris Longus		Fascia palmaris (3)
Flexor Carpi Ulnaris		Pisiform (4) and base of 5th metacarpian (5)

Figure 4. Flexion of wrist muscles.

Table 4. Flexion and extension force for male and female.

Flexion	Male	Female	Extension	Male	Female
90°	104.24 N	75.23 N	15°	76.87 N	46.90 N
75°	101.05 N	79.89 N	30°	68.26 N	47.01 N
60°	76.99 N	58.05 N	45°	60.35 N	42.31 N
45°	81.60 N	59.76 N	60°	52.24 N	37.46 N
30°	81.06 N	63.16 N	75°	54.29 N	40.46 N
15°	76.36 N	57.15 N	90°	76.87 N	59.03 N

Numerical section

We want to investigate mechanical behavior of wrist prosthesis against different forces. This purpose we choose ABAQUS to analysis our project with Finite Element Methods (5). In mathematics, the finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function (13). Analogous to the idea that connecting many tiny straight lines can approximate a larger circle, FEM encompasses methods for connecting many simple element equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain. The finite element methods software separate our shape to different elements (mesh), add forces and solve each elements separately at the end we can achieve the main stress, strain, energy and etc.

Bone scan

One part of our works was scanning real bone. For this purpose we have a real human radius bone. We used laser 3d scanner Roland Picza LPX-60 at INSA (Strasbourg, Lgeco). The Roland LPX 3D laser Picza™ scanner series is compact and enclosed, producing high-resolution digital data using an advanced non-contact laser sensor and high quality optics to capture parts. The combination of precision laser optics and motion control within a rigid enclosure lets design engineers produce high quality scans with minimal surface noise.

We can analysis the problem of scanning and in first improved I used fix tab and used auto repair option. With this option, I found 21023 inverted normal, 7145 bad edges, 5 bad contours and 71 shells, for repairing these issues I used auto fixoption but unfortunately despite of these improvement after import my STL file in ABAQUS.

Numerical method

I imported STEP file from Autodesk Inventor® to ABAQUS Part but our geometry had a lot of problem when it was imported in ABAQUS so I try to refine it, I build a lot of surface and fill a lot of shells. After importing our geometry, we should add our material properties in section property. For this purpose in first step, I define each material properties. In next step, we should add type of our material in part section. In next step, I go to assembly part. The main purpose of this part is match all parts of my project together. One of most important part of my numerical solution is how can I simulate my analysis, In this case, I select Standard Static for solving my project. In a general static analysis the code is iteratively solving [Kt]{du} = {dF}, where [Kt] is the tangent stiffness matrix, {du} is the vector of unknown nodal displacements and {dF} is the incremental load vector. In an explicit dynamic analysis, the code is solving {a} = {F}[M] -1, where {a} is the nodal acceleration vector, {F} is the force vector, 0 and [M] is the mass matrix. The first analysis type is for static (time-independent) and quasi-static (rate-dependent, but not involving inertia) problems. In interaction part, I selected the contact between each parts together for stopping criterion.

First force is 400 N applied in 90 degree but the other forces will be applied in 45 degree. Type of my forces are surface load. Next important part of my work is how I can define boundary condition. I used 2 different types of boundary condition: 1) Symmetry/Antisymmerty and 2) Displacement/Rotation.

In next part, I build a mesh around my models, in all of my models I used Tet mesh. The components were meshed in Hyper Mesh, using a semi-automatic surface meshes and then exported into Abaqus where the surface mesh was converted into volumetric mesh and the finite element analysis wasncarried out. The mesh consisted of 4 node tetrahedral elements C3D4. The total number of elements was 252,453 for the real model.

Conclusion

From whole of my work, I understand that the majority of loading is transmitted through the cortical shell of the radius. In fact medullar bone does not withstand large stress. I compared my results articles with results and I achieved good results. In our model, prosthesis head had minimum amount of stress. In my opinion, this prosthesis work very well during normal activities.

References

1. Bhatia R. Total wrist arthroplasty. OA Orthopaedics. 2014; 2(1):1.
2. Swanson A, Biddulph SI, Hagert CG. A silicone rubber implant to supplement the Keller toe arthtroplasty. NY Univ Inter Clin Inform Bull. 1971;10:7–14.
3. Meuli H C. Meuli total wrist arthroplasty. Clin Orthop Relat Res. 1984;(187):107-11.
4. Volz R G. The development of a total wrist arthroplasty. Clin Orthop Relat Res. 1976;(116):209–214.
5. Bajuri MN1, Kadir MR, Raman MM, Kamarul T. Mechanical and functional assessment of the wrist affected by rheumatoid arthritis: A finite element analysis. Med Eng Phys. 2012;34(9):1294-302. doi: 10.1016/j.medengphy.2011.12.020.
6. Harlingen Dv, Heesterbeek PJ, J de Vos M. High rate of complications and radiographic loosening of the biaxial total wrist arthroplasty in rheumatoid arthritis: 32 wrists followed for 6 (5–8) years. Acta Orthop. 2011;82(6):721-6. doi:10.3109/17453674.2011.636669.
7. Srnec JJ, Wagner ER, Rizzo M. Total Wrist Arthroplasty. JBJS Rev. 2018;6(6):e9. doi: 10.2106/JBJS.RVW.17.00123.
8. Baumbach SF, Krusche-Mandl I, Huf W, Mall G, Fialka C. Linear intra-bone geometry dependencies of the radius: Radius length determination by maximum distal width, Eur J Radiol. 2012;81(5):947-50. doi: 10.1016/j.ejrad.2011.02.030.
9. Baufeld B, van der Biest O. Mechanical properties of Ti-6Al-4V specimens produced by shaped metal deposition. Sci Technol Adv Mater. 2009;10(1):015008. doi:10.1088/1468-6996/10/1/015008.
10. Rho JY, Kuhn-Spearing L, Zioupos P. Mechanical properties and the hierarchical structure of bone. Med Eng Phys. 1998;20(2):92-102. doi: 10.1016/s1350-4533(98)00007-1.
11. Hallbeck MS. Flexion and extension forces generated by wrist-dedicated muscles over the range of motion. Appl

Ergon. 1994;25(6):379-85. doi: 10.1016/0003-6870(94)90057-4.
12. Herzberg G. Prospective study of a new total wrist arthroplasty: short term results. Chir Main. 2011;30(1):20-5. doi: 10.1016/j.main.2011.01.017.
13. Kirwan B. Human error identification in human reliability assessment. Part 2: Detailed comparison of techniques. Appl Ergon. 1992;23(6):371-81. doi: 10.1016/0003-6870(92)90368-6.