Direct Coupling of Robotic Hands or Prostheses with the Radius Ulna Complex

Nicola Pio BELFIORE, Massimiliano SCACCIA, Andrea CAPPELLANI, Matteo VEROTTI

Abstract: A new method of mechanically connecting artificial or robotic hands to the human arm is herein described. The idea is based on techniques which make use of fracture fixation devices, very well known in orthopedics. The presented connecting system consists in a real 3 DOF (w.r.t. the humerus) mechanism that has two end plates which are fixed directly, one on the radius, on the ulna the other. Since the system is a new concept project, no data exists about its reliability. Therefore, in the paper, a feasibility study on the most delicate components is described. In particular, FEA has been performed on the screws and on the bone-nut-screws, and some experimental tests *in vitro* have been made on a pig rib.

Keywords: Biomaterials, artificial hands, prosthesis, coupling mechanism.

1 Introduction

During the last decades, the use of artificial implant has increased, thanks to the progress in Material and Medical Sciences. The invasive biomaterial [1] is carefully selected and finished before use as an implant. Research is devoted to avoid failure that causes serious diseases and troubles to the patients that have been subject to an implant operation, in terms of pain and motion disability. An implant may be necessary for many reasons. Infirmity or traumatic injuries are usually the causes. Some of such unfortunate events may deprive an individual from one hand or from its full motion capacity due to wrist injuries. In case of serious wrist injury or bone fracture, bone fracture plate and screws may be used with success for both functional and aesthetic goals. In the unfortunate case of loss of the whole hand, the actual remedy consists in the adoption of an artificial hand. Such prosthesis may be easily mounted and dismounted by acting on a system of flexible lashes, which may give a psychological sense of deprivation in the dismounting maneuver.

In the medical literature, there is a great amount of papers that describe how to fix a screw on a bone and the consequences of this action. However, those concerning the radius and the ulna are much less. The previous contributions that are somehow similar to the case under analysis can be restricted to two main topics: fracture fixation devices [2] and universal total wrist prosthesis [3] and [4].

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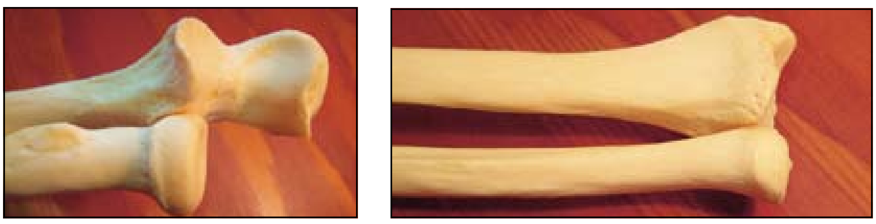


(a) (b)

Figure 1. *(a) Radius - ulna pair at the elbow; (b) Radius- ulna pair at the wrist.*

Figure 2. *The complete support system*

2 The construction of a bone-structure connection for artificial hand sustentation

Referring to a motion in the space, the humerus presents two kinematic elements that engage with both the radius and the ulna. After a simple *in vitro* test on a real human arm bone it appears that the humerus – ulna complex can be regarded as a cylindrical pair, while the humerus - radius system can be modeled as a simple contact pairs. Radius and ulna are in contact in two different zones, as shown in *Figure 1*. The pair in the elbow is regarded as a simple contact, while the pair at the wrist is estimated to behave as a spherical pair. The whole complex is composed of humerus, radius, ulna, radius plate-rod, ulna plate-rod and, finally, the hand support shaft, where plates are supposed to be rigidly connected to the bones. The radius plate-rod system is composed of two plates that are positioned with a tilt angle of about 60°. Finally, the hand support shaft is built in such a way to make a spherical joint with both the plate-rod systems. The support system is depicted in *Figure 2*. From Grübler's general topological formula there are 3 DOF for the relative motion of the *hand support shaft* with respect to the humerus. The obtained result is in accordance with the relative motion expected from the anatomical studies, which report a first rotation of the hand around the radius axis of about 20° and a second rotation of about 160° of the radius around the ulna. In our model, the third DOF consists in a rotation around the axis of the hand support shaft.

Since the radius and ulna have approximately a diameter of about 10 mm, with a cortical thickness of about 2 mm, the screws must be of the best quality as possible, and so, in this investigation, the state of the art materials and machinery had to be adopted. The whole system was made of titanium, with the exception of the interface at the support shaft spherical pairs, which have been built in Teflon. This choice is commonly used in precision mechanics and it allows to decrease the friction coefficient from $\mu = 0.54$ to about $\mu = 0.04$. The plates have a thickness of 1.5 mm in order not to be invasive much. The oval shape has been preferred. Furthermore, any sharp edge has been smoothed. They have been designed to be inserted from the wrist, and therefore a parabolic step has been designed in order to make simpler the insertion operation. The screws have been positioned according to known criteria adopted in engineering. Further details on the constructed components are depicted in *Figure 3*.

3 Screw design and selection

Two classes of screws were needed: bone screws and band screws. Three types of bone screws have been considered:

A) *cortical*: the screw is fastened only within the cortical zone;
B) *cortical-medullary*: the screw end exits the cortical thickness and enters inside the marrow;
C) *bi-cortical*: the screw end reaches the opposite cortex and the threads contribute to fasten on a second cortical zone.

For each one of the three types, three different constructive characteristics have been considered:

1) cylindrical, with the major diameter twice larger than the minor;
2) as for type 1) except that the shank is tapered;
3) as for type 2) except that the shank (variable) diameter is greater than in type 2).

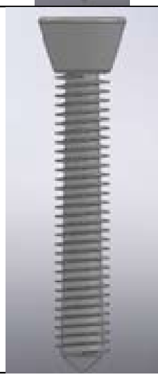
Since the screws function is *fastening*, it is convenient that the thread has a triangular profile. Furthermore, from previous experience, the tapered solution was expected to be more effective after bone regeneration. In particular, type C) screws have a hole at their ends in order to help regeneration (see *Figure 4 d*).

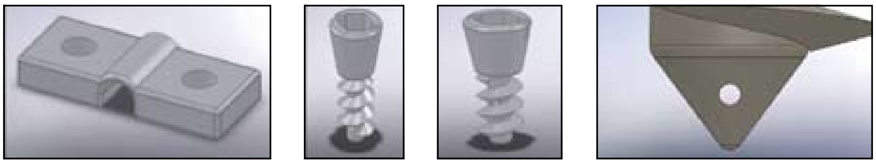
The class of band screws was adopted in order to keep stable the prosthesis. In fact, the rods that connect the

(a) *(b)* *(c)*

Figure 3. *Details on the screws a), the plates b) and the spherical rod head c).*

Table 1. *The nine different possible solutions*

	1	2	3
A			
B			
C			



(a) (b) (c) (d)

Figure 4. *Connection band (a); views of the band screws (b) and (c); type C) screw end (d).*

plates and the hand support shaft have been fastened to the bone by means of a short band (see *Figure 4 a*) fixed to the bones by two screws of the kind A (*Figure 4 b* and *4 c*).

4 Tests of the connection system.

The nine types of screws and the band screws have been firstly numerically tested; then an experimental test has been carried out on the whole connecting system. In more details, the following activities have been performed:

- design of the screws and of the whole sustaining system;
- creation of a 3D model for every element;
- creation of a 3D model for the nut-screw, with the mechanical properties of the bone;
- numerical test on the screws and the nut-screws, in different load conditions, via FEA by assuming a maximum strength for the screws and the bone;
- construction of every elements by means of a multi-axes numerical control machine;
- *in vitro* test of the screw-plate-rod system in different load conditions.

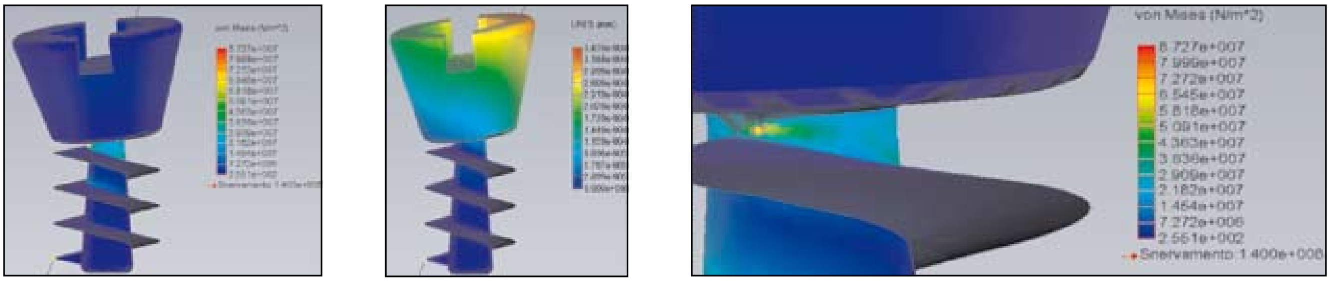
4.1 Numerical simulation via FEA

After the 3D models are created, various load conditions have been simulated (tests 1 – 7):

- test 1: screw constrained at the end, tensile load (reference value 2 MPa) on the screw head surface;
- test 2: screw constrained at the end, tensile load (1 MPa) on the upper thread surface;
- test 3: thread surface constrained, uniform pressure (2 MPa) on a screw head vertical surface;
- test 4: lower thread surface constrained, compressive load (1 MPa) on the screw head surface;
- test 5: upper thread surface constrained, tensile load (1 MPa) on the screw head surface;
- test 6: thread surface constrained, torque (normal to the screw axis) obtained by applying compressive load (2 MPa) on half screw head surface and tensile load (2 MPa) on the mirror one;
- test 7: thread surface constrained, force (3 N) on the screw head surface normal to the screw axis (shear test).

Reference loads have been gradually increased until the maximum tensile strength has been reached in the worst node. The maximum strength has been assumed as equal to 500 MPa for titanium. The better screw is therefore the one that may support the maximum external load (or pressure). *Figures 5* and *6* report representative samples of the results obtained during the campaign of FEA on the screws and on the connecting band.

However, FEA on screws would be rather useless if a similar analysis had not been performed on the nut-screw, because on the bone the stress conditions are more effective than on the titanium. Therefore, a 3D model of the nut-screw was necessary. This problem has been solved by using 3D solid Boolean operation. In particular, the 3D model of a portion of the cortical bone has been defined, firstly. Then the solid model of the screw has been overlapped over the bone material. Finally, the screw volume has been subtracted from the bone in order to recreate a void space within the reconstructed bone. After subtraction, the mesh has been recalculated and then optimized (see Figure 6). The internal threads on the nut have been then loaded with a pressure field, either on the upper or on the lower faces, in order to simulate the



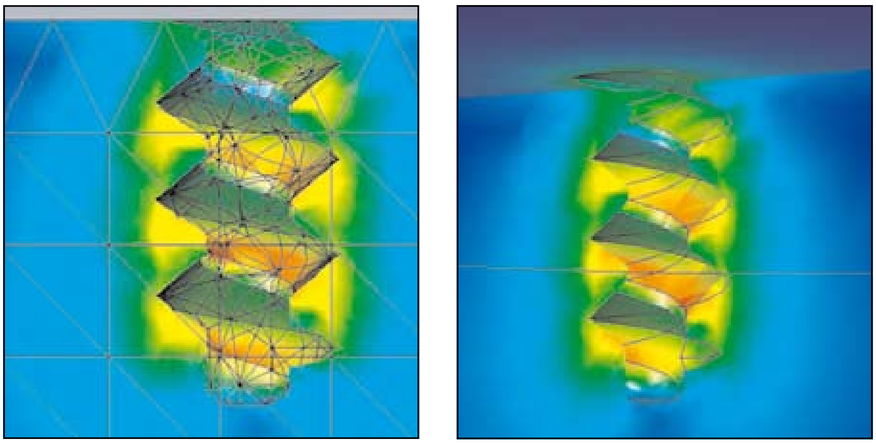
(a) (b) (c)

Figure 5. *Tensile stress on 1 MPa applied on the screw head, by constraining the thread upper surface: a) stress; b) displacements; c) stress (detail).*

action on the screw on the bone-nut-screw. The actual values of the pressure fields have been obtained from the FEA performed over the screw, by applying the action and reaction principle. Therefore, based on the results obtained on the 3D models of the screw (Tests 1 – 7), it has been possible to evaluate the maximum load that the system composed of the screw and the bone-nut is able to sustain before fragile collapse of the bone. Similarly, it is possible to evaluate the factor of security for the system under a given applied load. Radius and ulna have been modeled by assuming the mechanical properties listed in *Table 2*.

Table 2. *Radius and ulna*

Property	Radius	Ulna
Elasticity modulus	18.6 GPa	18.0 GPa
Tensile strength	149 MPa	148 MPa
Compressive strength	114 MPa	117 MPa



(a) (b)

Figure 6. *Detalis on the mesh used in the bone-nut representation: a) planar cross sectional view; b) axonometric view.*

Figure 7 shows a synoptic histogram of the results obtained in 7 different tests, which, as mentioned in the previous paragraph, have been based on different load conditions on the screws. This group of 7 tests has been applied to each one of the nine screw types that result from the combination of the different constructive solutions that are reported in Table 1. Labels A, B, and C refer to the *cortical*, *cortical-medullary*, and *bi-cortical* types, while labels 1, 2, and 3, correspond to the different characteristics reported in paragraph 3. The reported parameters consist of the factor of safety in the system. For the sake of the present investigation, such factor has been evaluated by considering the screws as ductile and the bone as brittle materials. Hence, for the screws, the factor of safety has been evaluated as the ratio of the material ultimate tensile strength by the maximum value of the applied equivalent stress inside the material, the latter evaluated by means of the von Mises criterium. For the bone, such factor has been estimated by evaluating the ratio of the uniaxial tensile (or compressive) strength by the greatest tensile (or compressive) stress. Details on the von Mises and the maximum normal stress criteria are available in several textbooks, such as, for example [6]. Figure 7 reports the lowest value of the safety factor in the system for each of the 49 tests.

4.2 Experimental setup and procedure

A single plate-rod system has been fixed by two screws on a framed pig rib (see *Figures 8* and *9*). The end of the rod has been gradually loaded until collapse. With reference to Figure 9, the plate *p* is attached on a framed pig bone. Two screws *s* are tightened on the external cortical zone *r* of the bone, without affecting the internal medullary kernel *m*. Only type A has been considered because it is the more critical and innovative. On one side of the plate, a clip *c* is attached in order to sustain a magnetic probe *n* which interacts with the Hall sensor *h*. The load is provided on the spherical tip through the load cell *l*. The measurement chain is equipped with an FPGA control system that is able to control the load, linearly applied, until bone collapse. The same FPGA system acquires the digital input from the Hall sensor for each instant of the time interval.

The static balance of the system allows to evaluate the forces acting on the screws and on the bone. Since the mutual distance between the screws

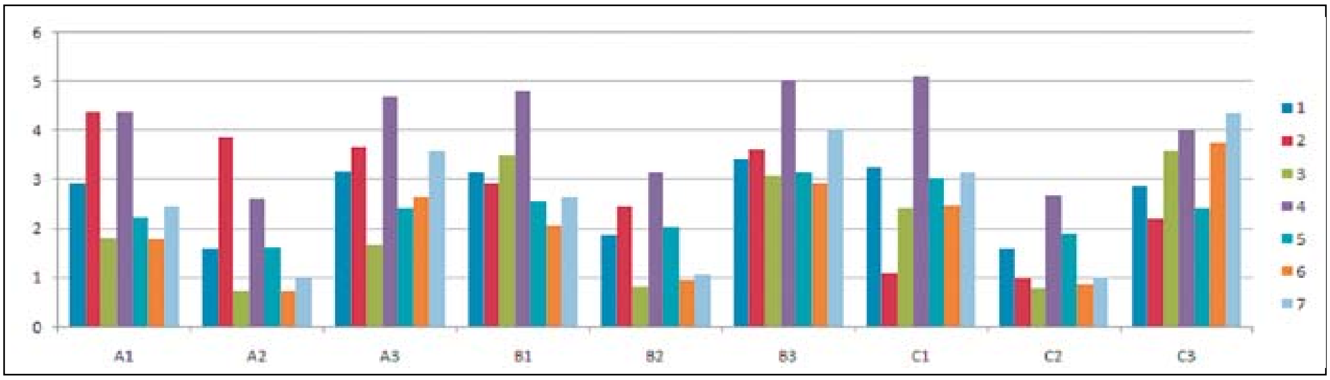


Figure 7. *Factor of safety for seven different load conditions on the screws, for the system screw-bone*

Figure 8. *Plate mounted on a pig rib for the extraction test.*

is much smaller than the distance of the externally applied load, the reaction force exerted by the screws can be much greater than the external load itself.

The application of the static force balance is trivial since the geometry is fully known. In particular, the distance of the load application point from the fulcrum is about 66 mm and the distance between the screws axes is 12 mm.

4.3 Results obtained on the *in vitro* bone

At the end of the experimental campaing the bone material showed a fragile behaviour (see Figure 10). In fact, for low values of the load the displacement of the magnetic proble was practically null until load exceeds a critical value, after which small displacements were measured

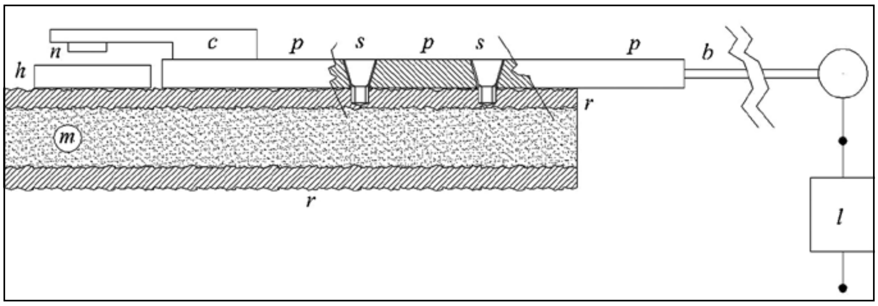


Figure 9. *Plate mounted on a pig rib for the extraction test*

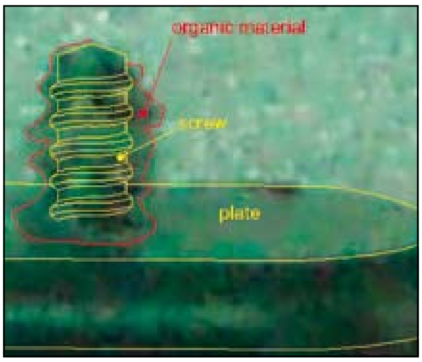


Figure 10. *Cortical fragments attached on the screw after bone collapse*

before collapse. In all the cases, the probe displacements never overpassed $2 \cdot 10^{-1}$ mm. A second group of tests has been repeated by using one screw only, which made the extraction force more easily to be evaluated. During these tests, an average critical load of about 60 N has been detected, and therefore it could be inferred that the screw extraction force may reach about 330 N.

By examining the screw after collapse, a certain amount of organic matter could be detected that was attached on the screw. This occurrence underlined the fragile behavior of the cortical bone, with many fractures around the screw body. One possible explanation is the anisotropic pattern, which the bone is composed of. As explained in [5], the tensile strength can be 12 times greater if applied in the longitudinal direction than in the radial one.

Finally, it is worth noticing that the performed experiments have been planned *in vitro* under dry condition. However, the ultimate strength strongly depends on the bone condition (wet or dry), and also upon the strain application rate. Therefore, the actual values of the critical loads can be greater than the ones figured out in the present investigation.

5. Conclusions

After numerical and experimental analysis on the screws, the types C3 and B3 have been selected, respectively, for the ulna and the radius (where two plates are used). Considering the whole arm-plates system, the final target is to develop a connecting system that could sustain a load of about 800 N on the artificial hand. Since three plate-rod systems are simultaneously used, together with several screws per plate, such target seems to be reasonable to obtain with an acceptable reliability.

References

[1] Clemson Advisory Board for Biomaterials, Definition of the word biomaterial, 6th Annual

Int. Biomaterial Symposium, April 20 – 24, 1974.
[2] Hunter, T.B., Taljanovic, M.S., Overview of Medical Devices, Curr. Probl. Diagn. Radiol., July/August 2001, Vol. 30, pp. 89 – 140 (doi: 10.1067 / mdr.2001.114499).
[3] Adams, B.D., Total Wrist Arthroplasty, Journal of the American Society for Surgery of the hand, Vol. 1, No. 4, Nov. 2001, pp. 236 – 248.
[4] Menon, J., Universal Total Wrist Implant: Experience With a Carpal Component Fixed With Three Screws, The Journal of Arthroplasty, Vol. 13 No. 5, 1998, pp. 515 – 523.
[5] Park, J.B., Biomaterial Sciences and Engineering, Plenum Press, New York, 1984.
[6] Juvinal, R.C., Marshek, K., Fundamentals of machine component design, Second Edition, John Wiley and Sons, New York, 1993, ISBN 0-471-62281-8.

Neposredna namestitev robotske roke ali proteze na radioulnarni sklep

Razširjeni povzetek

Ob izgubi roke v ožjem smislu je najpogostejša nadomestitev z umetno roko. V večini primerov je to preprost izdelek, prekrit z estetsko rokavico. Tovrstna proteza se preprosto namešča in snema z uporabo elastičnih pasov, kar pa lahko povzroči občutke prikrajšanosti.

Trdno zaupajoč v prihodnji razvoj robotskih naprav smo v naši raziskovalni skupini pričeli s teoretično in eksperimentalno študijo razvoja sistema za direktno namestitev robotske roke na kosti podlahti, na koželjnico in podlahtnico. Ta ambiciozni pristop je predlagan kot alternativa obstoječim pritrdilnim pasovom ali kot nov način integracije telesa človeka z mehanskimi napravami, ki tako postajajo trajni del telesa. Če bi bilo možno te naprave tudi voditi, po možnosti z aktivnostjo človeka, bi bila dosežena popolna integracija.

Privzeta ideja temelji na uporabi pritrdilnih elementov za fiksacijo kostnih zlomov, ki so dobro uveljavljeni v ortopediji. Predstavljeni pritrdilni sistem je sestavljen iz mehanizma s tremi prostostnimi stopnjami gibanja (3 DOF glede na nadlahtnico) in dvema pritrdilnima ploščama, od katerih je ena pritrjena na koželjnico in druga na podlahtnico. Ker je sistem nov, ni podatkov o njegovi zanesljivosti. Zato v prispevku predstavljamo izvedljivostno študijo uporabe najbolj delikatnih komponent.

Izvedena je bila analiza končnih elementov na vijakih za pritrditev na kosti, pa tudi eksperimentalni testi *in vitro* na svinjskem rebru. Preučeni so bili trije tipi pritrditve vijakov:
a) kortikalno: vijak je pritrjen samo v območju kortikalne kosti;
b) kortikalno-medularno – vrh vijaka zapusti območje kortikalne kosti in vstopi v območje spongioze;
c) bi-kortikalno – vrh vijaka doseže območje kortikalne kosti na drugi strani, kar dodatno učvrsti spoj

Za vsakega od treh tipov spojev so bile preučene karakteristike naslednjih vijakov:
1) cilindrični s premerom glave dvakrat večjim, kot je premer stebla;
2) enak tip kot pod 1, le da je na steblu vijaka samorezni navoj,
3) enak tip kot pod 2, le da je premer stebla vijaka večji.

Po izvedeni numerični in eksperimentalni analizi vijakov sta bila izbrana tipa C3 in B3 kot primerna za pričvrstitev na koželjnico in podlahtnico. Glede na znane obremenitve je končni cilj razvoja sistem za pritrditev roke, ki lahko prenaša obremenitve okrog 80 kg. Ker so hkrati uporabljeni trije povezovalni sistemi, ki so učvrščeni z več vijaki na vsako ploščo, je zastavljeni cilj možno doseči tudi z dovolj dobro zanesljivostjo

Ključne besede: biomateriali, umetne roke, proteze, pritrditveni mehanizem