Functional Design Of A Transmission For A Myoelectric Elbow Prosthesis

Federico Casolo, Simone Cinquemani [*], Matteo Cocetta

Abstract—**Many artificial arms include myoelectric hands and passive elbows. Myoelectric elbows can profitably substitute the passive ones only if they can guarantee: durability, low noise, adequate torque, low power consumption, low weight, easy motion control and natural movements. Most of these objectives can be reached by good mechanical design of the system. Mechanical efficency of the mechanism is one of the key factors and can be achived only avoiding long chains of gears. The adoption of a serie of linkages allows to transform efficently the high speed of the engine, to the low angular velocity of the elbow. By the kinetic point of view the system of linkages has roughly to mantain a costant ratio between the above velocities. For the efficency of the transmission, angles must be always over a critical value and the links must have low momentum of inertia. This work shows the functional approach in a new designed elbow prosthesis.**

Keywords: ***elbow prosthesis, mechanical efficency, transmission ratio, angles of transmission***

1 Introduction

A good prosthesis design has to take into account all the problems related with the interaction between human and machines. Since the very first need of an amputee is the social and psicological rehabilitation, patients should have a good feeling with their prosthesis. They should be able to perform daily activities without stress and excessive mental load. Patient refusal, in fact, is certainly the main cause limiting the use of an active prosthesis. It depends on excessive weight, limited speed, noise, poor reliability and very high power consumption [1]. It means that patient has to carry big batteries and can't use the prosthesis for a long time. Otherwise, myoelectric prosthesis are very appreciated for their easiness in controlling the movements and for the absence of wires and braces: they exploit electromyographical signals of two residual antagonist muscles of the stump to command the system. Actually, only a few externally powered elbow prostheses are commercially available: the NY Electric Elbow, the Boston Elbow, the Utah Arm, the Otto Bock Dynamic Arm [2] and the INAIL elbow [1]. This work is related with the functional design and optimization of the elbow prosthesis used in a full active prosthetic arm with 5 d.o.f. for shoulder amputees developed by the Department of Mechanics of Politecnico di Milano [3] (fig.1).

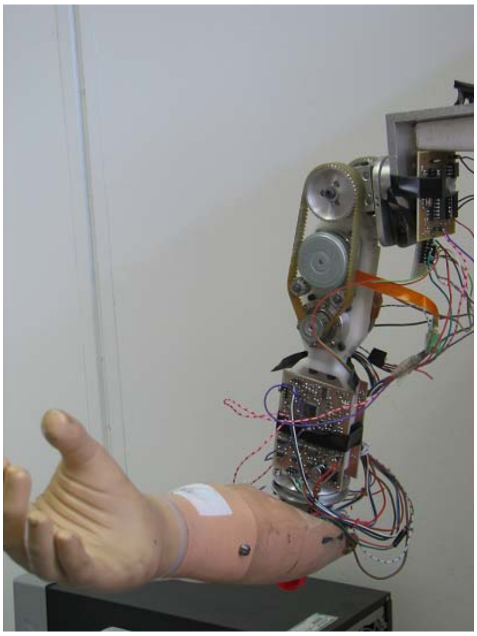

Figure 1: Full active prosthetic arm

2 Elbow physiology

The elbow joint allows two main different movements:

- The hinge-like bending and straightening of the elbow (flexion and extension) happens at the articulation ("joint") between the humerus and the ulna. Amplitude of this movement is about 135° (fig.2).
- The complex action of turning the forearm over (pronation or supination) happens at the articulation between the radius and the ulna (this movement also occurs at the wrist joint). In the anatomical position (with the forearm supine), the radius and ulna lie parallel to each other. During pronation, the ulna remains fixed, and the radius rolls around it at both the wrist and the elbow joints. In the prone position, the radius and ulna appear crossed.

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While the elbow prosthesis should reproduce the flexio-extension movement, pronation and supination is usually replicated by a prosthetic wrist.

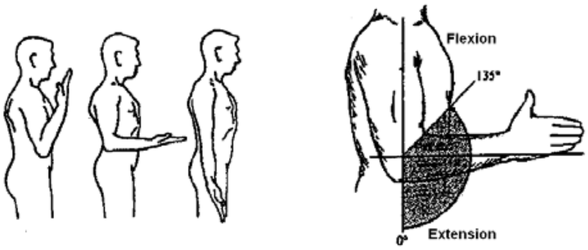

Figure 2: Flexo-extension movement

3 Functional project

The way to give to patients a device, directed towards a functional and psicological rehabilitation, is to have a good mechanical design of the prosthesis taking into account some important features:

- Comfort: the prosthesis must be noiseless, wearable, and the movements should reproduce the natural ones as much as possible.
- Weight and dimensions: the device should be light in order to be easily coupled to the stump without modify the patient posture (natural arm weight is approximatly 3.2 kg). Moreover, the higher is the weight the motor has to move, the bigger is the battery the patient has to carry.
- Performance: the device should reproduce human movement with, at least, the same speed of a natural arm ($\approx$ 0.45 rad/s) in a physiological way. The patient should be able to carry a mass of at least 0.6 kg and the range of motion should be has wide as possible to allow the patient to reach objects in space.
- Reliability: the prosthesis should work at least 5000 hours/year without maintenance. Both mechanical and electrical components must work correctly, avoiding breaking and breakdown.
- High mechanical efficency: to reduce power consumption and batteries dimensions, the transmission should guarantee high efficency, in order to minimize loss of energy. Moreover a well designed and effective transmission is often silent because of reduced clearances.
- Reverse power flow: it must be avoided in order to reduce the motor workload when the patient is extending the artificial arm.
- Appearence: since it has a very important social function, the device dimension should be the same of a natural arm and colour of all the visible parts should reproduce human skin.

All these aims can be satisfied through a good mechanical design of the transmission.

3.1 Transmission design

Transmission is the most important element of the prosthesis and the performances of the system highly depends by how it works: since a multi-stages transmission is often required to have an high trasmission ratio to adequate the elbow speed to the motor one, it's fundamental to realize a system characterized by an high mechanical efficency. To avoid a long chain of gears, usually used in this application, transmission is made by an innovative linkage solution (fig. 3,4).

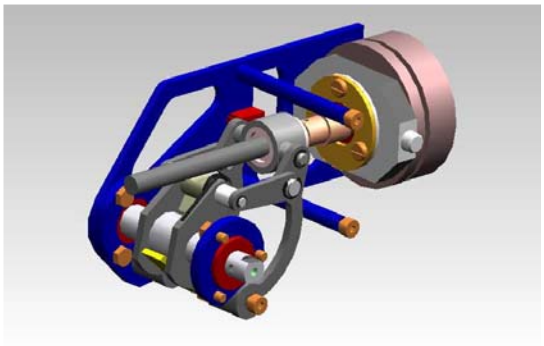

Figure 3: Elbow prosthesis 3D model

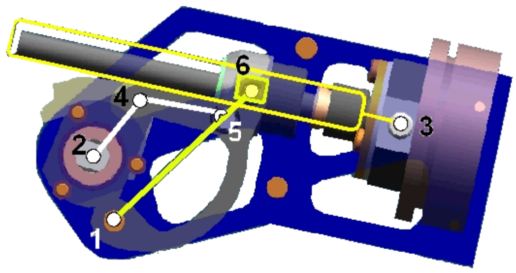

Figure 4: Prosthesis layout

As shown in figure 4, the mechanism is constituted of two linkages in series: a crank and slotted link (1-6-3) and a four bar linkage (2-4-5-1). A "pancake" brushless motor, used because of its reduced dimension along longitudinal axis, is directly coupled with a screwball. The system motor-screwball swings around a joint (3) and the nut screw (6) is connected to the top of the follower bar (1-6). This element actuates the four bar linkage and elbow

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speed dovetails with angular velocity of the crank (2-4). This kind of transmission allows to achive some important results:

- high transmission ratio ($\tau \simeq 1/140$)
- mechanical efficency is very high ($\eta \simeq 0.86$): it's made possible because of reduced friction of the system (in joints and in the screwball) and the absence of gears.
- the system is constituted of few elements: it's easy to be assembled and it has a good mechanical reliability;
- overall dimensions and weight are reduced thanks to motor dimension ad mechanism configuration.

3.2 Kinematical analisys

A kinemathical analysis of the system is needed to optimize the mechanism transmission ratio. To perform it, the system can be divided into two linkages: the four bar one and the crank and slotted link.
Referring to figure 5, it's possible to substitute the four bar linkage with vectors:

$$z_1 = a \cdot e^{i\alpha} \qquad z_2 = b \cdot e^{i\theta} \qquad z_3 = c \cdot e^{i\gamma} \qquad z_4 = d$$

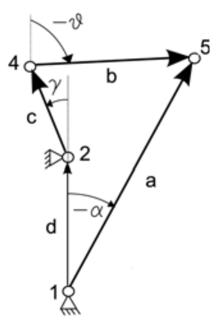

Figure 5: Four bar linkage - vectorial representation

and write the equation:

$$z_1 - z_2 - z_3 - z_4 = 0 \tag{1}$$

$$a \cdot e^{i\alpha} - b \cdot e^{i\theta} - c \cdot e^{i\gamma} - d = 0 \tag{2}$$

that can be projected on real and imaginary axes:

$$b \cdot \cos\theta = a \cdot \cos\alpha - c \cdot \cos\gamma - d \tag{3}$$

$$b \cdot \sin\theta = a \cdot \sin\alpha - c \cdot \sin\gamma \tag{4}$$

Squaring both equation and summing to eliminate θ:

$$a^2 - b_1^2 + c^2 + d^2 - 2ac \cdot \cos\gamma \cdot \cos\alpha -$$
$$-2ac \cdot \sin\gamma \cdot \sin\alpha - 2ad \cdot \cos\alpha + 2cd \cdot \cos\gamma = 0$$

and substituting:

$$\begin{aligned} A &= -2ac \cdot \sin\gamma \\ B &= -2ad - 2ac \cdot \cos\gamma \\ C &= a^2 - b_1^2 + c^2 + d^2 + 2cd \cdot \cos\gamma \\ D &= \sqrt{A^2 + B^2 - C^2} \end{aligned}$$

it's possible to highlight the function $\alpha = \alpha(\gamma)$:

$$\sin\alpha = -\frac{AC - BD}{A^2 + B^2} \tag{5}$$

$$\alpha = \arcsin\left(-\frac{AC - BD}{A^2 + B^2}\right) \tag{6}$$

Angle θ can be obtained from equations (3)(4)(6):

$$\begin{aligned} \sin\theta &= \frac{c \cdot \sin\gamma - a \cdot \sin\alpha}{b} \\ \cos\theta &= \frac{d + c \cdot \cos\gamma - a \cdot \cos\alpha}{b} \end{aligned}$$

from which:

$$\theta = \arctan\left(\frac{c \cdot \sin\gamma - a \cdot \sin\alpha}{d + c \cdot \cos\gamma - a \cdot \cos\alpha}\right) \tag{7}$$

Let's now consider the crank and slotted link. Referring to its geometry (fig.6), it's possible to determine the relationship between angles:

$$\alpha_1 = \alpha + \psi \qquad \beta_1 = \beta + \psi$$

and the vectorial equation:

$$b_1 \cdot e^{i\alpha_1} - l \cdot e^{i\beta_1} - d_1 = 0 \tag{8}$$

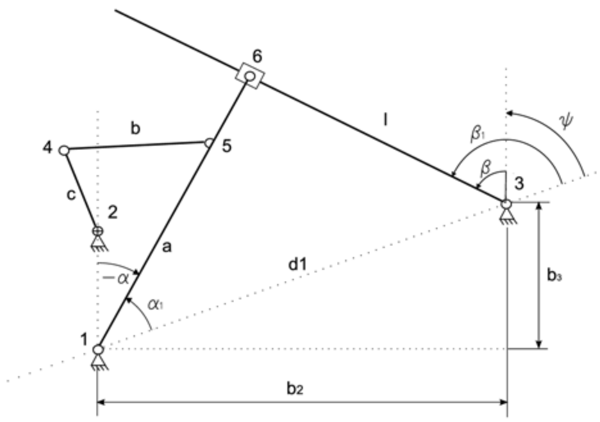

Figure 6: Prosthesis layout

It can be projected on real and imaginary axes:

$$l = \sqrt{b_1^2 + d_1^2 - 2b_1 d_1 \cdot \cos\alpha_1} \tag{9}$$

$$\sin\beta_1 = \frac{b_1 \cdot \sin\alpha_1}{l} \tag{10}$$

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where l is the translation of the nut screw along the screwball.
Since β_1 can't be less than 90^0 :

$$\sin\beta_1 = \pi - \arcsin\left(\frac{b_1 \cdot \sin\alpha_1}{l}\right) \tag{11}$$

Since motor shaft is directly coupled with the screwball, nutscrew position (l) and speed ($\dot{l}$) can be expressed as a function of motor rotation (θ_m) and speed ($\dot{\theta}_m$):

$$l = \frac{p_{screw} \cdot \theta_m}{2\pi} \qquad \dot{l} = \frac{p_{screw} \cdot \dot{\theta}_m}{2\pi} \tag{12}$$

where p_{screw} is the screwball pitch. Mechanism transmission ratio can be expressed as the ratio between the elbow speed ($\dot{\gamma}$) and motor speed ($\omega_m = \dot{\theta}$). First parameter can be found deriving equation 2 and projecting it on real and imaginary axes:

$$\dot{\gamma} = \dot{\alpha}\frac{a \cdot \sin(\alpha - \theta)}{c \cdot \sin(\gamma - \theta)} \tag{13}$$

which is a function of the four bar linkage driver speed ($\dot{\alpha}$). Since this rod is also the driven one of the crank and slotted link, its speed can be obtained through equation 8, as a function of $\dot{l}$:

$$\dot{\alpha} = -\frac{\dot{l}}{b_1 \cdot \sin(\alpha_1 - \beta_1)} \tag{14}$$

Finally, substituting equations (12)(13)(14), the elbow transmission ratio is:

$$\tau_{gom} = \frac{\dot{\gamma}}{\omega_m} = \frac{p_{screw} a \cdot \sin(\alpha - \theta)}{2\pi b_1 c \cdot \sin(\gamma - \theta) \cdot \sin(\alpha - \beta)} \tag{15}$$

The designed mechanism has a trasmission ratio that changes with the position of the elbow. Unfortunatly, to avoid sudden variation of arm speed, it should be costant as much as possible. Therefore, the lengths of each element of the linkage and the angles they form have been optimized, taking into account all the mechanical and the geometrical contraints. It's done minimizing the objective functions:

$$F_1 = \frac{max(\tau) - min(\tau)}{max(\tau)} \tag{16}$$

$$F_2 = max\left|\frac{\partial\tau}{\partial\gamma}\right| \tag{17}$$

where γ is the flexo-extension angle of the elbow.

The two functions represent respectively the percentage variation of the transmission ratio and the maximum inclination of the curve as a function of the angle. Assuming the motor speed is constant, the elbow velocity has little acceptable variations (fig.7). To better understand how geometry and dimensions affect transmission ratio, its trend is represented as a function of mechanism rod length (fig.6). A good parameter that shows the linkage

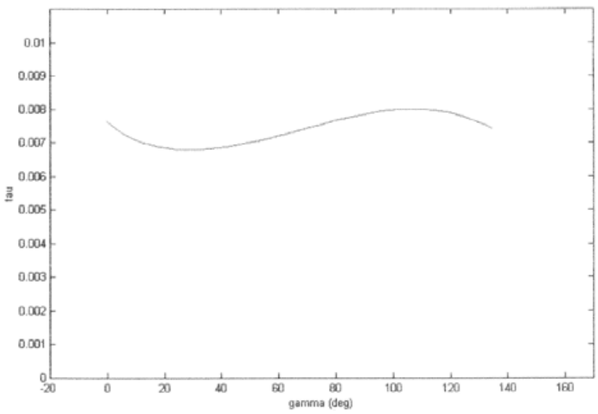

Figure 7: Optimized transmission ratio

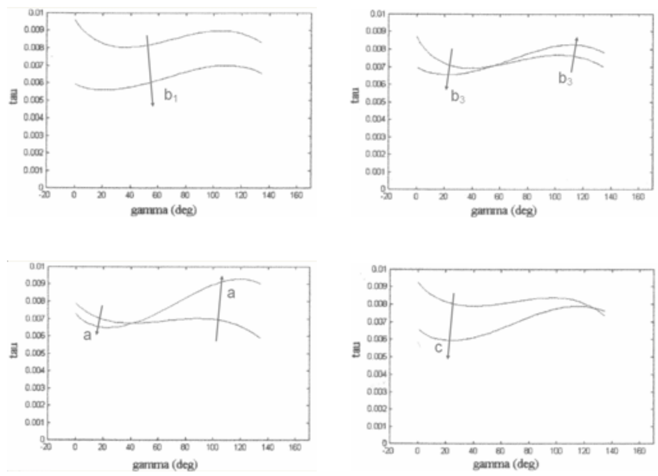

Figure 8: $\tau = \tau(b_1)$, $\tau = \tau(b_3)$, $\tau = \tau(a)$ and $\tau = \tau(c)$

capability in transmit motion is the angle of transmission [4][5]. In four-bar linkages it's defined as the lower of the angles between connecting rod and rocker arm directions, while in the crank and slotted link it's the angle between the two rods (fig.9).

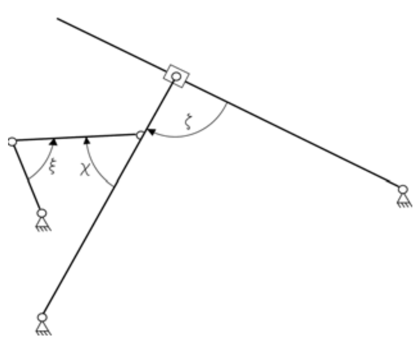

Figure 9: Transmission angles

The lower is the transmission angle, the lower is the mechanical efficency. Moreover, if transmission angle goes under 40°, the effects of backlashes and flexibility are amplified, causing vibrations and malfunctions. Figures

10, 11, 12 show the transmission angles trends: their values confirm the linkage is always able to transmit motion properly.

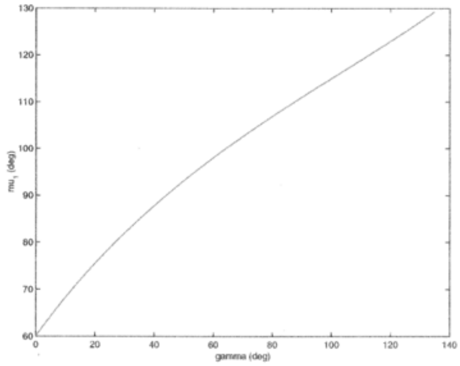

Figure 10: Transmission angle ζ

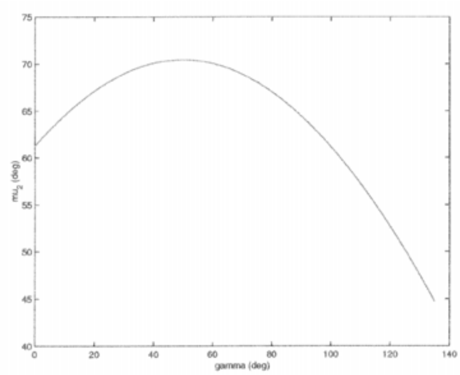

Figure 11: Transmission angle χ

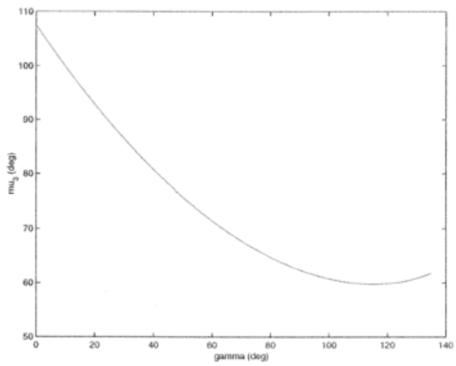

Figure 12: Transmission angle ξ

3.3 Dinamical analisys

The system has been modeled using the multibody software ADAMS to evaluate the prosthesis dynamic performances and to calculate the torque exerted by the motor. It depends by imposed load, inertia and forearm position, as a function of shoulder motion.In order to perform movements reproducing daily activities (such as drinking or eating), motions are constituted of combination of flexo-extension and adduction-abduction movements of the shoulder and flexo-extension movements of the elbow.

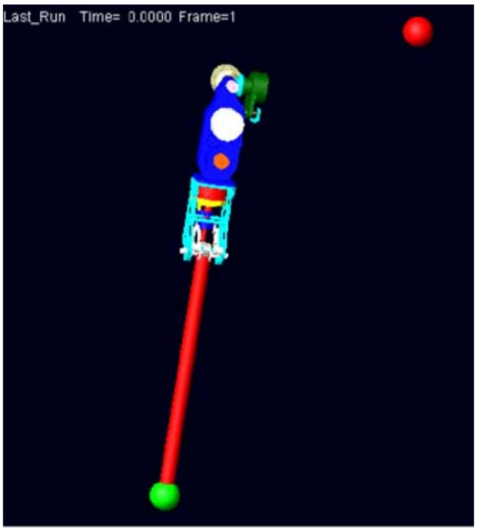

Figure 13: Multibody model

To model the shoulder degrees of freedom, an existing model has been used [3] representing the full prosthetic arm developed (fig.13). Forearm is replaced by a rod with suitable weight and moments of inertia, while in the hand extremity a mass has been applied to simulate a load to be moved.

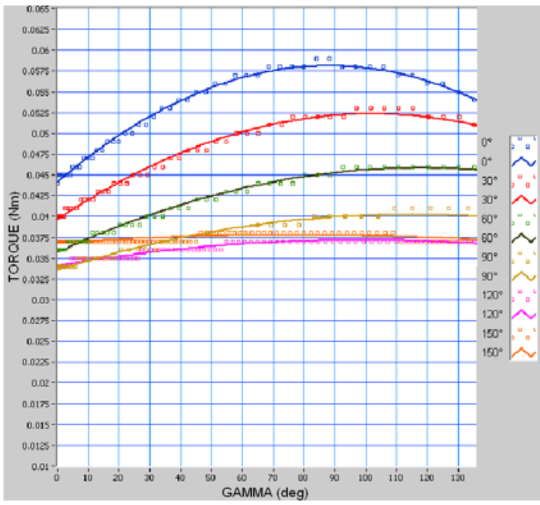

Figure 14: Simulation results

Simulations allow to evaluate the maximum torque needed in different conditions (fig.14) and permit to chose a correct motor.

4 Conclusions

Patients with transomeral amputation using a myoelectric prosthesis are able to perform daily activities recov-

ering their autonomy. The developed elbow prosthesis is an helpfull and effective device designed to minimize all the problems related with human-machine interaction. Its transmission has been projected to optimize mechanical efficency and reduce energy loss: it allows to increase device autonomy and reduce batteries dimensions. Moreover, it permits a better and faster social and psicological rehabilitation thanks to a silent system able to perform natural movements. Kinematical analysis showed system effectiveness in the transmission of motion and highlighted transmission ratio dependency by geometry and dimensions. At last, dinamical analysis supported motor choice evaluating system performances in doing different movements.
Actually the prosthesis is in testing phase and will be used by patients in short-time.

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