A WIRED ACTUATED ELBOW FOR HUMAN PROSTHESIS

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Solutiile mecatronice utilizate in robotica sunt din ce in ce mai mult utilizate si in alte domenii. Echipe de cercetatori lucreaza in domeniile de cercetare ale protezelor de brate, dezvolta noi actuatori si structuri mecanice. Ideea importanta este de a dezvolta sisteme mecanice, actuatori si surse de energie. Aceasta lucrare prezinta o noua structura a articulatiei de cot ce poate fi implementata pe un brat artificial al unei proteze umane. Sistemul se bazeaza pe trei actuatori hidraulici conectati printr-un sistem de fire la componentele bratului. O structura complexa de fire permite functionarea actuatorului cu o linearitate aproape constanta. In partea a doua este prezentat un model cinematic 3D virtual. Autorii au decis sa foloseasca 3 actuatori redundanti in loc de 2, pentru a modula complianta mecanica a bratului artificial in functie de miscarea pe care pacientul doreste sa o realizeze. In paralel, autorii lucreaza cu al treilea piston corelat cu ceilalti, pentru a optimiza volumul si a minimiza efortul.

The mechatronic solutions used in robotic field are more and more used in other areas. Conspicuous research teams are working on arm prosthesis, investigating and developing new mechanical architecture and actuator. The mean aspect is to set up mechanical devices, actuators and energy supply. This paper presents a new mechanical elbow to install on artificial arm for human prosthesis. The device is based on 3 hydraulic actuators connected through some wires to the following forearm components. A complex and optimized path of wires makes actuators work with almost constant linearity between extensions of pistons and flexion-extension and pronation-supination angles. A kinematic 3D virtual model is presented at a second step of geometrical optimization. The authors decided to use redundant actuators, 3 instead of 2, to modulate the mechanical compliance of the artificial arm depending on the kind of operation the patient will wish perform. Moreover, in parallel, the authors are working with the third piston that collaborates with the others to optimize the volume and minimize the stresses.

Keywords: Robot arm, Human Reliability, Tridimensional mechanisms, Hydro-pneumatic actuator, Biomechanics.

1. Introduction

In the last ten years the robotic techniques are migrating in other fields, specific experiences are produced in prosthetic human arm. Even if Leonardo da Vinci started to think on artificial arms, just in 2001 the first cybernetic working

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arm was installed on amputee arm man, thanks to the work of bionic research at the Rehabilitation Institute of Chicago, *ric.org*. [1]. The first effective arm is dc motor actuated, but some research teams are investigating on the use of other kind of actuator. The first concept design about a fully pneumatic actuated artificial arm was introduce by *Festo* [2] in 2007. Most of the studies are focused on the use of open mechanical chain; we can find just few examples of closed chain, i.e. Mendoza Vázquez et al. [6], Kevin et al. [5]. They use a pneumatic actuator as part of the closed chain to increase stiffness, but they not obtain to reduce sprung masses.

This paper proposes a new architecture of artificial elbow based on wired parallel mechanism with simple and light structure. The forearm is connected to upper arm with 2 cylindrical hinges with perpendicular axes. Three hydraulic mini cylinders, two principal and one secondary, are used. Even if the elbow needs to produce just two relative rotation degrees of freedom between lower and upper arm, the authors decided to install the third actuator to modulate the total complaint depending on kind of operation the patient wish perform. To optimize the volume, all the pistons are on the upper arm, the two principal pistons are place on the front, and the secondary piston is placed on the back. Some wires connect the rods of pistons with the lower arm plate in order to transmit the force and control the arm posture.

The paper is organized in three sections: in the first section the device is described and a short report about kinematic optimization is detailed. The second section reports about the kinematics behaviour and lengths-rotations laws. In the third section a last geometrical adjustment to correct the variation of wire lengths is described.

2. Description of the elbow and the device

The human elbow makes the lower arm perform an articulated spatial motion relative to the upper arm. However, to produce an artificial mechanism, this motion could be reduced to two simplified. The first rotation, flexion-extension, has his axis perpendicular to mean longitudinal direction of upper arm and parallel to the front human plane in stand-up posture. The second rotation, pronation-supination, has his axis perpendicular to the above mentioned and parallel to the mean longitudinal axis of forearm. Usually, in the elbow prosthesis, these rotations have to cover a angles range of about 150 and 180 degrees respectively. The normal requirement for artificial arm is to work with a 5 kg mass in the hand to perform daily works. To design the elbow pictured in this paper, a 80% dimensions are used.

By considering the simplified motion, the proposed device uses the most elementary structure to produce the kinematics principal chain: two cylindrical hinges, each one with one relative DOF, that leave the two wished rotations. In Fig. 1 a solid 3D scheme is shown; the upper hinge, with axis 1, allows the flexion-extension motion; the lower hinge, with axis 2, provides to the pronation-supination motion.

With this layout, a simplification of spherical motion is obtained, moreover an assembling and maintenance is guarantied. The forearm motion, relative to the arm, is controlled by the two principal pistons mounted on the front of the device, as in Fig. 2, left picture. The mounting of two double effect hydraulic pistons needs to transmit the force and the piloted parameters to the lower plate that will be connected to the forearm prosthesis. Some flexible synthetic wires are used. The heads of the rods of all the pistons mount one pulley each. The employed wires can be divided in three principal family, as the Fig.3 shows. The front family of principal actuators provides the movement: each rod mounts an end of a wire, the other end is mounted on the front of the forearm plate, but on the opposite side, in order to have a crossing path. This family leads to equilibrate torques applied to the forearm that induces extension motion and/or pronation-supination motion.

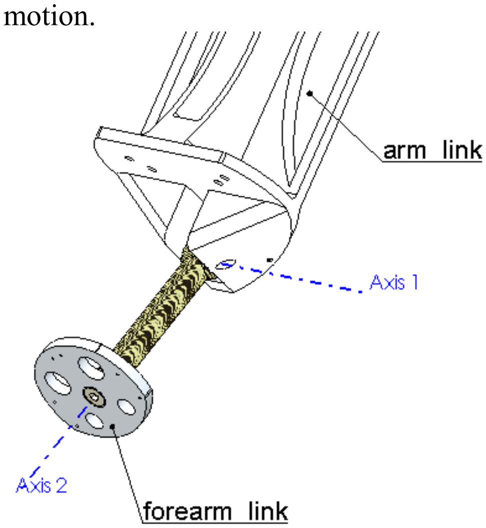

Fig. 1. Mechanical scheme.

The rear family of principal actuators works in this way: a wire goes on the pulley mounted on the end of the rod, one wire for each actuator. Each of these two wires goes through a fixed axis pulley mounted on the frame and the other wire end is tied to a moving pulley. This last pulley works with another wire that has an end fixed on the frame and the other end linked to the forearm plate. In this way a double tackle is realized: the first part amplifies by two the stroke of the piston, and the second reduces it by two. At first sight, the total ratio of the tackle is one, but because the angles of the paths of primary and secondary tackle change during the motion, a nonlinear transformation of the motion of the wire end on the forearm plate relatively to the rod movement is introduced. The transform function is required to partially compensate the difference of total lengths of the wires in various configurations. Moreover, this layout reduces parasite forces on the rods so it's possible to reduce pistons' sizes, in order to gain longer life. The secondary family transmits the second effect of the piston to the forearm plate: the forces transmitted are useful to equilibrate torques on the forearm, in opposition with torques equilibrated by front wire family.

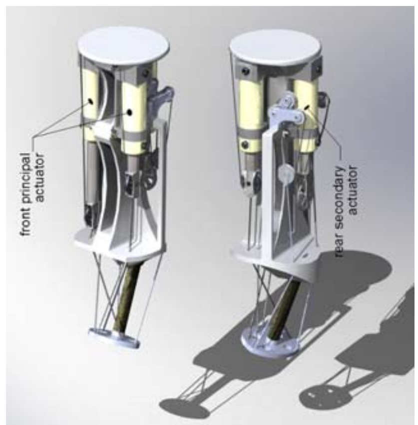

Fig. 2. The elbow device, lateral front and lateral rear views.

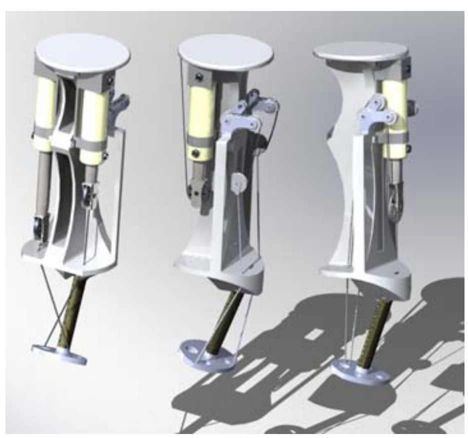

Fig. 3. Wire paths, principal front, principal rear, secondary.

The family of secondary actuator supports the movement: a wire has both ends connected to the forearm plate. The wire goes up towards two pulleys mounted on the frame, then a pulley mount on the rod of the secondary piston push the wire. This family has two principal functions: to collaborate with both principal actuator to equilibrate the bending of the forearm and to adapt the stiffness to external random load variations, depending also on the different operation the subject could do. The use of this secondary actuator would be useful to supply circuit and logic control.

By day, the authors are developing a hydropneumatic supplying with the aim to recuperate the energy during the resistive movements of the arm. Therefore, the use of the three pistons, instead of two, is required also by energy saving and reutilization of the energy coming by passive or resistive phases of movements. This topic will not be discussed in this paper.

In Fig. 4, the elbow device is mounted on its place on a dummy representing the 80%, in order to appreciate its dimension. It use just the normal useful available volume.

Fig. 4. The elbow device on a dummy.

3. Kinematic model

The device is based on a parallel mechanism, in which the motion along the required DOFs is obtained acting on the lengths of the “legs”, L_1 and L_2, that connect the points B_1-P_1 and B_2-P_2 (Fig. 5). L_1 and L_2 will be the Lagrangian parameters of the direct kinematic problem. The points $B_{1/2}$ are connected to the fixed base, that will be the terminal part of the humerus of the arm, while the points $P_{1/2}$ are part of the floating platform, that will be connected to the forearm.

Leading to constrain the mobile platform, there are two cylindrical joints with mutually perpendicular axes, positioned at the extremities of the rigid central leg.

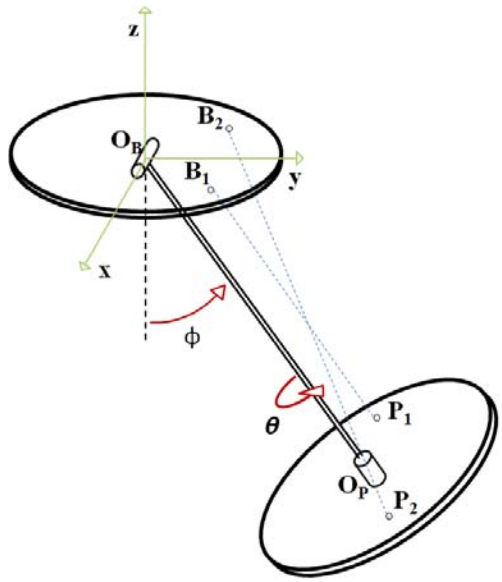

Fig. 5. A schematic representation of the device.

The calculus of the DOFs is obtained by (1), known as Grübler Formula:

$$F = 3(l-1) - 2j_1 - j_2. \quad (1)$$

with l number of the bodies including the frame (3 in the model), j_1 number of inferior kinematic couples (the 2 hinges) and j_2 number of superior kinematic couples (none). So the system allows two DOFs, called Φ and θ, that refer respectively to flexion-extension and pronation-supination. The rotation matrices **[$\mathbf{R_\Phi}$]**, eq. (2) and **[$\mathbf{R_\theta}$]**, eq. (3), combined in the matrix **[$\mathbf{R_{\Phi,\theta}}$]**, eq. (4), describe the motion of the floating platform.

$$[\boldsymbol{R}_\phi] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos[\phi] & -\sin[\phi] \\ 0 & \sin[\phi] & \cos[\phi] \end{bmatrix} \quad (2)$$

$$[\boldsymbol{R}_\theta] = \begin{bmatrix} \cos[\theta] & -\sin[\theta] & 0 \\ \sin[\theta] & \cos[\theta] & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$[\boldsymbol{R}_{\phi,\theta}] = \begin{bmatrix} \cos[\theta] & -\sin[\theta] & 0 \\ \sin[\theta]\cos[\phi] & \cos[\theta]\cos[\phi] & -\sin[\phi] \\ \sin[\theta]\sin[\phi] & \cos[\theta]\sin[\phi] & \cos[\phi] \end{bmatrix} \quad (4)$$

4. Actuators positioning and wires lengths

The coordinates of the points are indicated in Table 1 and collected in the matrices **[ForeBase]** and [**ForePlat**].

$$[\boldsymbol{ForeBase}] = \begin{bmatrix} B_{1x} & B_{2x} & B_{3x} & B_{4x} \\ B_{1y} & B_{2y} & B_{3y} & B_{4y} \\ B_{1z} & B_{2z} & B_{3z} & B_{4z} \end{bmatrix} \tag{5}$$

$$[\boldsymbol{ForePlat}] = \begin{bmatrix} P_{1x} & P_{2x} & P_{3x} & P_{4x} \\ P_{1y} & P_{2y} & P_{3y} & P_{4y} \\ P_{1z} & P_{2z} & P_{3z} & P_{4z} \end{bmatrix} \tag{6}$$

$$[\boldsymbol{ForeLegs}] = [\boldsymbol{R}_{\phi,\theta}][\boldsymbol{ForePlat}] - [\boldsymbol{ForeBase}] \tag{7}$$

$$[\boldsymbol{ForeLegsB}] = [\boldsymbol{ForePlat}] - [\boldsymbol{ForeBase}] \tag{8}$$

$$[\boldsymbol{Fore}\,\Delta L] = [\boldsymbol{ForeLegs}] - [\boldsymbol{ForeLegsB}] \tag{9}$$

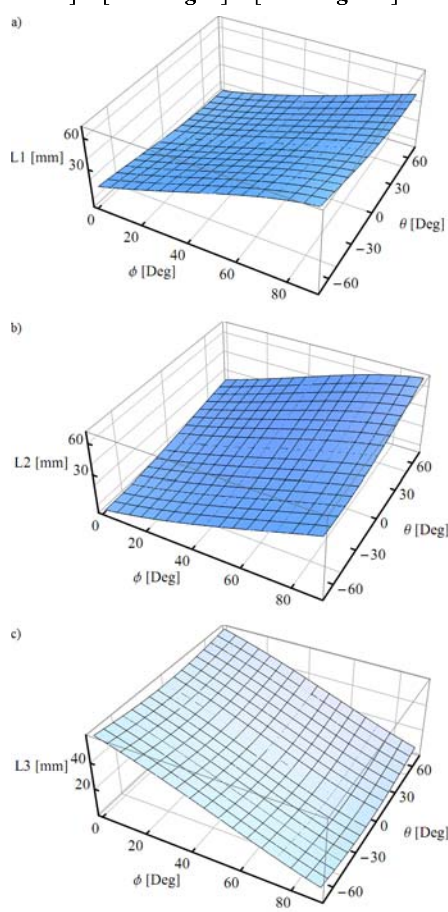

Fig. 6. Positioning of principal (a and b) and secondary pistons (c), depending on Φ and θ.

Their positions are the results of several kinematic optimization loops, aimed to obtain variation length scalar functions $L_1=f_1(\Phi, \theta)$ and $L_2=f_2(\Phi, \theta)$, as linear as possible with reference to Φ and θ, that are the Lagrangian parameters of the inverse kinematic problem. The exact expression of these functions is obtained by the equation (9). The first two columns of the matrix **[*ForeΔL*]** represent the components of the functions along the x, y, z axes; the total scalar functions are shown in the graphics in Fig. 6, a) and b). The legs of the model are wires moved by hydrodynamic linear actuators, so the values on the graphics are referred to the position of the two pistons, with zero-reference when Φ=0 and θ=0. As shown, regarding to the mentioned purpose, an optimum result has been obtained. The points B_3-P_3 and B_4-P_4 are referred to eventual auxiliary wires. The secondary rear piston controls them; its positioning is shown in Figure 6, c).

Leading to increase system stiffness there are two wires, connected to the same two principal pistons, that connect the rear part of the base with the rear part of the mobile platform (B_1,rear, P_1,rear and B_2,rear, P_2,rear, with coordinates in Table 1). They move in opposition to the two principal wires. Obviously, there will be an error between **[*ForeΔL*]** and **[*RearΔL*]** (calculated with an analogue approach unnecessary to explicit), variable with Φ and θ. A kinematic optimization of the z-coordinates of the posterior base points has determined a very small error, acceptable for the required issue. The total scalar functions, relatives to the two closed-chain wire loops, are shown in Figure 7, a) and b).

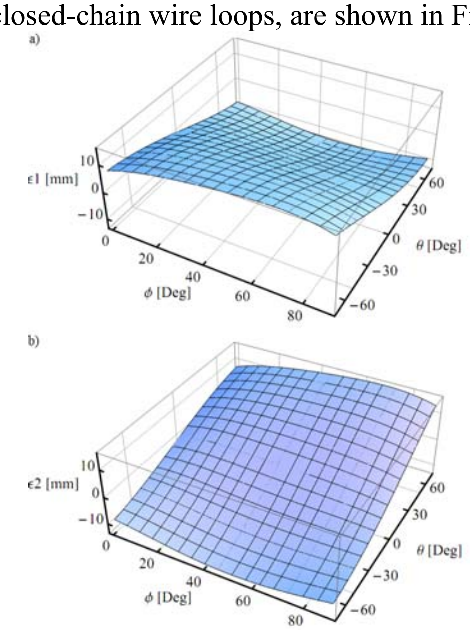

Fig. 7. Error of total lengths of wires for piston 1 (a) and piston 2 (b).

Table 1

Points spatial coordinates

Point	*x* [mm]	*y* [mm]	*z* [mm]
B_1	25	40	22
B_2	-25	40	22
B_3	17.5	33	22
B_4	-17.5	33	22
P_1	-25	5	-80
P_2	25	5	-80
P_3	3	23	-80
P_4	-3	23	-80
$B_{1,rear}$	10	-15	-36
$B_{2,rear}$	-10	-15	-36
$P_{1,rear}$	2	-12	-80
$P_{2,rear}$	-2	-12	-80

6. Conclusions

A new mechanical architecture for prosthesis elbow is presented. The device uses two cylindrical elementary hinges to connect forearm and arm, three hydraulic actuators are placed on upper arm to reduce moving masses. The actuators are divided in principal (front placed) and secondary (rear placed). Each principal actuator is linked with two wires, one towards front forearm and one, following an opposite path, towards the rear part of the forearm. The rear piston brings a pulley that forces another wire connected with the front of the forearm.

After some geometrical optimization, almost linearity between hydraulic actuators and arm rotation (flexion and prono-supination) is obtained. The posture study produced some optimistic results that induces the authors to develop a dynamic investigation, already begun.

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