Design of a Novel Elbow Joint for an Upper-Limb Exoskeleton

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***Abstract*—This paper deals with the design and the kinematic analysis of a novel elbow joint for an upper limb exoskeleton, that is aimed to help workers in the performing of hard operations. This research activity was developed within the framework of a scientific collaboration with the IIT (Italian Institute of Technology) of Genoa, Italy. The proposed elbow-joint exoskeleton consists of a ten-bar mechanism, which includes a kinematic sketch of the human arm. In particular, a Watt six-bar mechanism represents the exoskeleton mechanism and a crossed four-bar linkage sketches the human arm, which are coupled between them, through a prismatic joint. This novel design gives two main advantages, with respect to conventional designs that can be found in literature, the installation of the electric drive and its speed-reducer outside the elbow joint and a more anthropomorphic coupling with the human arm.**

Keywords—Upper-limb exoskeleton, elbow joint, planar mechanisms, kinematic analysis and synthesis.

I. Introduction

In the last decades, the research in the field of robotics has gradually moved from the industrial robotics to non-industrial robotics, which includes mobile and walking robots, humanoids, robotic prostheses and exoskeletons [1]. Many efforts were addressed to the mechatronic design and control of exoskeletons for the physical rehabilitation of lower and/or upper limbs of human beings [2-3].

Robotic rehabilitation is now a field that experienced a rapid expansion, but, more recently, the interest of researchers was also addressed to other types of exoskeletons, which are aimed to help workers in the performing of hard operations.

The content of this paper is intended to give a scientific contribution to the design of innovative upper-limb exoskeletons, in order to support the manual tasks of workers with the aim to prevent risks of injuries and musculoskeletal diseases. This research activity was developed within the framework of a scientific collaboration with the IIT (Italian Institute of Technology) of Genoa, Italy.

Thus, the design and the kinematic analysis of a novel elbow joint ten-bar mechanism for an upper-limb exoskeleton is proposed along with a first prototype.

II. Exoskeleton & Human Arm: Ten-Bar Mechanism

Elbow joint exoskeleton and human arm are sketched through a ten-bar mechanism, where the first is a Watt six-bar mechanism and the second is a crossed four-bar linkage, which are connected each other by a moving prismatic pair. Figure 1 shows the case where the Watt six-bar mechanism is represented by the double articulated parallelogram A_0B_0ABCDE and the human arm is sketched through a crossed four-bar linkage. They are coupled each other by the moving prismatic pair at point *H*. Member 1 is assumed as fixed frame, since attached to the arm, while 2 is the driving link and 6 the coupler link of the double articulated parallelogram, which is also provided of links 3, 4 and 5. The piston 7 is joined to 6 by a revolute joint in *H* and moves along the straight slot of link 8, which is the coupler of the crossed four-bar linkage that sketches the human elbow joint.

In fact, link 8 is attached to the forearm and, consequently, the elbow joint exoskeleton can assist the bending of the human arm when it is loaded over a given limit. The other links of this mechanism are 1 (arm), 9 and 10.

When member 1 is attached to the human arm, the double articulated parallelogram allows a pure rotation of its coupler link 6 around point *O*, but the relative motion between the human arm and forearm is not a pure rotation. In fact, the coupling of the elbow bones, i.e. humerus with radius and ulna, can be sketched with a simple revolute joint at first approximation only, because their relative motion is more similar to a generic planar motion.

A more accurate kinematic sketch of the elbow joint would require the use of conjugate profiles and higher kinematic pairs, but these can be substituted by equivalent mechanisms with lower kinematic pairs, conveniently. This approach was here simplified by assuming a crossed four-bar linkage to sketch the human elbow joint and introducing the moving prismatic pair of point *H*, in order couple both mechanisms to obtain the proposed ten-bar mechanism.

In particular, the relative rotation of the forearm of length *a*, with respect to the fixed arm 1 of length *b*, is given by angles α_1 and α_2 for the full flexion and full extension of the forearm 8, respectively. The dimensions of links 1, 2, 3, 4, 5 and 6 are ($A_0B_0=d$), ($A_0A=c$), ($AB+BC=d+c$), ($B_0B+BE=c+e$), ($ED=c$) and ($CD=e$), respectively. Thus, the kinematic analysis of the proposed ten-bar mechanism was formulated using the fundamentals reported in [5, 6] and considering separately, the Watt six-bar mechanism (double articulated parallelogram) and the crossed four-bar linkage (antiparallelogram), which algorithms were then coupled to analyze the whole mechanism.

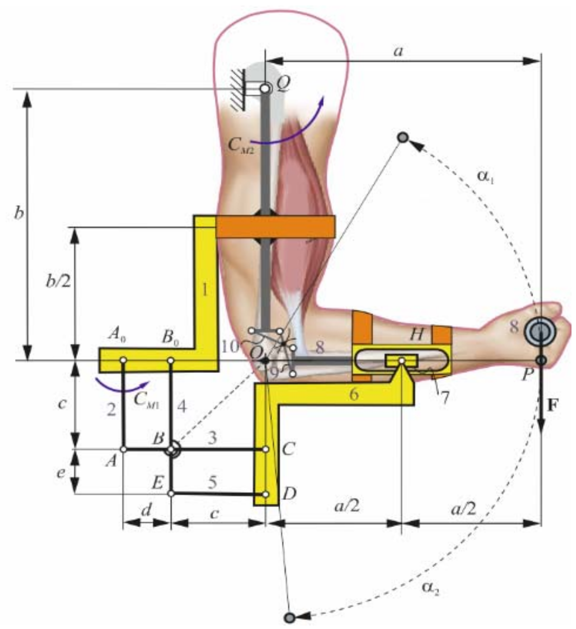

Fig.1 - Ten-bar mechanism: elbow joint exoskeleton & human arm.

III. Ten-bar Mechanism: Kinematic Analysis

Referring to Fig. 2, the ten-bar mechanism in the form of the double articulated parallelogram A_0B_0ABCDE and the crossed four-bar linkage M_0MNN_0 that are joined each other at point H. In this case, the coupler link 6 of the Watt six-bar mechanism performs a pure rotation around the instantaneous center of rotation point P_6, which is also the intersecting point between links 1 and 8 of human arm and forearm, respectively. P_6 is fixed in this particular case,

Nevertheless, the planar motion of the forearm with respect to the fixed arm is not a pure rotation about P_6, since attached to the coupler link 8 of the crossed four-bar linkage. In fact, the instantaneous center of rotation of 8 is P_8 that falls at the intersecting point between links M_0M and N_0N.

Thus, according to the Aronhold-Kennedy theorem, the instantaneous center of rotation P_{68} for the relative motion between the coupler links 6 and 8 of the Watt six-bar mechanism and the four-bar linkage, respectively, is aligned with the joining line passing through P_6 and P_8. Moreover, P_{68} must belong to the normal line to the axis of the prismatic pair that is composed by the piston 7 and the slot of link 8.

The well-known vector equation:

$$\mathbf{v}_{H6} = \mathbf{v}_{H8} + \mathbf{v}_{H68} \tag{1}$$

expresses the relation among the velocity vectors $\mathbf{v}_{H6}$ and $\mathbf{v}_{H8}$ of point H, as belonging to the coupler links 6 and 8, respectively, along with their relative velocity vector $\mathbf{v}_{H68}$.

Thus, Eq. (1) gives

$$\mathbf{v}_{H8} = \omega_8 \times P_8H, \quad \mathbf{v}_{H6} = \omega_6 \times P_6H, \quad \mathbf{v}_{H68} = \omega_{68} \times P_{68}H \tag{2}$$

from which the following scalar equation is obtained

$$\omega_6 P_6 P_{68} = \omega_8 P_8 P_{68} \tag{3}$$

Therefore, Eq. (3) allowed the connection between the two formulations for the kinematic analysis of the Watt six-bar mechanism and the four-bar linkage and, consequently, a whole algorithm for the kinematic analysis of the proposed ten-bar mechanism was formulated.

A Matlab result is shown in Fig. 3, where the velocity vectors of the most significant points are also shown in scale for the particular configuration with crank angle $\theta_2 = 300°$ of A_0A of the proposed ten-bar mechanism with one d.o.f.

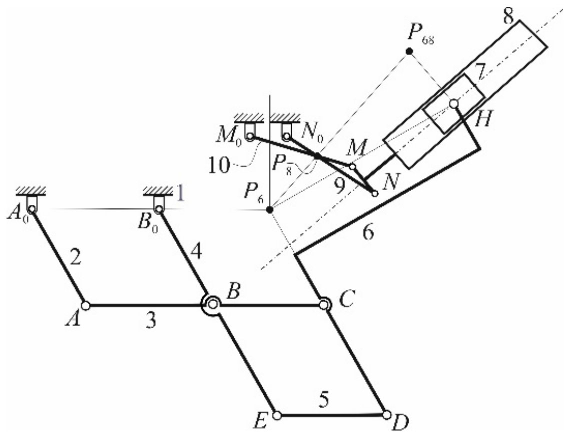

Fig. 2 Ten-bar mechanism in the form of the double articulated parallelogram A_0B_0ABCDE and the crossed four-bar linkage M_0MNN_0 that are joined in H.

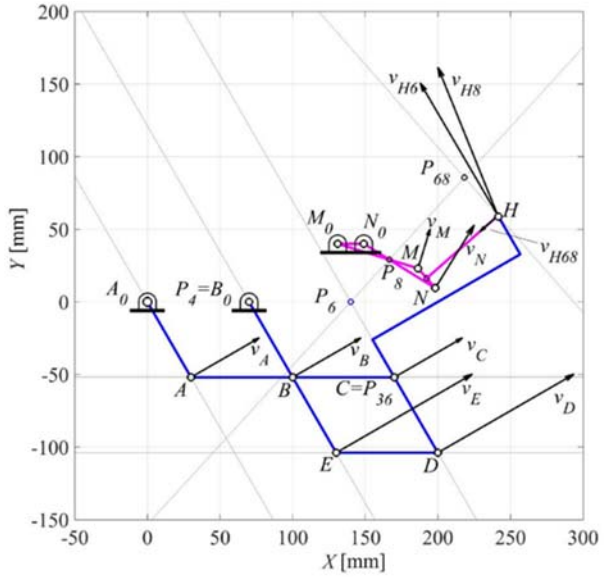

Fig. 3. Ten-bar mechanism: Matlab result for a crank angle $\theta_2 = 300°$ of A_0A.

IV. Conclusions & Prototype

The innovative design of a novel elbow joint for an upper limb exoskeleton in the form of a ten-bar mechanism with one d.o.f. was proposed and its mechanical design was also developed to build and test the first planar prototype of Fig.4, which was manufactured by means of a 3D printer.

Fig. 4 Novel elbow joint prototype.

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