Novel solutions for actuation of an above elbow prosthesis

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Abstract. The above elbow prosthesis must provide the movement of the elbow, which naturally is composed by a flexion – extension movement. The mechanical system must fulfil a set of conditions regarding kinematics, dynamics, precision, size and load. The paper describes two novel solutions to generate the flexion – extension movement of the elbow. The description contains the kinematic scheme, elements of calculus and the CAD generated constructive solution.

1. Introduction
The limbs of the human bodies, whose functions have been attenuated or cancelled by traumas or accidents, can be partially or totally replaced with proper prosthesis. Regarding the upper limb and according to the level of amputation, the prosthesis can be [1]:
- From shoulder
- Above elbow
- Below elbow.

The above elbow prosthesis can be a very complex technical assembly because of its specific mobility within an open kinematic chain. The movement of the natural elbow is composed by a wide amplitude flexion – extension movement (~150 deg).

The market offers a large range of products, which embody different solutions regarding the actuation, the control, mechanical system etc. [2 … 6].

The control of prosthesis recorded an obvious progress from command operating with myoelectric or piezoelectric signals to direct cortical signals [7, 8]. The trend is to get more and more sophisticated ways of control with the purpose of making the prosthesis easier to handle by its user.

The actuation system consists of miniature electric/hydraulic motors, according to the technological evolution, which made possible smaller and smaller components.

The mechanical system which conveys the energy into movements with given trajectory and amplitude, alike the natural behaviour is still subject to improvement.

These systems are kinematic chains [9], on which the following minimum set of initial conditions is imposed:
- Trajectory of the final point (and, eventually, of other points on the chain)
- Velocity of displacement
- Precision of displacement
- Maximal handling load
- Overall dimensions
- Overall weight.

The existing solutions are based on complex linkages [10], gears [11], wires and pulleys or combinations of these. The present paper proposes two novel solutions to generate the flexion –
extension movement of the elbow:
- Mechanism with bevel gears and wires
- Mechanism with linkages and gears.

2. Elbow prosthesis driven by a mechanism with bevel gears and wires
The prosthesis consists of two jointed parts corresponding to the arm and the forearm. The mechanism contains a bevel gear train and a wire transmission (fig. 1).

The driving bevel gear (1) meshes with the driven identical bevel gears (2) and (3), placed in symmetrical positions in order to generate identical antagonistic angular displacement $\phi_2 = \phi_3$. The shafts of the bevel gears (2) and (3) are mounted in bearings held in the housing of the forearm. On the shafts are fastened the identical pulleys (2') and (3') with antagonistic movement and working in a wire transmission that also includes the pulley (4). The pulley is jointed in the centre of the elbow joint, which is fixed in the housing of the arm allowing the rotation of the forearm in regard with the arm. The value of the rotation angle in the elbow is limited by attaching the wire to the pulley (4).

By actuating of the drive bevel gear the wire is developed from the pulley (2) drive the pulley (4) and enveloped around the pulley (3). The computation of the transmission function of the actuating mechanism is given by considering the transmission ratios with the relationship:

$$\varphi_4 = \frac{z_1}{z_2} \cdot \frac{r_2'}{r_4'} \cdot \varphi_1,$$

where: $\varphi_1$, $\varphi_4$ is the angular displacement of the drive gear and pulley transmission,
$z_1, z_2 = z_3$ - the number of teeth of bevel gears,
$r_2 = r_3, r_4$ - the radii of the pulleys.

Considering the entrance data:
- $z_1 = 16$
- $z_2 = z_3 = 32$
- $r_2' = 8 \text{ mm}$
- $r_4' = 16 \text{ mm}$,

the transmission function is linear as it is given in figure 2.
The actuation of the mechanism is assured by a stepper motor series. The mechanism in extreme positions, corresponding to maximum flexion and extension, is represented in figure 3 a, b as CAD generated models.

The system is designed to handle on object of 2.5 kg along an extension of 150 deg by an angular displacement of the stepper motor of 600 deg. The maximum angle of rotation of the driving element (1) is 1200 deg. Considering the length of the forearm of 250 mm, the torque needed to handle the imposed mass is 6.25 Nm.

3. Elbow prosthesis driven by a mechanism with geared linkages
The mechanism is conceived so that the linear actuator (2 and 3) is attached to the forearm and the driven element – spur gear (5) is fixed with the housing of the arm (fig. 4 a and b). The joint denoted B0 corresponds to the elbow joint.

A gear segment is attached to the slider (3), which meshes with the driven spur gear (5).
The mechanism is actuated with the linear servo motor. The transmission function of the geared mechanism [12, 13] can be computed based on the scheme in figure 4b as follows:

\[ \phi(s) = (1 - \rho) \cdot \phi(s) + \rho \cdot \psi(s), \]

where:
- \( \psi(s) \) - output angle or transmission function,
- \( \rho = \pm r_3 / r_5 \) - gear ratio
- \( \phi(s), \phi(s) \) - transmission functions of the base four-bar linkage:

\[ \phi(s) = 2 \cdot \arctan\left( \frac{B(s) \pm \sqrt{A(s)^2 + B(s)^2 - C(s)^2}}{(A(s) - C(s))} \right), \]

with:
- \( A(s) = 2 \cdot l_1 \cdot e_S \),
- \( B(s) = 2 \cdot l_1 \cdot (s_0 + s) \),
- \( C(s) = -l_1^2 - e_S^2 - (s_0 + s)^2 + l_4^2 \),

and

\[ \psi(s) = \arccos\left( \frac{e_S^2 + (s_0 + s) - l_1^2 - l_4^2}{2l_1l_4} \right). \]

The synthesized mechanism considered the lengths of the linkages (\( l_1 = 100 \text{ mm}; l_4 = 21 \text{ mm} \)) and the transmission ratio (\( i = r_5/r_3 = 0.5 \)) known and provided:
- minimum transmission angle of the base mechanism: \( \mu_{\text{min}} = 35 \text{ deg} \)
- stroke of the slider: \( s = 32.3 \text{ mm} \) (for the initial position \( s_0 = 84 \text{ mm} \)).

The transmission functions (fig. 5, 6 and 7) show that the angular displacement of the forearm is about 150 deg according to the imposed design parameters.
The mechanism in extreme positions, corresponding to maximum flexion and extension, is represented in figures 4 and 5 as CAD generated models.

**Figure 8.** CAD model of the mechanism with linkages and gears – maximum extension

**Figure 9.** CAD model of the mechanism with linkages and gears – maximum flexion

4. Conclusions

Two solutions of mechanisms to generate the flexion – extension movement of the elbow are proposed. Both solutions fulfil the conditions regarding the amplitude of the angular movement. Furthermore, they are compact in construction and small in size. The elements do not imply special geometry, so that they are easy to machine at low cost. The actuation force or torque is small for usually tasks of the human hand.

The both mechanism structure generate linear or approximately linear transmission functions, which are favourable to be controlled and actuated, in order to generate the oscillating motion of ~150 deg.
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