

Analysis of the movement of an exoskeleton for the upper limb

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Abstract. The theme approached in this paper falls within the general lines of an interdisciplinary research field, strategies provided by the European health insurance programs: Social Challenges (Health, Demographic Change and Wellbeing) and respectively in the national classification: Health (Fundamental and Border Research). The main objective of the research is the identification and knowledge of the biomechanical analysis elements that contribute to the increase of the mobility of the upper limbs in the persons with different motor dysfunctions (recoverable and rehabilitated dysfunctions), using customized exoskeleton-type systems together with opto-electronic systems to diversify the scope. In the first part of the paper are presented general aspects related to variants and fields of use of types of exoskeleton for upper limbs. The biomechanical analysis of upper limb movements, performed for the purpose of determining the action limits, is presented in the second part of the paper. The results of the analyses and the conclusions of this research are presented in the final part of the paper, along with the description of the proposed constructive variant of the exoskeleton.

1. Introduction

The design of the exoskeleton systems requires a systemic approach, starting from the anthropometric dimensions, personalized features of each subject, continuing with the identification and knowledge of motor dysfunctions (limits of anatomical and physiological functioning), simulating then computerized or experimental, certain situations of action, to follow the way of working in rehabilitation, training and recovery procedures, considering the movements of upper limb shown in figure 1. These mechanisms of action and the fundamental design aspects form the theoretical basis of research and represent a necessary step in the design of the structure of the proposed variant. The constructive variants on the market of these products are made of different materials, such as: metal, casted or moulded plastic, powders or composite alloys.



Figure 1. Types of movements and limit of action of upper limb [1]

2. Theoretical basis of upper limb movement

In order to carry out a generalized analysis of the movements of the arm-forearm assembly, it starts from the Denavit-Hartenberg Convention (D-H Convention), a form of calculation of the links that exist between the segments of an articulated system consisting of two bars, a coupling joint between them and an attachment joints with other elements of the human trunk. As mentioned in various papers [2-4] coordinate frames are attached to the joints between two links such that one transformation is associated with the joint, $[Z]$, and the second is associated with the link $[X]$. The coordinate transformations along a serial robot consisting of n links form the kinematics equations of the robot:

$$[T] = [Z1] [X1] [Z2] [X2] \dots\dots\dots [Zn] [Xn] \quad (1)$$

where $[T]$ is the transformation locating the end-link [3].

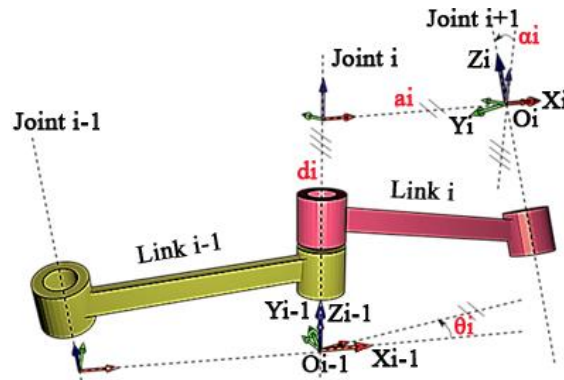


Figure 2. The four parameters of classic D-H Convention [3]

The parameters of the D-H Convention which will be used in the description of movements at the level of the upper limb are as it follows: d : offset along previous z to the common normal; θ : angle about previous z , from old x to new x axis; r : length of the common normal; α : angle about common normal, from old z axis to new z axis [3].

By using the D-H Convention method, a coordinate axis system will be attached to each kinematic chain and at the end it will be obtained, according to figure 2, transformation matrices 4x4 type between the two successive links (link $i-1$ and link i). The D-H Convention also allows the writing of kinematic equations (velocities, accelerations) or dynamic (linear and angular momentum, forces and couples) by using those forms of transformation matrices specific to determinations.

In addition to this, the D-H convention parameters can be modified, the difference between classical parameters as in equation (2) and modified parameters as in equation (3) consisting in moving the coordinate system from $i+1$ junction (classical convention) to $i-1$ junction (modified convention) [3, 5, 6]:

$${}^{n-1}M_n = \begin{bmatrix} \cos\theta_n & -\sin\theta_n \cos\alpha_n & \sin\theta_n \sin\alpha_n & r_n \cos\theta_n \\ \sin\theta_n & \cos\theta_n \cos\alpha_n & -\cos\theta_n \sin\alpha_n & r_n \sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R & T \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$${}^{n-1}M_n = \left[\begin{array}{ccc|c} \cos\theta_n & -\sin\theta_n & 0 & a_{n-1} \\ \sin\theta_n \cos\alpha_{n-1} & \cos\theta_n \cos\alpha_{n-1} & -\sin\alpha_{n-1} & -d_n \sin\alpha_{n-1} \\ \sin\theta_n \sin\alpha_{n-1} & \cos\theta_n \sin\alpha_{n-1} & \cos\alpha_{n-1} & d_n \cos\alpha_{n-1} \\ \hline 0 & 0 & 0 & 1 \end{array} \right] \quad (3)$$

where R is submatrix 3x3 which describes the rotation movement and T is submatrix 3x1 which represents the translation movement.

To study human arm behaviour, it must be taken into account that it is assimilated to a complex structure, but usually in biomechanical calculations, the joints and segments of a human arm are simplified in a 7-DOF kinematic chain. The arm joint with the shoulder structure can be modelled as a 3-DOF spherical joint and the elbow joint as a cylindrical joint. In the same way, the wrist joint can be modelled as a 3-DOF joint which assembles with the forearm structure [7].

Using the modified D-H convention, it will be possible to model the motion of the proposed exoskeleton according to the scheme shown in figure 3, where a_1 represents the length of the arm, a_2 represents the length of the forearm and J_1 , J_2 and J_3 represent the joints of the entire upper limb in the following order: shoulder joint, elbow joint (between arm and forearm) and wrist joint.

As shown in the paper [8] the trajectories used in this research correspond to passive flexion/extension movements for shoulder, elbow and wrist joints used in passive rehabilitation exercises or in the evaluation processes. The initial values of the system are selected as $q(0) = [0, \pi/2, 0]^T$, $\dot{q}(0) = [0, 0, 0]^T$.

The parameters of the sliding surface function are $p = 7$, $q = 9$, and the diagonal gain matrices are $\alpha = 3 \text{ I}$, $\beta = \text{I}$. For the control law, the gain matrix $\lambda = 10^3 \text{ diag}([0.1, 0.3, 3])$. The initial value of the adaptation term $\hat{A}$ is equal to zero and the adaptation gain is $\Gamma = 10^2 \text{ I}$.

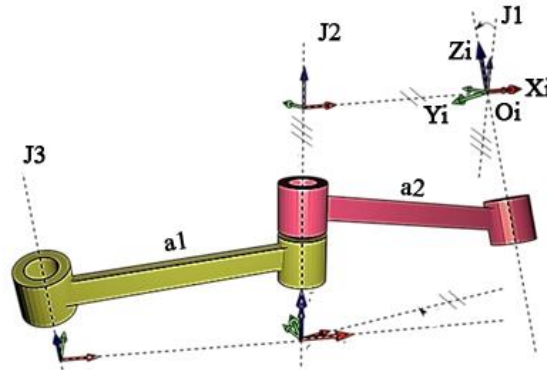


Figure 3. The simplified form of D-H Convention [3]

3. Determination of upper limb movement elements

Values of mass characteristics for segments of upper limb can be found in various papers [9]. Values for range of motion are shown in table 1.

The basic relationship that is generally applied for defining the dynamic behaviour of the exoskeleton structure is presented as in equation (4):

$$M(\theta) \cdot \ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) = \tau_{joints} \quad (4)$$

where: θ is the joint variables vector, τ is the generalized torques vector, $M(\theta)$ is the inertia matrix, $V(\theta, \dot{\theta})$ is the Coriolis /centrifugal vector, $G(\theta)$ is the gravity vector [9].

Table 1. Range of motion [9]

Type of motion	Anatomical range [9, 10]				
	Source 1 [°]	Source 2 [°]	Source 3 [°]	Source 4 [°]	Source 5 [°]
Elbow & Forearm					
Flexion	140	140	145	120	116
Extension	0	0	5-15	0	0
Pronation	80	90	80	80	70
Supination	80	85	90	80	85

The joints noted with Ji-1, Ji and Ji + 1 represent the joint of the shoulder (assimilated to a cylindrical joint due to the proposed exoskeleton model), joint of elbow and joint of the wrist, which are linked by segments, their length being noted with a1, respectively a2.

In mechanics, a joint is an assembly, a linking element, based on a material shaft that allows angular displacement of the assembled parts. According to the paper [10], the elbow joint represents the link that forces the rigid solid to stay with one of its axis in permanent contact with a fixed axis in space. The position of a rigid linked through a cylindrical joint, which provides a fixed axis in space, will be determined by a single scalar parameter – the angle of rotation around this axis. Consequently, it will have only one degree of freedom (1 DOF), resulting in the fact that joint blocks five degrees of freedom (5 DOF). The torques of active mechanical stresses and reactions in J2 joint will have the following forms:

$$\vec{\tau}_0(\vec{F}_i) = \left\{ \begin{array}{c} \sum_i \vec{F}_i \\ \sum_i \vec{M}_0(\vec{F}_i) \end{array} \right\} = \left\{ \begin{array}{c} \sum_i X_i \\ \sum_i Y_i \\ \sum_i Z_i \\ \sum_i M_{x_i} \\ \sum_i M_{y_i} \\ 0 \end{array} \right\} + \left\{ \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \sum_i M_{z_i} \end{array} \right\} = \vec{\tau}_b + \vec{\tau}_l \quad (5)$$

In this case the torque of these mechanical stresses may be written in the following form as in equation (6), showing that the joint can be replaced with a single action having two components. Determining degrees of mobility (M), is based on the Gruebler & Kutzbach equation, which takes into account the number of connections in the system (L - Links), number of joints (J - Joints) and respectively the number of grounded links (G – Grounded links) as in equation (7).

$$\vec{\tau}_0(\vec{F}_i) = \left\{ \begin{array}{c} \sum_i \vec{F}_i \\ \sum_i \vec{M}_0(\vec{F}_i) \end{array} \right\} = \left\{ \begin{array}{c} \sum_i X_i \\ \sum_i Y_i \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right\} + \left\{ \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \sum_i M_{z_i} \end{array} \right\} = \vec{\tau}_b + \vec{\tau}_l \quad (6)$$

$$M = 3L - 2J - 3G \quad (7)$$

In the case of any real mechanism, there is at least one grounded link, therefore G has the value 1 and the Gruebler & Kutzbach equation becomes:

$$M = 3(L - 1) - 2J \quad (8)$$

4. Conclusions

According to these observations, the structure of an exoskeleton robot for the upper limb can assure the rehabilitation process in the circumstances that the whole arm leans in the elbow, on a hard surface and the shoulder movement is considered simplified as a movement that appears in a cylindrical joint.

The exoskeleton designed for training and rehabilitation procedures performs limited elbow movement without involving the movement of the shoulder or wrist. The last two movements are taken into account both for the initial positioning and for establishing the coordinate systems, taken as a reference in the elbow movement analysing. The anatomical elements involved in this analysis have been estimated according to the upper limb properties of a typical adult.

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