Conference Paper

Kinematic and Dynamic Analysis of the Human Hand's Articulation for Wearable Soft-Robotic Device Applications

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ABSTRACT

Robot-assisted therapy, particularly hand exoskeletons, has emerged as a promising approach to address hand function limitations caused by neurological diseases that can significantly impact mobility, balance, and posture, leading to physical, psychological, and societal challenges. Traditional rigid-body robots, while helpful, have limitations in safety and dexterity, spurring research into soft robotics in neurorehabilitation. The research presented in this manuscript focuses on the advancement of a Soft Robotic Glove prototype developed for neurorehabilitation, integrated into the NeuroSuitUp Body-Machine Interface. This glove, composed of five PneuNet pneumatic actuators and a multi-sensor system, is designed to facilitate natural hand movements. To optimize the glove's functionality, kinematic and dynamic analyses of the human hand were conducted. Specifically, a kinematic model of the hand, with 19 links representing human bones (phalanges) and 24 joints connecting them, was developed indicating the 24 degrees of freedom of the human hand. By understanding the forces applied to the finger phalanges, the movement of the entire finger can be predicted. This knowledge aids in designing personalized exoskeletal hand devices tailored to individual patient needs. Further research aims to combine this model with a dynamic model of the actuators and investigate the device's effect on hand performance through computer simulations.

Keywords—*Soft robotic device, Kinematics, Dynamics.*

INTRODUCTION

Neurological diseases, such as Cerebral Palsy (CP), Parkinson's Disease (PD), and Spinal Cord Injury (SCI) affect a great percentage of the world's population. These diseases can significantly affect a person's mobility, balance, and posture, having a significant physical, psychological, as well as societal impact.[1] In the past few decades, a wide range of studies about robot-assisted therapy have been developed to help alleviate the effects of these diseases. These neurological pathologies usually affect the proper physical functions of a patient's hand and therefore, they can create limitations in performing activities of daily living. As a result, numerous hand exoskeleton systems have been developed aiming to the hand rehabilitation.

This research focuses on the mathematical analysis of the human hand's kinematics and dynamics, for the purpose of developing more efficient rehabilitation devices. Through mathematical modeling, the exact motion and forces of the interaction between a robot and the human body can be determined. More specifically, the degrees of freedom, position, and orientation of the end effector, as well as the forces that need to be applied for the system's operation, can be defined. This result enables the personalization of rehabilitation devices and exercise regimens, depending on each patient's condition and the specific system operational parameters.

As an assistance to the aforementioned motor disabilities, ongoing development of soft robotics for neurorehabilitation purposes has been observed in the past years. This emerging field uses lightweight, flexible, and compliant devices, built from materials with mechanical properties similar to those of living organisms. Compared to the traditional rigid-body robots, these new types of robotics are designed and manufactured in a very innovative way in order to secure safety with the patient, dexterity, but also high performance.[2]

A wearable prototype in the shape of a glove has been designed and developed for neurorehabilitation purposes, as mentioned above. As shown in Figure 1, it consists of an actuation system with five PneuNet pneumatic actuators initiating the typical human hand movement, such as grasping an object, and a multi-sensor system.[3] The device is part of the NeuroSuitUp body-machine interface (BMI), which is a platform consisting of a wearable robotics jacket and glove, along with a serious game application for neurorehabilitation purposes.[4] In order to understand and optimize the soft robotic glove's future function, the proposed research describes the kinematic and dynamic analysis of the human hand and fingers, specifically.

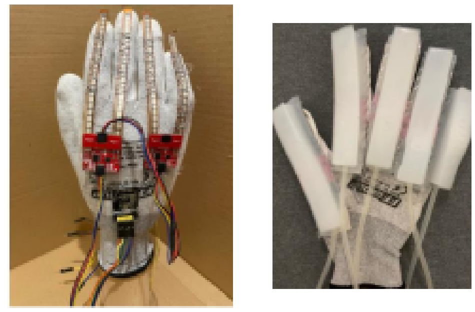

FIGURE 1. Soft-robotic glove device.[3]

METHODS

The proposed kinematic model of the hand consists of 19 links, which imitate the corresponding human bones (phalanges), and 24 joints, which connect the phalanges/links of the fingers. Therefore, the hand system is defined as having 24 DoFs. Figure 2 depicts the kinematic configuration of the human hand with all the joints J(i,j) of the five fingers, where i ={1,2,3,4,5} is the number of fingers and j ={1,2,3,4} is the number of joints in each finger. The four joints of the fingers, starting from the palm to the fingertip, are the Carpometacarpal (CMC), Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP), and Distal Interphalangeal (DIP) joint.[5,6]

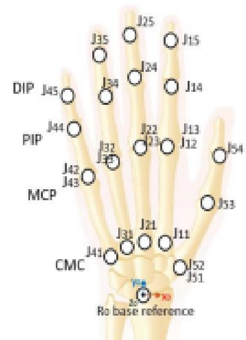

FIGURE 2. Configuration of the human hand joints.

Figure 3 presents the open-chain kinematic configuration for one of the index, middle, ring, and little finger. The joints represented are the CMC, MCP, PIP, and DIP. As shown, the MCP joint consists of 2 DoFs, since the one is for the flexion-extension movement and the second one is for the adduction-abduction movement of the finger. All the other joints perform the flexion-extension movement. Each joint is represented by its own frame of origin with regard to the wrist reference frame R_0.

The aforementioned configurations are used to calculate the Direct Kinematics equations in order to define the position and orientation of the end-effector (fingertip) as functions of the joint variables. In this modeling, the Denavit-Hartenberg (DH) method is used and the parameters are shown in Table 1.[7]

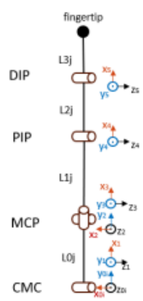

FIGURE 3. Kinematic configuration of the index finger.

TABLE 1. DH parameters for the Direct Kinematics.

Joint		aj	αj	dj	θj
CMC	1	0	π/2	0	θCMC
MCP(ab/ad)	2	L01	−π/2	0	θMCPa/a
MCP(f/e)	3	0	π/2	0	θMCPf/e
PIP	4	L11	0	0	θPIP
DIP	5	L21	0	0	θDIP

The general form of the Transformation Matrix Ti, based on the DH parameters, is the following:

$$T_i = \begin{bmatrix} \cos\theta_j & -\sin\theta_j\cos\alpha_j & \sin\theta_j\sin\alpha_j & a_j\cos\theta_j \\ \sin\theta_j & \cos\theta_j\cos\alpha_j & -\sin\theta_j\cos\alpha_j & a_j\sin\theta_j \\ 0 & \sin\alpha_j & \cos\alpha_j & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Equation 1 shows the final Direct Kinematics Modeling of one finger i:

$$Ti = {}^{1}_{0i}T_i(\theta_{CMC}) \cdot {}^{2}_{1}T_i(\theta_{MCPa/a}) \cdot {}^{3}_{2}T_i(\theta_{MCPf/e}) \cdot {}^{4}_{3}T_i(\theta_{PIP}) \cdot {}^{5}_{4}T_i(\theta_{DIP}) \cdot {}^{6}_{5}T_{fingertip} \quad (2)$$

where Ti is a matrix representing the final position and orientation of the fingertip; ${}^{j}_{j-1}T(\theta_j)$ is a geometrical transformation matrix from the (j−1) reference frame of the i-finger to its j-reference frame; ${}^{6}_{5}T_{fingertip}$ is a geometrical transformation matrix representing the final position of the fingertip regarding the 5th reference frame.

After the development of the kinematic model of each finger, the Dynamics equations can be calculated using the Euler-Lagrange method. In this case, it applies on one of the four fingers (index, middle, ring, middle) and it is considered to have the Metacarpophalangeal joint fixed for simplification purposes.

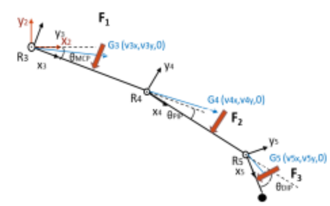

FIGURE 4. Dynamic configuration of the index finger.

The dynamic configuration of the index finger is presented in Figure 4, and consists of the three MCP, PIP, and DIP joints. Each joint has its own reference frame, while the R_3 is the base reference frame. It is assumed that the center of mass of each link is located as shown in Figure 3 and has a position vector G_j. As a result, the three generic position vectors of the three links with respect to the base frame R_3 are calculated and are the following[6]:

$$\begin{gathered} \hat{G}_3 = \begin{bmatrix} v_{3x}\cdot cos\theta_3 - v_{3y}\cdot sin\theta_3 \\ v_{3x}\cdot sin\theta_3 - v_{3y}\cdot cos\theta_3 \\ 0 \end{bmatrix} \\ \hat{G}_4 = \begin{bmatrix} v_{4x}\cdot cos\theta_4 - v_{4y}\cdot sin\theta_4 \\ v_{4x}\cdot sin\theta_4 - v_{4y}\cdot cos\theta_4 \\ 0 \end{bmatrix} + \begin{bmatrix} L_1\cdot cos\varphi_3 \\ -L_1\cdot sin\varphi_3 \\ 0 \end{bmatrix} \\ \hat{G}_5 = \begin{bmatrix} v_{5x}\cdot cos\theta_5 - v_{5y}\cdot sin\theta_5 \\ v_{5x}\cdot sin\theta_5 - v_{5y}\cdot cos\theta_5 \\ 0 \end{bmatrix} + \begin{bmatrix} L_1\cdot cos\varphi_3 \\ -L_1\cdot sin\varphi_3 \\ 0 \end{bmatrix} \\ + \begin{bmatrix} L_2\cdot cos\varphi_4 \\ -L_2\cdot sin\varphi_4 \\ 0 \end{bmatrix} \end{gathered} \quad (3)$$

where φ4 = θMCP + θPIP and φ5 = θMCP + θPIP + θDIP.

The Lagrange-Euler equation is the following:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = F_{gen} \rightarrow \frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}}\right) - \frac{\partial K}{\partial \dot{q}} + \frac{\partial P}{\partial q} = F_{gen}, \quad (4)$$

where L=K−P. K is the kinetic energy of the system, P the potential energy of the system and F_{gen} the generalized external forces applying on the upper side of the finger phalanges, while q is the generalized coordinate, which in this case is the angle θ_j. The term of F_{gen} is not being described thoroughly at the present time, but will be estimated in future research.

The kinetic energy of the center of mass of each finger joint is obtained through the following equation:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = F_{gen} \rightarrow \frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}}\right) - \frac{\partial K}{\partial \dot{q}} + \frac{\partial P}{\partial q} = F_{gen}, \quad (5)$$

where m_j is the average mass of each joint j, J_{vi} is the linear velocity Jacobian, $J_{\omega j}$ is the angular velocity of the joint, I_j is the moment of inertia of the joint and $\dot{\theta}$ the angular velocity.

The dynamic energy of the center of mass, which includes the gravitational term, is obtained:

$$P = \sum(m_i \cdot g \cdot \hat{G}_j) \quad (6)$$

DISCUSSIONS

Further research in the future will aim to combine both the aforementioned model and the dynamic model of the actuators, as well as the way the exoskeletal device affects the performance of the patient's human hand. Moreover, executing computer simulations is proposed, in order to validate the results of the above research.

CONCLUSION

The emerging progress of the soft-robotics field has led to the development of numerous exoskeletal soft robotic devices aiming at neurorehabilitation. The above research describes the kinematic and dynamic model of the human finger, in order to solve the direct dynamics of the finger. Therefore, given the forces applied on the phalanges of the finger, the movement of the whole finger can be calculated and a suitable personalized exoskeletal hand device can be designed.

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