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Grasp-oriented human hand model for use in rehabilitation robotics

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Abstract

Losing hand functions due to ischemic or haemorrhaging stroke, often resulting in spasticity, causes difficulties in the activities of daily living (ADL), making rehabilitation challenging and important. Using robotic rehabilitation devices is a promising novel approach to exercise the hands, promote patient volition and increase the neural connections. The human hand, with its many degrees of freedom (DOFs), evolutionary formed for precision and power gripping, introduces, however, difficulties in developing specialized rehabilitation devices. Grasp-oriented modelling of hand's kinematics with simplified but effective mathematical representations is, therefore, critical. The kinematic characterisation performed in this work simplifies the available 24 DOFs biomechanical model to 9 DOFs by constraining the joints via synergies specific to different grasp types and fingers' inclination angles.The acquired model is compared to the anatomical one, and the effects of intra- and inter-dependent joints are studied. Although the used dependencies reduce slightly the joints' ranges of motion (ROMs), the important grasping types and the ROMs used in ADL are preserved. The proposed model increases also positioning accuracy.

Rehabilitation robotics, grasp-oriented hand model, joint dependency constraints, open-source implementation

1. Introduction

In the case of strokes, losing the ability to perform the ADLs implies the need of prompt rehabilitation. Robotic rehabilitation devices are an excellent tool for reducing the waiting lists, while providing an adequate therapy intensity. As the foundation for the biomechatronic design [1], a human hand model, based on anthropometric data, describing its wide range of movements and its grasping capabilities, is required. In contrast to proprietary developed representations [2], an upper extremity open-acces model, based on the 50th percentile male bones and including the thumb and index fingers, is available [3]. Significant efforts to reduce the complexity of the hand model and the corresponding number of DOFs are also reported in literature [4].

In order to enhance the usability in rehabilitation robotics and customize the process for specific grasp types, the principles of model simplification are implemented in this study. Using regression analysis, the number of parameters is thus reduced from eight [5] to five. The aim is to rebase the available joint dependency constraints [4], generalize them to the overall trajectories, investigate motion deficits (MDs), develop a functional forward kinematics model of the fingers, and implement the model in the open source Robot Operating System (ROS). The resulting inter- and intra-finger constraints, the respective motion studies, and a full forward kinematics solution are thus presented. The number of parameters required to describe motion kinematics is then reduced, and the attained improvements in positioning accuracy are validated.

2. Grasp-oriented kinematic characterisation of the hand

The performed study is based on the 24 DOFs hand model with five fingers (thumb - T, index - I, middle - M, ring - R, and little - L), with T having 4, and each of the I, M, R, and L fingers 5 DOFs. The identical kinematic chains of I, M, R and L, depicted in Fig. 1, comprise 4 joints: CMC (carpometacarpal), MCP (metacarpo-phalangeal), PIP (proximal interphalangeal) and DIP (distal interphalangeal). All joints allow flexion/extension (FE), while MCP allows also abduction/adduction (AA). The TMC (trapezio-metacarpal), MCP, and IP (interphalangeal) joints form, in turn, the T kinematic chain. TMC enables herein FE and AA, while MCP and IP only the FE movements. As per Cutkosky's taxonomy, two different grasp types are then studied: circular and prismatic.

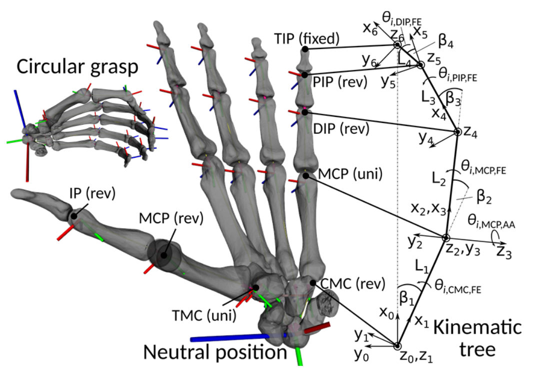

Figure 1. Hand kinematics implementation (◉ "out of plane" direction)

2.1. Dependency constrained trajectories

Inter- and intra-joint dependencies are generalized to the constrained trajectories, and obtained by using a glove reporting joints' angles during different hand gestures [4]. The linear dependency between the constrained θ_{cons} and the base joint θ_{base}, dependant on slope *m* and intercept *b*, is modelled as:

$$\theta_{\mathrm{cons}}/^{\circ} = m\theta_{\mathrm{base}}/^{\circ} + b/^{\circ} \quad (1)$$

Since the neutral position of T differs between the musculo-skeletal [3] and the model with dependencies [4], the intercept term *m* is used for T only. Determining the base joint for each dependency is critical, as its ROM dictates the ROM of the respective constrained joint and its MD. To broaden the ROM of each dependent joint, all intra-finger FE constraints are thus rebased to the corresponding MCP joint ($\theta_{\text{base}} = \theta_{i,\text{MCP,FE}}$, $i \in \{\text{L, R, M, I, T}\}$). In Table 1 can then be seen that MD grows down the kinematic chain, ranging from 3.5° for the FE motion of the TMC joint, to 50° for the DIP joint.

Table 1. Model simplification parameters and MDs for intra-finger constraints related to the FE motions (the base joint is MCP)

Finger	T					R, L				I, M			
Joint:	TMC			IP		PIP		DIP		PIP		DIP	
Grasp	*m*	*b*/°	MD/°	*m*	MD/°	*m*	MD/°	*m*	MD/°	*m*	MD/°	*m*	MD/°
Circular	$\frac{11}{10}$	- 45	3.5	$\frac{5}{4}$	-	$\frac{3}{4}$	25	$\frac{1}{2}$	35	$\frac{3}{4}$	25	$\frac{1}{2}$	35
Prismatic				$\frac{5}{6}$	27					$\frac{2}{3}$	33	$\frac{1}{3}$	50

In Table 2 are reported the palmar arc (PA) and AA motions using inter-finger dependencies that connect the same joint through different fingers. In the modelling of AA movements, the dependencies between M→I and R→L MCP joints are present, with MDs of up to 34°. However, for the ADL actions, only a fraction of the AA movement is used [6]. PA dependency is, in turn, represented as a chain linking 4 fingers (I→M→R→L). By employing these constrains, the resulting hand model is finally simplified to 9 DOFs: 5 MCP (all fingers) and 1 CMC (L) FE motions, as well as 2 MCP (I, L) and 1 TMC (T) AA movements.

Table 2. Model parameters and MDs for inter-finger constrained dependencies related to AA and PA movements

Movement:	AA				PA			
Joint:	MCP AA				CMC FE			
cons → base:	M→I	Free I	R→L	Free L	I→M	M→R	R→L	Free L
m	$^1/_5$	-	$^1/_2$	-	1	$^1/_2$	$^2/_3$	-
MD/°	34	30	30	20	-	-	-	-

2.2. Forward kinematics modelling and implementation

The modified Denavit-Hartenberg (DH) convention [7] is used to perform the forward kinematics procedure, thus obtaining the transformation matrix coupling the position and orientation of each joint in a defined coordinate system to the value of the 9 used joint parameters. As schematically represented in Fig. 1, the procedure is applied to the I, M, R and L fingers. Each joint is herein modelled as a revolute (rev - enabling only FE motion) or a universal (uni - enabling both FE and AA motions) one, with the fingertip TIP being fixed. The model of the bones, implemented in ROS, is adapted from [3]. Consistently with [3], the center of rotation of each joint is located slightly below the root of the corresponding phalange, since the articulate surface of the latter dictates the radius of the cylinder fitted to it. In Fig. 1 is depicted the sample cylinder for the T MCP joint. The kinematic tree is then described using 6 'virtual' links, corresponding to the joints. The addition of the inclination angles $\beta_{i=1...4}$ of the fingers increases then slightly the complexity of the model, but improves considerably its positioning accuracy. Symbolic computing in Python [8] is finally used to implement the modified DH parameters proposed in [5].

3. Results and validation

To validate the errors, the inclination angles are measured on the I finger in its neutral position using the musculoskeletal model [3]. The inclinations are: $\beta_1 = 2°$; $\beta_2 = 0°$; $\beta_3 = 7°$; $\beta_4 = -3°$. Although the phalange lengths do not match exactly the distances between the neighbouring rotation centres, they can be used to increase model's applicability, as it is time consuming to measure the exact distances for each subject. The relations and hand lengths given in [2] can then be used to obtain all the 19 phalange lengths. Using the proposed model and the listed parameters, two metrics are thus used: the absolute error (AE), defined as the Euclidean distance between two points in space (with and without the inclination angles), and the relative error (RE), obtained as AE scaled to the total finger length.

The model is evaluated over a grid of unconstrained joints (CMC FE, MCP FE and MCP AA), and the analysis-of-variance (ANOVA) is performed on the resulting errors, including also joint and grasp types as well as a sex partition. It is therefore shown that AE is affected by MCP FE, joint and grasp type, as well as sex, while sex has no significant effect on RE (Fig. 2). The AE metric for male subjects (dash-dotted line) is slightly larger than that of females (continuous line). AE is also slightly larger in the case of the circular grasps for the DIP (max. 4.5 mm) and TIP (max. 5.1 mm) joints. MCP AE (max. 2.5 mm) remains constant, while PIP AE (max. 3.9 mm) decreases with the variation of MCP. DIP and TIP AE maintain an increasing trend. In all the cases, RE has a similar trend as AE, with both values remaining constant for MCP (1.6 % of the total finger length), varying from 1.8 – 2.3 % for PIP, 1.1 – 2.9 % for DIP and 0.7 – 3.3 % for TIP.

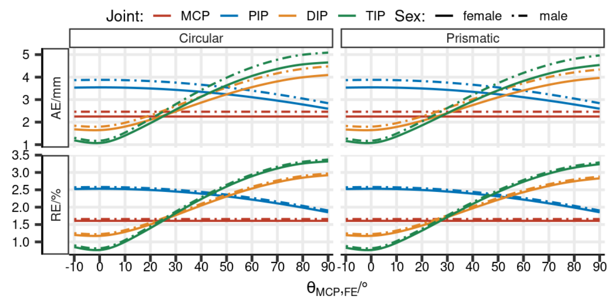

Figure 2. Relative and absolute errors between the models with and without the finger inclination angles

4. Conclusions and outlook

A modular grasp-oriented simplified hand kinematics model is developed and implemented in this work in the ROS environment. The number of parameters needed for the kinematic description is herein reduced from 8 to 5 only, presenting a valid compromise between the complex and the oversimplified kinematic models. The intended use of the model is in automated rehabilitation therapy of specific grasp types. Compared to the 9 DOFs model available in literature [4], the proposed model results in a relative positioning accuracy improvement of up to 3.3 % of the total finger length.

In future work, a systematic study aimed at describing and further simplifying thumb kinematics, while defining additional constraints for different grasp types, as well as additional parametrisations of hand inclination angles, will be performed.

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