Development and Evaluation of a 25-Degree of Freedom Hand Kinematic Model

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ABSTRACT

The human hand is a complex interface, able to perform various tasks, such as grasping, communicating, etc. In this paper, a 25-degree of freedom (DOF) hand model was proposed. The Denavit-Hartenberg (D-H) method was used to establish the transformation between joint angles and fingertip positions. The forward kinematics (FK) method was used to position the hand model, i.e., given the joint angles, to determine the fingertip position. In the model, the bone lengths were predicted as proportion of hand length. The model was evaluated against data from an experiment in with a 3D motion capture system was used to measure hand postures and positions of 5 participants for grasping two cylinders with different diameters. The mean and standard deviation values of the prediction error were reported. Potential applications of this research include ergonomic design of hand-held devices and evaluation of hand musculoskeletal disorders.

Keyword: Hand kinematic model, Forward kinematics, Hand anthropometry, 3D motion capture system

1. Introduction

The human hand is a complex interface for humans to perform numerous tasks in everyday life, such as object grasping, musical instrument playing, communicating, etc. In the virtual environment, the human hand needs to play a similar role as in the real world. Therefore, a scalable and accurate virtual human hand has been needed for applications in 3D computer-aided ergonomic design, medical simulation, virtual reality, and computer games.

Modeling the human hand is difficult due to its complicated shape and structure and high degrees of freedom. Several hand models have been developed. Rijpkema et al. [1] presented their hand model (Fig. 1a). However, the model is not accurate because it leaned on superficial anatomical assumptions and did not consider the hand anthropometry properly. Some simulation software using digital human hand models have been commercialized [2] (Fig. 1b). However, the hand models included in the human models of such software do not necessarily satisfy with desired accuracy and size variation of human hands. Recently, Pitarch et al. [3] developed a 25-DOF hand model (Fig. 1c). They used the hand anthropometric data from Buchholz et al. [4] which was based on 6 hands and therefore not representative.

According to the deficiencies of previous models, the main purpose of this study is to develop a scalable and necessarily accurate hand kinematic model. The secondary purpose is to evaluate our model against the data from an experiment in which a 3D motion capture system is used to measure hand postures and positions.

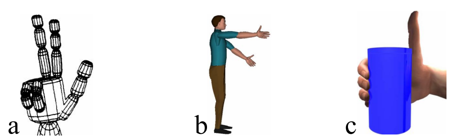

Fig. 1a-c. Various hand models

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2. Methods

2.1 Hand Model

The hand was represented by a rigid linkage system incorporating 25 DOFs shown in Fig. 2: 1 DOF each at the nine interphalangeal (IP) joints, 2 DOFs each at the five metacarpophalangeal (MCP) joints, 3 DOFs at the carpometacarpal (CMC) joint of the thumb, and 3 DOFs at the wrist. In this paper, we adopted the hand anthropometric data reported by Greiner [5] which was based on 59 male hands.

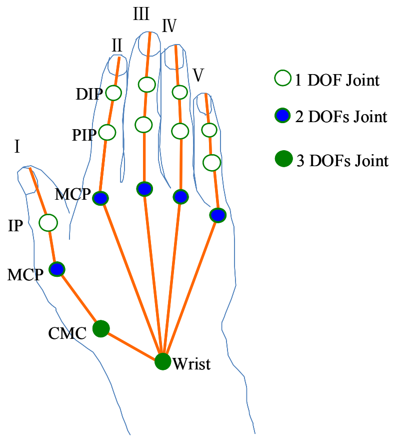

Fig. 2. Hand degrees of freedom

2.2 Forward Kinematics

With the forward kinematics, given the hand posture, i.e. joint angles, we can know the fingertip position. In our model, the D-H method Denavit et al. [6] was used to establish the transformation between joint angles and fingertip position. Take the index finger for example. Fig. 4 shows the sketch of D-H method and Table 1 shows the D-H parameters.

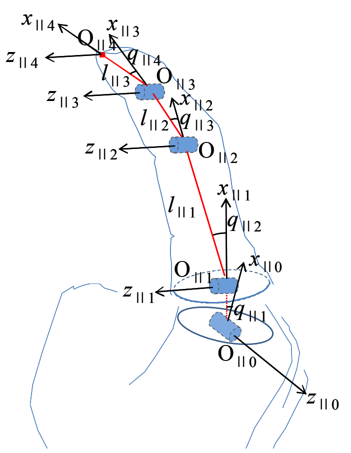

Fig. 3. Model for the index finger

Table 1. D-H parameters

	q_{IIj}	d_{IIj}	a_{IIj}	α_{IIj}
1	q_{II1}	0	0	$-\pi/2$
2	q_{II2}	0	l_{II1}	0
3	q_{II3}	0	l_{II2}	0
4	q_{II4}	0	l_{II2}	0

After we get the position of fingertip $\mathbf{P}_{II0}$ in local coordinate system $\mathbf{O}_{II0}$, we need to transform it to global coordinate system. We have the transformation matrix defined by

$$\mathbf{H}_{II} = \begin{bmatrix} 0 & 1 & 0 & l_{II0}\sin\gamma_{II} \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & l_{II0}\cos\gamma_{II} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where γ_{II} is the angle between ray II and the global z axis shown in Fig. 5.

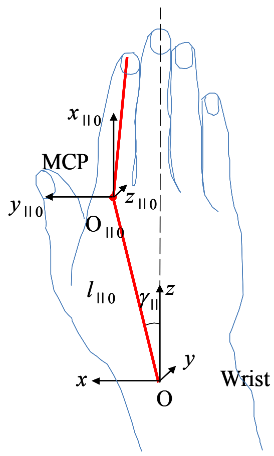

Fig. 4. Global and local coordinates

Therefore, the position vector with respect to the global coordinate system **O**, denoted by $\mathbf{P}_{II}$, is defined by

$$\begin{bmatrix} \mathbf{P}_{II} \\ 1 \end{bmatrix} = \mathbf{H}_{II} \begin{bmatrix} \mathbf{P}_{II0} \\ 1 \end{bmatrix} \quad (1)$$

2.3 Participants

Five participants (male and right-handed) were recruited and reported no history of hand or wrist injuries. Table 2 provides the demographics for the participants.

Table 2. Participant demographics

	Mean (SD)	Range	
		Minimum	Maximum
Age	26.4 (2.1)	24	29
Hand Length (cm)	19.2 (10.1)	17.8	20.6
Hand Width (cm)	9.0 (5.1)	8.4	9.8

2.4 Apparatus

An optoelectronic motion capture system (Motion Analysis Cor. CA USA) was used to capture the hand postures and fingertip position. Six Eagle Digital Cameras were used in the system. Twenty-seven passive markers, with diameter of 7 mm were attached on the dorsal surface of the hand as described in Fig. 5.

(Fig. 5)

2.5 Experimental design

Participants were asked to sit upright in a chair next to a table with the forearms midway between pronation and supination on the table. The elbow was flexed to 90 degrees. The wrist was kept in neutral. Marker coordinates were acquired for 3 s during two static position of the hand shown in Fig. 6.

a  b 

Fig. 7a. Hand grasping a cylinder with a diameter of 40mm.

Fig. 7b. Hand grasping a cylinder with a diameter of 50mm

2.6 Evaluation of the Hand Model

The joint angles and fingertip positions were obtained from the experiment. The measured joint angles were inputted into our model to get the predicted fingertip positions. Then the distance between the predicted fingertip positions and measured fingertip positions were calculated to obtain the prediction error of the hand model.

3. Evaluation Results

For postures of gripping the smaller cylinder (D = 40 mm), the grand mean value of the prediction error is 18. 57 mm. For the larger cylinder (D = 50 mm), the grand mean is 15.34 mm, which is smaller than the smaller cylinder. The model is proved to be necessarily accurate.

4. Discussion

This work aimed to develop a scalable and necessarily accurate 3D hand kinematic model and to evaluate the model. Our model is scalable since the bone lengths are predicted as proportion of hand length. And the prediction error of our model for predicting the position of the hand are less than 5 mm for gripping both of the two cylinders. That means the model is necessarily accurate. The model is practically useful in applications such as computer-assistant ergonomic design.

The error may be caused by several aspects. The variability of grip postures due to personal preferences is an inherent reason. Besides, the bone lengths are predicted as proportion of hand length. The deviation between the predicted hand bone lengths and measured bone lengths is inevitable.

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