

Development of a 25-DOF Hand Forward Kinematic Model Using Motion Data

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ABSTRACT

This paper describes the development of a 25-DOF hand forward kinematic model based on optical motion capture data. In the proposed model, an evolutionary strategy method (ESM)-based optimization algorithm is proposed to determine hand link lengths based on measured surface marker motions *in vivo*. The Denavit-Hartenberg (D-H) method was employed to predict fingertip positions given hand postures. To evaluate the proposed model, an experiment was conducted in which a 3D motion analysis system was employed to measure the 3D positions of spherical retro-reflective markers placed at the hand surface landmarks during grasping a ball with a diameter of 50 mm. The predicted fingertip positions by the model were compared with those measured by a motion capture system. Compared with the SANTOSTM hand model, the proposed model had a smaller grand mean value of fingertip position prediction error (5.8 mm for SANTOS and 2.7 mm for the proposed model). The proposed model can be applied to computer-aided ergonomic design of hand-held devices.

Keyword: Hand forward kinematic model, Motion capture, Hand link length, Fingertip position prediction

1. Introduction

3D digital hand models such as hand models in Jack[®] and RAMSIS[®] benefit the design of hand-held devices in terms of size and shape formation according to the grip posture of the hand models and time efficiency compared with the traditional product design process. With these hand models, design and evaluation of products (such as cell phone and handle of tools) can be easily fulfilled through effective prototyping and visualization and diagnosis of the fitness of an object to the hand in the product development process. The 3D computer-aided ergonomic design method using a hand model leads to the iterative process of design evaluation, diagnosis, and redesign more rapid and economical (Chaffin, 2001; Jung et al., 2009).

Modeling the hand in a kinematic way is hard due to the difficulty of hand link length (HLL) estimation. To estimate HLLs, two types of different approaches (*in vitro* and *in vivo*) have been used. *In vitro* studies, the researchers tried to find the relationship between HLLs and surface hand anthropometric sizes such as hand length and width. For example, Buchholz et al. (1992) developed regression models to estimate HLLs based on the surface hand dimensions by an *in vitro* study.

On the other hand, *in vivo* study, motion capture systems were used for estimating HLLs. Silaghi et al. (1998) proposed an optimization method that minimizes the inconsistency of marker defined link model over the human body motion to calculate the posture of the

internal body linkage. If the accuracy of HLLs is not important, this approach can be performed. However, in case of hand with high degrees of freedom in a small motion space, posture estimation can fail to converge in the aforementioned optimization process (Miyata et al., 2004). Halvorsen et al. (1999) proposed a method to derive the joint center of rotation (COR) from the relative movement of adjacent segments. This method provides relatively accurate hand link lengths through a calibration motion. However, the method demands at least three markers at each target joint. In this case, occlusion is often caused by other part of the hand since adjacent fingers always move in the neighborhood of each other. An increase in the number of markers at the target joint often leads to frequent failure of motion capture and relatively large error in captured marker position, making the estimation of hand link lengths an ill-posed problem (Miyata et al., 2004; Zhang et al., 2003).

Furthermore, in motion capture approach, Zhang et al. (2003) have made improvements. They suggested a minimal set of surface markers which offers consistency and simplicity and maximizes the marker separation for motion capture. They proposed an analytical method to determine the hand joint CORs from 21 surface markers during finger flexion-extension movements. However, the major limitation of the method is the reliability that there might be different solutions under the same condition due to local minima in the cost function (Chang and Pollard, 2007).

Therefore, the purposes of this paper are to (1) propose an optimization method for the estimation of HLLs based on surface measurement, (2) develop a 25-DOF hand forward kinematic model based on the estimated hand link lengths and (3) evaluate the proposed model using actual motion capture data.

2. Development of the Model

2.1 Hand Link Structure

As shown in Figure 1, the kinematic hand of this study is modeled as a rigid linkage system which has 25 degrees of freedom (DOFs). The wrist joint and the carpometacarpal (CMC) joint of the thumb have 3 DOFs (flexion-extension (f-e), abduction-adduction (ab-ad), and pronation-supination (p-s)) each. The five metacarpophalangeal (MCP) joints have 2 DOFs (f-e and ab-ad) each. Lastly, the nine interphalangeal (IP) joints have 1 DOF (f-e) each.

2.2 Estimation of Hand Link Lengths

The geometric relationship between the surface markers and the joint CORs was established to estimate HLLs (Figure 2). In Figure 2, M_{FT} , M_{DIP} , M_{PIP} , M_{MCP} , and M_{Wrist} denote the surface markers positioned at the landmarks of fingertip (FT), distal interphalangeal (DIP), proximal interphalangeal (PIP), MCP, and wrist; $\vec{l}_{i,0}$ is the vector from the wrist joint to MCP joint, $\vec{l}_{i,1}$ the vector from MCP to PIP, $\vec{l}_{i,2}$ the vector from PIP to DIP, and $\vec{l}_{i,3}$ the vector from DIP to FT at digit i , $i = II, III, IV, V$; $\vec{L}_{i,0}$ is the vector from M_{Wrist} to M_{MCP} , $\vec{L}_{i,1}$ the vector from M_{MCP} to M_{PIP} , $\vec{L}_{i,2}$ the vector from M_{PIP} to M_{DIP} , $\vec{L}_{i,3}$ the vector from M_{DIP} to M_{FT} ; $\vec{D}_{i,0}$ is the vector from M_{Wrist} to the wrist joint COR, $\vec{D}_{i,1}$ the vector from M_{MCP} to MCP joint, $\vec{D}_{i,2}$ the vector from M_{PIP} to PIP joint, and $\vec{D}_{i,3}$ the vector from M_{DIP} to DIP joint.

Since the hand was represented by a rigid linkage system, we assume that the hand link vector $\vec{l}_{i,k}$ does not change its length during hand movement whereas the surface link vector $\vec{L}_{i,k}$ does. The vector $\vec{D}_{i,m}$ also maintains a constant length during hand movement. Therefore, the optimization routine minimizes the variation of hand link lengths and depths from surface markers to joint CORs through determination of hand link length $\|\vec{l}_{i,k}\|$ during the entire hand movement:

$$C_i = \sum_{t=1}^T \left\{ \sum_{k=0}^3 \left[\|\vec{l}_{i,k}(t)\| - \|\vec{l}_{i,k}\| \right]^2 + \sum_{m=0}^3 \left[\|\vec{D}_{i,m}(t)\| - \|\vec{D}_{i,m}\| \right]^2 \right\},$$

$i = II, III, IV, V$ (1)

where $\|\vec{l}_{i,k}(t)\|$ is the hand link length at time frame t , and $\|\vec{l}_{i,k}\|$ is the optimized hand link length; $\|\vec{D}_{i,m}(t)\|$ is the depth from surface marker to joint COR at time frame t ,

and $\|\vec{D}_{i,m}\|$ is the optimized depth.

2.3 Forward Kinematics Algorithm

The fingertip positions can be predicted by a forward kinematics algorithm given the hand postures (e.g., joint angles). In the proposed hand model, the D-H method was applied to establish the transformation between joint angles and fingertip positions. Figure 3 shows the sketch of D-H method and Table 1 shows the D-H parameters for the index finger. The parameter d_{IIj} denotes the link offset from origin O_{IIj-1} to axis x_{IIj} along axis z_{IIj-1} at digit II; a_{IIj} denotes the link length between axes z_{IIj-1} and z_{IIj} along axis x_{IIj} ; α_{IIj} denotes the link-twist angle from z_{IIj-1} to z_{IIj} , $j = 1 \dots 4$; q_{II1} denotes the ab-ad angle of the MCP joint, q_{II2} the f-e angle of the MCP joint, q_{II3} the f-e angle of the PIP joint, and q_{II4} the f-e angle of the DIP joint; and l_{II1} denotes the proximal phalanx link length, l_{II2} the medial phalanx link length, and l_{II3} the distal phalanx link length.

The capitate bone (phalanx center) was selected as the origin of the global coordinate system of the hand model (Miyata et al., 2004). The origin of the local coordinate system at the i th digit ($i = II, III, IV, V$) was located at the COR of the i th MCP joint.

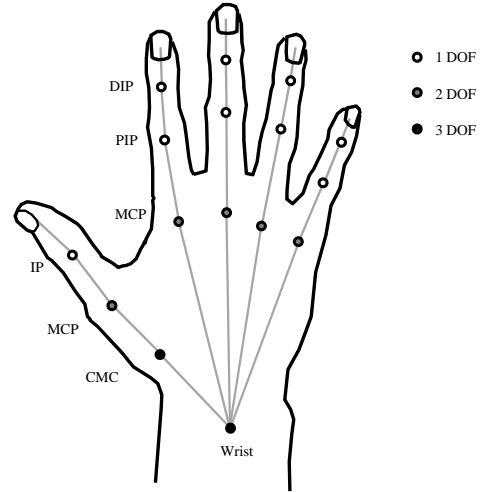


Figure 1. Hand link structure

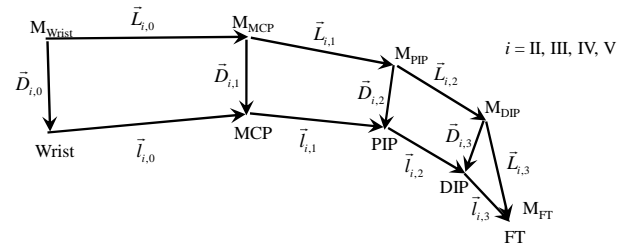


Figure 2. Geometric relationship between surface markers and joint CORs

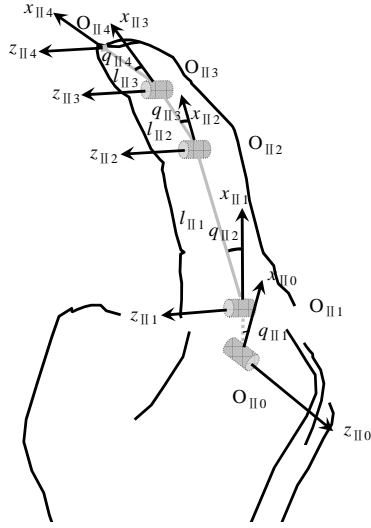


Figure 3. D-H notations for the index finger (digit II)

Table 1. D-H parameters for the index finger (digit II)

	q_{IIi}	d_{IIi}	a_{IIi}	α_{IIi}
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_{II3}	0

3. Evaluation of the model

An experiment, in which cylindrical grip motions were captured by a motion analysis system, was conducted to estimate hand link lengths and evaluate the proposed hand forward kinematic model. The proposed experiment protocol includes participants, apparatus, and experimental design. After the experiment, the proposed model was evaluated based on the actual motion capture data.

3.1 Participants

Five right-handed male participants (age: mean = 26.3 years, SD = 2.1) with no history of hand and wrist injuries were participated. Their hand lengths—distance from the distal crease at the wrist to the tip of the middle finger on the palmar side of the right hand—ranged from 178 to 206 mm. The average (SD) of hand lengths for the participants was 192 (10.1) mm which is similar to the mean (186 mm) and SD (8.2 mm) of the Size Korea data (SizeKorea, 2004).

3.2 Apparatus

Reflective markers ($d = 5$ mm) were attached on the dorsal side of each participant's right hand as shown in Figure 4. The Hawk motion capture system (Motion



Figure 4. Marker set protocol

Analysis Co., USA) with six cameras was used to record the three-dimensional positions of the markers at a sampling frequency of 60 Hz during grasping a ball ($\phi = 50$ mm).

3.3 Experimental Design

Participants were asked to grasp a ball with the right hand. The participants were seated with the torso upright, the right upper arm approximately vertical and forearm midway between pronation and supination on the arm rest of the seat. The participants began the motion with the right fingers in a natural full extension, and the wrist in neutral position. In addition, the participants were asked to keep the wrist not moving during grasping motions and instructed to perform a comfortable grip. Sufficient practice was allowed before actual motion was captured.

3.4 Model Evaluation

To evaluate the model, the predicted fingertip position by the proposed model was compared with the measured fingertip positions from the motion capture data. The distance between the predicted fingertip position and measured fingertip position was calculated to obtain the fingertip position prediction error of the model. Furthermore, the performance of the model was compared with the SANTOS™ hand in terms of fingertip position prediction error.

4. Results

Table 2 shows the mean (SD) value of the fingertip position prediction errors by the proposed model and the SANTOS™ hand. The prediction errors were larger at the middle and ring fingers than the other ones. Furthermore, the grand mean of prediction error of the proposed method was 2.7 mm, which was smaller than that of the SANTOS™ hand (5.8 mm). Lastly, the SD of the prediction error at the middle finger was the largest

and then tended to decrease at the other fingers.

Table 2. Mean (SD) value (mm) of the fingertip position prediction error by the proposed model and the SANTOS™ hand developed by Peña-Pitarch et al. (2005)

Hand model	Index	Middle	Ring	little
Proposed model	2.2 (2.5)	3.6 (3.2)	3.1 (2.8)	1.8 (1.5)
SANTOS™ hand	5.4 (3.2)	6.3 (3.7)	5.7 (1.5)	5.9 (1.3)

5. Discussion

This study aimed to develop an ESM-based optimization method for estimating hand link lengths based on surface measurement, establish a protocol for hand forward kinematic modeling, and evaluate the proposed model. The rigid linkage representation of the hand and an optical motion capture system for in vivo human hand motion studies (Chiu et al., 1998, 2000; Somia et al., 1998) allowed us to develop an optimization procedure for estimating hand link lengths with the objective function of minimizing the variations of hand link lengths and the depths from surface markers to joint CORs during the entire ball grasping motion. To avoid local minima in the cost function, a genetic algorithm (an evolutionary strategy method) was employed. Based on the estimated hand link lengths, the anatomical study of the hand joints, and the implementation of a forward kinematics algorithm, a 25-DOF hand forward kinematic model was developed. Lastly, the model was evaluated by comparison with the SANTOS™ hand model in terms of fingertip position prediction error. The proposed model can be applied to computer-aided ergonomic design of hand-held devices.

The smaller value of the grand mean of the fingertip position prediction error of the proposed model (2.7 mm), compared with the SANTOS™ hand (5.8 mm), demonstrates its better accuracy. The result might be due to the different methods used to estimate hand link lengths in the two models, since the link lengths dramatically affect the performance of hand model. The SANTOS™ hand adopted the regression equations of link lengths onto hand surface dimensions proposed by Buchholz et al. (1992), which was based on a small sample size (two female and four male hands).

We noticed that the proposed optimization method has larger prediction errors at the middle and ring fingers than the other fingers. Furthermore, the degrees of dispersion of prediction errors at the middle and ring fingers are higher than the other fingers. These results

might be related to the different finger lengths at different fingers.

The future work includes the development of a hand inverse kinematic model for predicting hand postures given fingertip positions.

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