Development of an Optimization Method for Determining Human Hand Link Lengths Based on Surface Measurement

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Determining internal hand link lengths accurately is necessary in hand modeling for the application of ergonomic design and evaluation in virtual environment. Misconceived or cursory estimation of hand link lengths is however not rare in literature or practice. This article describes an optimization method for deriving hand link lengths from measured surface maker data. The method employs an optimization routine which minimizes the variations of hand link length and the depth from surface marker to joint center simultaneously during the hand grasping motion. To test the proposed method, an experiment was conducted, in which a 3D optoelectronic motion capture system was utilized to measure hand and finger positions of 18 male participants for grasping two different cylinders. The grand mean of the Root-mean-square (RMS) differences between link lengths estimated by the proposed method for larger cylinder (d = 50 mm) and smaller cylinder (d = 30 mm) was 1.7 mm. The grand mean of RMS differences between link lengths estimated by the proposed method and regression method of Buchholz et al. (1992) was 3.0 mm. The grand mean of RMS differences between estimated wrist-to-fingertip (WTF) lengths by the proposed method and calculated WTF lengths by motion data was 4.7 mm, which was smaller than the grand mean of RMS differences of WTF lengths estimated by the regression method (9.1 mm). The proposed optimization method can estimate hand link lengths based on surface measurements and be utilized in human hand modeling required in the fields such as ergonomics, medical science.

INTRODUCTION

Human hand modeling is required in many fields such as ergonomics, biomechanics, robotics, medical science. To measure the human hand motion, optical motion capture systems are usually used for capturing hand movements. The motion capture systems require markers to be attached to the bony landmarks on the surface of the hand. Current motion capture systems are usually able to construct and display a linkage model of the surface markers. However, the link model does not represent the underlying human skeletal structure since the link represents the line between markers attached to the surface of the hand.

To estimate the hand link length, two types of different approaches (in vitro and in vivo) have been used. In vitro studies, the researchers tried to find the relationship between the hand link length and the surface hand anthropometric sizes such as hand length and width. For example, Buchholz et al. (1992) developed regression models to estimate the hand link lengths 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 the hand link length. Silaghi et al. (1998) proposed an optimization method that minimizes the inconsistency of the marker defined link model over the hand motion to calculate the posture of the internal hand linkage. If the accuracy of the hand link lengths is not important, this approach can be performed. However, in the case of hand with high degrees of freedom in very small space, posture estimation can fail to converge in the above 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 the 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).

In motion capture approach, Zhang et al. (2003) have made great 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 optimization algorithm to determine the hand joint centers of rotation based on surface measurement. However, their objective function only considered the variation of the hand link length and the algorithm did not distinguish the difference between the surface marker position and the distal phalanx tip (DPT) position. Furthermore, they did not provide convictive proofs of the validity of the algorithm.

The purposes of this paper are to (1) propose an optimization method for the estimation of the hand link lengths based on surface measurement and (2) evaluate the proposed method. The optimization procedure minimizes the variations of hand link length and the depth from surface marker to joint COR during the entire hand grasping motion. A three-step evaluation process was developed to validate the proposed optimization method.

PROPOSED OPTIMIZATION METHOD FOR ESTIMATING HAND LINK LENGTHS

Kinematic model of the hand

The kinematic hand of the present study was defined as a rigid linkage system including 25 degrees of freedom (DOFs) by referring Yang et al. (2008). As illustrated in Figure 1, the nine interphalangeal (IP) joints have 1 DOF (flexion-extension (f-e)) each, and the five metacarpophalangeal (MCP) joints have 2 DOFs (f-e, abduction-adduction (ab-ad)) each. Lastly, the carpometacarpal (CMC) joint of the thumb and the wrist joint have 3 DOFs (f-e, ab-ad, pronation-supination (p-s)) each.

The fingertip position can be estimated by forward kinematics with the given hand and finger posture (e.g., joint angles). In the proposed hand model, the Denavit-Hartenberg (D-H) method (Denavit et al., 1955) was applied to establish the transformation between joint angles and fingertip position. Figure 2 shows the sketch of D-H method and Table 1 shows the D-H parameters for the index finger. Parameter d_{IIj} denotes the link offset from origin O_{IIj-1} to axis x_{IIj} along axis z_{IIj-1}; 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…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 proximal interphalangeal (PIP) joint, and q_{II4} the f-e angle of the distal interphalangeal (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 (wrist 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 ith finger (i = II, III, IV, V) was located at the center of rotation (COR) of the ith MCP joint. The transformation from the local coordinate system to the global coordinate system for the index finger is described in Eq. (1):

$$\begin{bmatrix} \mathbf{P}_{II} \\ 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & l_{II0}\sin\gamma_{II} \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & l_{II0}\cos\gamma_{II} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{P}_{II0} \\ 1 \end{bmatrix} \quad (1)$$

where $\mathbf{P}_{II}$ is the index fingertip postion with respect to (wrt) the global coordinate system, and $\mathbf{P}_{II0}$ the index fingertip postion wrt the local coordinate system; l_{II0} denotes the distance between MCP of the index finger and the wrist joint, and γ_{II} is the angle between the metacarpal of the index finger and the z axis of the global coordinate system (Figure 3). The origin of the local coordinate system of the thumb was positioned to the COR of the CMC joint.

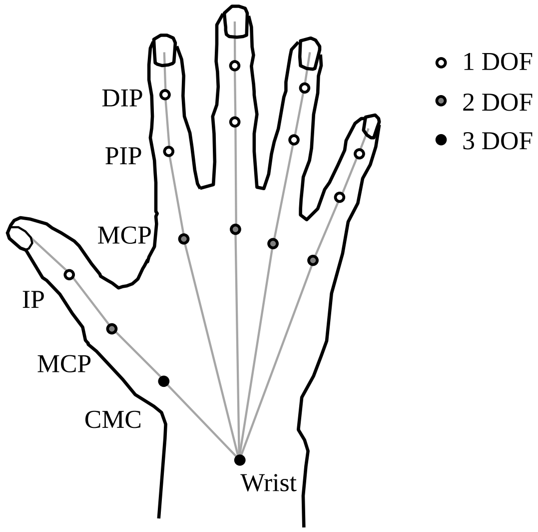

Figure 1. Hand kinematic model

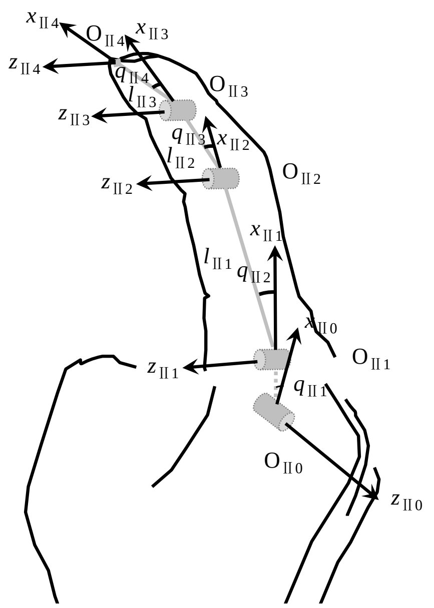

Figure 2. D-H notations for the index finger (digit II)

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

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

Optimization method for estimating hand link lengths

In order to estimate the hand link length, an optimization model was established to represent the geometric relationship between the surface markers and joint centers of rotation as shown in Figure 4. In the optimization model, M_{FT}, M_{DIP}, M_{PIP}, M_{MCP}, and M_{Wrist} denote the surface markers positioned at the landmarks of fingertip (FT), DIP, PIP, MCP and wrist joint; $\vec{l}_{i,0}$ 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 PIP to DIP, and $\vec{l}_{i,3}$ the vector from DIP to the distal phalanx tip (DPT) 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} at digit i; $\vec{D}_{i,0}$ is the vector from M_{Wrist} to the wrist joint, $\vec{D}_{i,1}$ the vector from M_{MCP} to MCP, $\vec{D}_{i,2}$ the vector from M_{PIP} to PIP, $\vec{D}_{i,3}$ the vector from M_{DIP} to DIP, and $\vec{D}_{i,4}$ the vector from M_{FT} to DPT at digit i. 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 marker to joint COR through determination of $\left\|\vec{l}_{i,k}\right\|$ (i = II, III, IV, V; k = 0…3) during the entire hand movement:

$$C_i = \sum_{t=1}^{T}\left\{\sum_{k=0}^{3}\left[\left\|\vec{l}_{i,k}(t)\right\| - \left\|\vec{l}_{i,k}\right\|\right]^2 + \sum_{m=0}^{4}\left[\left\|\vec{D}_{i,m}(t)\right\| - \left\|\vec{D}_{i,m}\right\|\right]^2\right\}$$

$$i = \text{II, III, IV, V} \qquad (2)$$

where $\left\|\vec{l}_{i,k}(t)\right\|$ is the hand link length at time frame t, and $\left\|\vec{l}_{i,k}\right\|$ is the optimized hand link length, k = 0…3; $\left\|\vec{D}_{i,m}(t)\right\|$ is the depth from surface marker to joint COR at time frame t, and $\left\|\vec{D}_{i,m}\right\|$ is the optimized depth, m = 0…4.

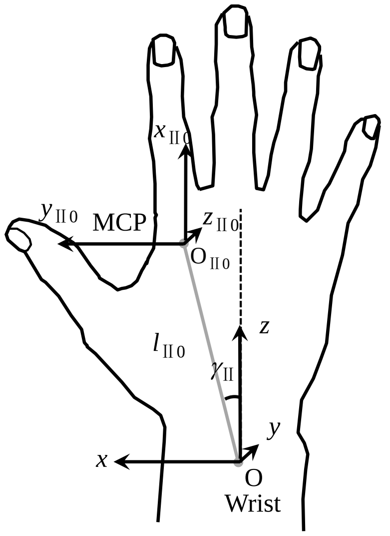

Figure 3. Relationship between the global coordinate system and the local coordinate system of the index finger

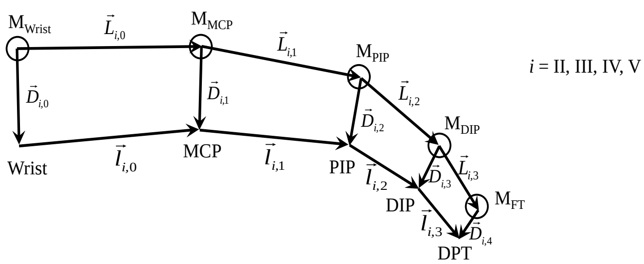

Figure 4. Geometric relationship between surface markers and internal joint centers

MATERIALS AND METHODS

Participants

Eighteen right-handed male participants (mean age: 26.3 yrs, SD: 2.1 yrs) 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 mm 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).

Apparatus

Reflective markers (d = 5 mm) were attached on the dorsal side of each participant's right hand as shown in Figure 5. A Hawk motion capture system with six cameras (Motion Analysis Co., USA) as displayed in Figure 6 recorded the three-dimensional positions of the markers at a sampling frequency of 60 Hz during cylinder grasping motions. The mean distance from the seat to each camera was 180 mm. The cameras were installed at different heights from floor to minimize marker loss during hand motions.

Experimental design

Participants were asked to perform right-hand motion of grasping two cylindrical handles (d = 30 mm and 50 mm). The participants were seated with the torso upright, the right upper arm approximately vertical and forearm midway (90°) between pronation and supination on a table. The heights of the seat and table were separately adjustable. Both of the cylindrical handles were 150 mm tall and attached to a supporting base whose height was adjustable and set approximately even with the table. 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 the actual motion was captured.

Figure 5. Marker set for hand motion capture

Figure 6. Experimental setup for motion capture

Evaluation

To validate the proposed optimization method, the present study compared three pairs of differences. First, the link length differences estimated by the proposed method for the two-cylinder grasping were compared. Second, the differences between link lengths estimated by the proposed method and regression method provided in Buchholz et al. (1992) were evaluated. Lastly, the differences between fingertip position estimated by the proposed method and fingertip position measured by the motion capture data were compared. Root-mean-square (RMS) values were computed to quantify these differences.

RESULTS

The RMS values of the differences between hand link lengths, estimated by the proposed optimization method, for the two grasping motions were displayed in Table 2. The maximum of the RMS difference (2.4 mm) was shown at the MCP-to-PIP link and DIP-to-Tip link of the little finger. The grand mean of the RMS differences across all joints was 1.7 mm.

The RMS differences between hand link lengths estimated by the proposed method and regression method were presented in Table 3. The maximum of the RMS difference (5.4 mm) was shown at the Wrist-to-MCP link of the ring finger. The grand mean of the differences across all joints was 3.0 mm.

The RMS errors of the fingertip positions predicted by the D-H model with the hand link lengths estimated by the proposed method and the regression method were shown in Table 4. The position errors, Euclidian distance between predicted position and measured position from motion data, were larger at the index and middle fingers than the other fingers. The grand mean of the position errors of the proposed method was 4.7 mm, which was smaller than the grand mean of the errors of the regression method (9.1 mm). The sign of mean of the position errors in Table 5 indicated a certain pattern of bias. The two methods consistently overrated the fingertip positions at the index and middle fingers, while the methods consistently underrated the fingertip positions at the ring and little fingers. Lastly, the SD of the position errors was the largest at the index finger and then tended to decease to the little finger.

Table 2. RMS differences between hand link lengths for the larger and smaller cylinders estimated by the proposed method

Digit	RMS differences (larger – smaller; mm)			
	Wrist-MCP	MCP-PIP	PIP-DIP	DIP-Tip
Index	2.2	1.8	1.7	1.6
Middle	0.8	1.4	1.4	1.6
Ring	1.2	1.7	1.3	1.7
Little	1.7	2.4	1.7	2.4

Table 3. RMS differences of hand link lengths estimated by the proposed optimization method and the regression method of Buchholz et al. (1992).

Digit	RMS differences (proposed – regression; mm)			
	Wrist-MCP	MCP-PIP	PIP-DIP	DIP-Tip
Index	3.1	2.1	2.4	3.3
Middle	1.9	3.8	3.8	2.4
Ring	5.4	2.2	3.3	2.7
Little	3.6	2.7	2.7	2.2

Table 4. RMS values (mm) of the errors of fingertip positions predicted by the proposed optimization method and regression method of Buchholz et al. (1992).

Method	Index	Middle	Ring	little
Optimization method	6.9	5.7	3.2	2.8
Regression method	12.5	11.1	6.8	5.8

Table 5. Mean (SD) (mm) of fingertip position errors by the proposed optimization method and regression method of Buchholz et al. (1992).

Method	Index	Middle	Ring	little
Optimization method	6.4 (3.3)	5.4 (2.2)	-2.8 (2.0)	-2.7 (0.8)
Regression method	12.4 (2.1)	11.0 (1.6)	-6.8 (0.5)	-5.8 (0.6)

DISCUSSION

This study aimed to develop an optimization method for estimating human hand link lengths based on surface measurement and to evaluate the optimization method. The rigid linkage representation of the human hand and the promise and efficiency of 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 with the objective function of minimizing the variations of hand link length and the depth from surface marker to joint COR during the entire hand grasping motion. A three-step evaluation process was developed to validate the proposed optimization. The proposed optimization method for estimating human hand link lengths can be applied to human hand modeling required in many fields such as ergonomics, medical science.

The small value of the grand mean of the RMS differences between hand link lengths for the larger and smaller cylinders, which is 1.7 mm, proves the reliability of the proposed optimization method. The comparison results between the hand link lengths estimated from the proposed optimization method and the regression method show no noticeable differences between them, except for the Wrist-to-MCP link of the ring finger. The large difference is most probably related to the methodology used to determine the anthropometric scaling factor which determines the Wrist-to-MCP link length of the ring finger according to the hand dimensions (hand length and width). The regression method utilized 2D X-ray images to describe the anatomy of the hand (Buchholz et al., 1992). The smaller prediction error of the proposed method proves its higher accuracy than the regression method.

We noticed that the proposed optimization method has larger prediction errors at the index and middle fingers than the other fingers. Furthermore, the degree of dispersion of prediction errors at the index and middle fingers is higher than the other fingers. These results might be related to the different finger lengths at different fingers. We also noticed that a certain pattern of bias exists in our model. As a future work, we will find the bias and eliminate it.

We also noticed that Zhang et al. (2003) proposed an optimization algorithm for determining the joint centers of rotation based on surface measurement. Compared with the previous algorithm, our optimization method is different in two aspects. We add another component, the variation of the depth from surface marker to the joint center of rotation to the objective function. Besides, we distinguish the deviation between the surface maker position and the distal phalanx tip (DPT) position. The comparison between the results of the two different optimization methods is needed.

REFERENCES

Buchholz, B., Armstrong, T. J. (1992). A kinematic model of the human hand to evaluate its prehensile capabilities. *Journal of Biomechanics* 25, 149-162.

Chiu, H. Y., Lin, S. C., Su, F. C., Wang, S. T., Hsu, H. Y. (2000). The use of the motion analysis system for evaluation of loss of movement in the finger. *Journal of Hand Surgery* 25B, 195-199.

Chiu, H. Y., Su, F. C., Wang, S. T., Hsu, H. Y. (1998). The motion analysis system and goniometry of the finger joints. *Journal of Hand Surgery* 23B, 788-791.

Denavit, J., Hartenberg, R. S. (1955). A kinematic notation for lower pair mechanisms based on matrices. *Journal of Applied Mechanics* 77, 215-221.

Halvorsen, K., Lesser, M., Lundberg, A. (1999). A new method for estimating the axis of rotation and the center of rotation. *Journal of Biomechanics* 32, 1221-1227.

Miyata, N., Kouchi, M., Kurihara, T., Mochimaru, M. (2004). Modeling of human hand link structure from optical motion capture data. In *Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, Sendai, Japan*.

Silaghi, M. C., Plankers, R., Boulic, R., Fua, P., Thalmann, D. (1998). Local and global skeleton fitting techniques for optical motion capture. *IFIP CapTech*'98, 26-40.

Somia, N., Rash, G. S., Wachowiak, M., Gupta, A. (1998). The initiation and sequence of digital joint motion: a three-dimensional motion analysis. *Journal of Hand Surgery* 23B, 792-795.

Yang, X., Park, J. Jung, K., You, H. (2008). Development and evaluation of a 25-degree of freedom hand kinematic model. In *Proceedings of the 2008 Fall Conference of the Ergonomics Society of Korea*.

Zhang, X., Lee, S. Braido, P. (2003). Determining finger segmental centers of rotation in flexion-extension based on surface marker measurement. *Journal of Biomechanics* 36, 1097-1102.

SizeKorea (2004). Korean anthropometric data. Available from http://sizekorea.kats.go.kr/