Estimation of Hand Joint Center of Rotation Using Surface Markers

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The present study estimated center of rotation (CoR) of a hand joint by the Delonge-Kasa method using an adjacent surface marker motion to the hand joint. The Delonge-Kasa method, originally proposed for CoR estimation of big joints that have a large range of motion is not suitable for estimation of hand joint CoRs due to a small range of motion at hand joints. The present study proposed to use the distal interphalangeal (DIP) marker motion to estimate the proximal interphalangeal (PIP) joint CoR instead of using its own marker motion because the DIP marker has a larger range of motion. The estimated CoR using DIP marker motion was more appropriate than using PIP marker motion. The average distance between PIP marker and the estimated CoR by DIP marker motion was 13.34 ± 0.97 mm, while the average distance between PIP marker and the estimated CoR by PIP marker motion was 4.21 ± 1.65 mm, which was obviously incorrect. The proposed method can be applied for hand joint CoR estimation to form a link model for ergonomic product design.

INTRODUCTION

Digital human hand modeling has been applied to clinical assessment of hand surgery, hand animation, hand anthropometry, and ergonomic product design. Hand kinematics has been analyzed and used to compare the changes of hand function before and after hand surgery (Duchenne and Kaplan, 1959; Landsmeer, 1963). Template modeling and skeletonization techniques based on 3D scanning of human body have been developed and applied to natural movement of human body (Anguelov et al., 2015; Ghosh et al., 2012; Le and Hodgins, 2016; Loper et al., 2014; Moccozet et al., 2004). Studies of analyzing shape changes according to various motions and postures have been conducted for ergonomic product design using digital human modeling techniques (Guan et al., 2012; Lee et al., 2013).

Hand link models can be derived by surface techniques with in-vivo hand movement data. Recently, surface techniques using marker and sensor adhered to palpable surface bony landmark are widely used to establish and visualize hand link models to analyze hand kinematics. But the link models generated by the surface techniques are regarded as not perfect rigid skeletal linkage (Zhang et al. 2003). To establish the optimal biomechanical hand structure, researches of finding joint center of rotation (CoR) between two adjacent hand segments were conducted (Cerveri et al., 2005; Ehrig et al., 2006; Gamage and Lasenby, 2002; Kasa, 1976; Knight and Semwal, 2007; Zhang et al., 2003; Veeger, 2000).

Existing CoR estimation methods are limited by complex computation, various assumptions, and data rectification. Daling et al. (1994) studied index finger motion with a motion analysis system by placing markers on the lateral side of the fingers which can result in unnatural hand gesture and interference between markers. Zhang et al. (2003) proposed a method to estimate CoRs by minimizing the displacement of hand links during a power grasp task using 21 markers attached to dorsal part of the hand joints. Ehrig et al. (2006) proposed a symmetrical CoR estimation (SCoRE) method to estimate the joint CoR using a sphere fit method which estimates the position of CoR with an initial guess of a few centimeters from the true center. Knight and Semwal (2007) proposed a generalized Delonge-Kasa method, an enhanced algorithm of Delonge-Kasa method with data rectification module, to minimize the systematic error of a least square function. However, their method was only suitable for large joints that have a large range of motion, such as leg, knee, and shoulder.

The present study estimated CoR of a hand joint from the motion of its adjacent surface marker captured by a motion analysis system by using the Delonge-Kasa method. An experiment was conducted to capture the motion of three retro-reflective markers attached to the dorsal part of the proximal interphalangeal (PIP), distal interphalangeal (DIP), and metacarpohalangeal (MCP) joints. CoR of the PIP joint was estimated using the motion of its own marker and that of its adjacent marker (DIP). The estimated CoRs were compared in terms of location and radius for accuracy assessment.

MATERIALS AND METHODS

Participants

One healthy male subject having no any neurological or musculoskeletal disorder in the hand participated in the study. The subject's age, body weight, and stature were 34 years, 68 kg, and 175 cm. Hand length, breadth, and hand depth at PIP joint of the index finger were measured as 185.7 mm, 79.5 mm, 15.0 mm (Figure 1).

Apparatus

In this study, a motion analysis system consisting of 5 infrared cameras (Motion Analysis Inc, USA) was used to capture the

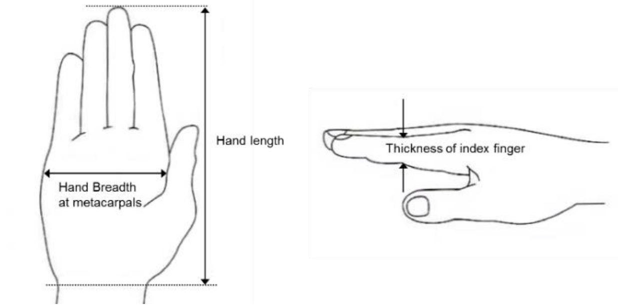

Figure 1. Hand dimension measurement

index finger motion at 60 Hz, as shown in Figure 2. Retro-reflective markers (Ø = 7 mm) were attached on the dorsal part of MCP, PIP, and DIP joints of the index finger.

Figure 2. Experimental setting with five infrared cameras for capturing hand motion and a chair with an arm supporter to fix the forearm and hand.

Experiment Procedure

After surface makers were attached at the bony landmarks of the MCP, PIP, and DIP joints of the participant, he was asked to naturally flex and extend the index finger three times. The motion of the index finger was captured by the motion analysis system.

Motion Data Processing

The motion data were transformed to the coordinate system as shown in Figure 3. The MCP marker was located at the origin of the coordinate system. The motion of the MCP marker was eliminated. The flexion/extension of the PIP and DIP joints occurred at the YZ plane.

Estimation of PIP Joint CoR of index finger

Delonge-Kasa estimator (Delonge, 1972; Kasa, 1976) was used to find the joint CoR (A, B) of the PIP joint. As shown in Figure 4, let (x_i, y_i) be the marker locations, the joint CoR (A, B) can be estimated by minimizing the difference between the squared distance of (x_i, y_i) to (A, B) and the squared radius (R) of the fitted circle over the trajectory of marker motion:

$$v = \sum_{i=1}^{N}[(x_i - A)^2 + (y_i - B)^2 - R^2]^2 = min \qquad (1)$$

Equation 1 can be solved by setting the derivatives to be

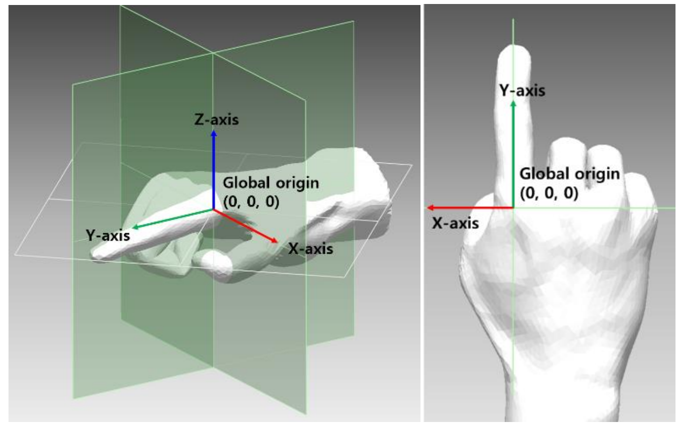

Figure 3. Coordinate system used for estimation of hand joint center of rotation

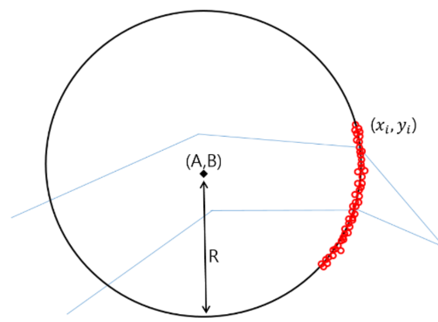

Figure 4. Circle fitting (radius: R) over the marker motion trajectory (x_i, y_i) to find joint center of rotation (A, B)

zero:

$$\frac{\partial v}{\partial A} = \frac{\partial v}{\partial B} = \frac{\partial v}{\partial R} = 0 \qquad (2)$$

$$\frac{\partial v}{\partial R} = \sum_{i=1}^{N}[(x_i - A)^2 + (y_i - B)^2 - R^2] = 0 \qquad (3)$$

$$\frac{\partial v}{\partial A} = \sum_{i=1}^{N}[(x_i - A)^2 x_i + (y_i - B)^2 x_i - R^2 x_i] = 0 \qquad (4)$$

$$\frac{\partial v}{\partial B} = \sum_{i=1}^{N}[(x_i - A)^2 y_i + (y_i - B)^2 y_i - R^2 y_i] = 0 \qquad (5)$$

After simplifications, the equations of each derivative function can be rewritten as a linear equation system for A, B and C, where C is a constant.

$$C = R^2 - A^2 - B^2 \qquad (6)$$

The linear equations are simply defined by using the classical Gaussian method.

$$A2\Sigma x_i + B2\Sigma y_i + CN = \Sigma({x_i}^2 + {y_i}^2) \qquad (7)$$

$$A2\Sigma {x_i}^2 + B2\Sigma x_i y_i + C\Sigma x_i = \Sigma({x_i}^3 + x_i {y_i}^2) \qquad (8)$$

$$A2\Sigma x_i y_i + B2\Sigma {y_i}^2 + C\Sigma y_i = \Sigma({y_i}^3 + y_i {x_i}^2) \quad (9)$$

The entire computation procedure was performed in MATLAB (The MathWorks, Inc., Natick, MA).

RESULTS

The present study found that the estimated PIP joint CoR using DIP marker motion was more appropriate than that using PIP marker motion. The average distance between the PIP marker and the estimated CoR using DIP marker motion was 13.34 ± 0.97 mm, while the average distance was 4.21 ±1.65 mm between PIP marker and the estimated CoR using PIP marker motion. The estimated CoR using PIP marker motion was obviously incorrect because the CoR was almost located at the surface of the PIP joint, as shown in Figure 5.

To validate the estimated PIP joint CoR, the depth of the PIP joint was measured using a digital caliper and the middle point of the depth of the PIP joint was considered as joint CoR. The distance between the PIP marker to the PIP joint CoR was measured as 12.49 mm which was similar to the estimated distance between the PIP marker and the estimated CoR using DIP marker motion (13.34 ± 0.97 mm).

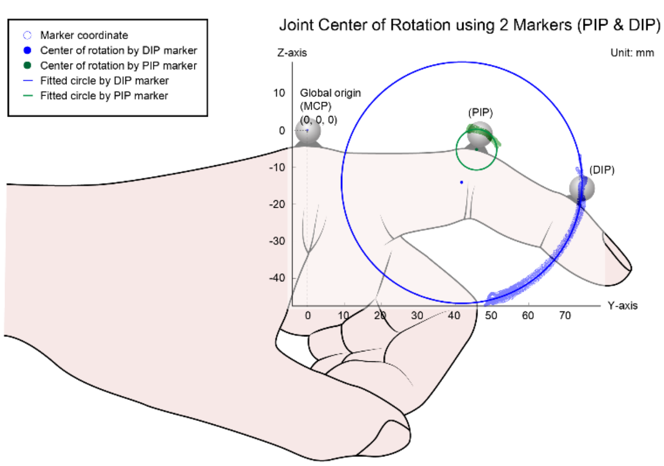

Figure 5. Estimated joint center of rotation positions from of the proximal interphalangeal (PIP), and distal interphalangeal (DIP) marker motion (PIP: green, DIP: blue)

DISCUSSION

The present study used Delonge-Kasa method to estimate the PIP joint CoR by a sphere fitting method with its adjacent marker (DIP) on the hand. The study suggested using DIP marker motion instead of PIP marker motion for a more appropriate PIP joint CoR estimation. Our method did not require any initial guess to estimate joint CoR and its computation is simpler compared to the existing methods. Ehrig et al. (2006)'s method required an initial guess of the joint CoR a few centimeters away from the true center. Zhang et al. (2003)'s method required a complex computation process due to a highly nonlinearity of their cost function.

The Delonge-Kasa method that was originally proposed for estimation of CoRs of big joints was extended to the hand joints that have small range of motion by using adjacent marker motion instead of their own marker motion in this study. The present study found that the PIP marker showed a small range of motion around the PIP joint CoR during flexion/extension of the PIP joint. On the other hand, the DIP marker showed a larger range of motion around the PIP joint CoR.

This study only analyzed one participant for joint CoR estimation. More participants need to be recruited for a further study. Statistical models of the joint CoR position can be established based on hand joint dimensions. For further validation of the proposed method, fluoroscopy of hand bone movement can be recorded and analyzed to find joint CoR as ground truth for comparison.

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