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METHOD FOR SIMPLIFYING MAGNETIC HAND MOTION CAPTURE: POSITION AND POSTURE ESTIMATION METHOD FOR FINGER SEGMENTS OF INDEX WITH TWO RECEIVERS

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ABSTRACT

This study presents a simplifying method for magnetic hand motion capture, which is important for capturing hand motion when using scissors-like surgical tools, such as laparoscopic instruments. In order to reduce physical collision between instruments and receivers, the receivers can only be placed on the dorsum of the hand and fingertips. Therefore, it is necessary to have a position and posture measurement method that does not require the placement of receivers on finger segments without receivers. Thus, we propose a method that consists of a joint center estimation method from motion capture data, a construction method for a skeletal finger model, a calibration method for receivers placed on fingertips, and an inverse kinematics method. An evaluation was done with the motion capture data from index fingers, and mean segment lengths during a grasping motion were calculated by determining the position of joint centers. The standard deviations of all estimated segment lengths were under 0.4 mm. In addition, we compared the positions of our method with a full set of four receivers. The mean distance between joint center positions estimated by our methods and a full set of receivers were under 3.4 mm, which was an improvement over past research. Lastly, the Pearson correlation coefficients between the joint center position estimated by our method and full set of receivers were calculated. The results found a strong correlation between the joint center positions estimated by our method utilizing two receivers and a full set of four receivers, thus confirming the robustness of our method.

KEYWORDS: Motion Capture, Finger Dexterous Motion, Joint Center Estimation, Inverse Kinematics.

I. INTRODUCTION

Motion capture is an important technology for training and ergonomic assessment of hand motions in laparoscopic surgery. In a previous research, one 6 Degree-Of-Freedom (DOF) magnetic tracking sensor was mounted onto each needle holder, and the motion data of sensors were recorded as the movement of laparoscopic instruments [1]. By analyzing the movements of laparoscopic instruments, it was possible to observe the differences between expert and novice surgeons. Other research has also investigated wrist angle and finger joint angles that were recorded directly with glove-based motion capture (CyberGlove™) [2]. With surface electrodes placed on the upper arm and shoulders, muscle activity during coordination, peg transfer, precision cutting and suturing were analyzed while using instruments. Meanwhile, the movements of instruments without sensors for capture has not been discussed. The CyberGlove™ itself does not provide a 3D positioning mechanism for finger joints, and as such could not be used in laparoscopic training. Thus, additional positioning devices are needed for finger joint position measurement [3]. Additionally, hand motion along with finger joint positions during laparoscopic surgery has not been discussed in previous laparoscopic surgery related research because of the lack of a finger position measuring method for laparoscopic training.

Hand motion capture methods while using tools, like laparoscopic training, are rare. However, there is some research about hand motion capture methods for dexterous movements [4], [5], applying methods such as optical motion capture. Because a single optical marker can only obtain one position, at least three markers have to be placed on one finger segment to calculate the posture. In a situation where the hand is not holding anything, three optical markers placed on each finger segment and dorsum of hand, can calculate finger joint positions by using

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Least Squares Optimization methods [4]. Furthermore, by solving kinematic problems with a mathematical hand model, it is possible to estimate finger position with motion capture data from markers on the fingertips and the dorsum of the hand [5]. The mathematical hand model is also called a skeletal hand model or link structure model in 3D CG modeling.

A mathematical hand model consists of various vectors that represent finger bones and rotation axis in a skeletal hand model. Flexion and extension are represented by the rotation axis of a finger joint, while the joint positions are represented by the rotation of finger bones. Joints with 1 DOF such as Distal Interphalangeal Joint (DIP joint) and Proximal Interphalangeal Joint (PIP joint) can be represented by one vector. For ergonomic evaluation, some researchers made a hand model that is a combination of a CT scanned mesh hand model and a skeletal hand model for an individual at reference posture [6]. While grasping or gripping, however, a self-occlusion problem occurs when using optical motion capture devices, and re-labelling markers hidden from the camera is time consuming. In some situations, these problems can be solved by optimizations techniques and kinematic calculations with a skeletal hand model. One research study applied a combination of optical motion capture and Microsoft Kinect, and solved self-occlusion problems, and markers could be labeled automatically, when holding nothing in the hands [7]. As such, previous research indicates that the self-occlusion problem can be solved and finger joint position can be measured when capturing motion of the bare hand.

To measure a sequence of surgical hand motions while using scissor-like tools, such as laparoscopic instruments, some cases of the self-occlusion problem with optical motion capture cannot be avoided, as optical markers may be occluded by either the hands or surgical instruments. To address this, it may be possible to apply a magnetic motion capture device that is capable of finger motion measurement without a self-occlusion problem, as the magnetic fields pass thru the hand. In previous research, an Automatic Joint Parameter Estimation (AJPE) method for the full body with magnetic motion capture, which is an optimization method, has been proposed [8]. However, the method limited for a full body cannot determine single-axis joint centers like the DIP joint of a finger.

The last problem that needs to be addressed is physical collision between instruments and magnetic receivers. When using scissor-like tools, the handler may collide with magnetic receivers. In order to reduce physical collision between instruments and receivers, receivers can only be placed on the fingertips and dorsum of the hand. Positions and posture finger segments without receivers can be calculated with Inverse Kinematics (IK) methods. There are several IK solutions for computing the position or posture via estimation of each segment of a link structure. Some solutions of IK problems are tasked as a problem of finding a local minimum of a set of non-linear equations [9]. One famous IK method in a biomechanically constrained situation is the Cyclic Coordinate Descent (CCD) algorithm [10], which is a heuristic iterative method with low computational cost for each joint per iteration without matrix manipulations. One IK solution that has a very low computational cost is the triangulation method [11]. Although the method has been improved, especially for unnatural looking problems for n-link IK problems, it is hard to apply to joint limits, which means that is hard to control the path in a 3D space. Because the triangulation can reach the target via one iteration, it has greater performance benefits over CCD. Our proposed method is based on the triangulation method. As our IK problem is focused on the hand, the solution to this typical problem can be improved by adding constraints and estimation methods for special conditions. One of the special conditions we want to introduce is finger extension, which usually is discussed in motion capture [12], but has rarely been considered in inverse kinematics.

This basic research paper investigates hand motion measurement while using scissors-like surgical tools such as laparoscopic instruments, by utilizing an estimation method for position and posture of a finger segment with magnetic motion capture receivers placed on the fingertips and dorsum of the hand. Figure 1 shows the placement of magnetic hand motion capture receivers. The hand motion examined in our method is grasping of a circular cylinder, which is used in building a kinematic hand model [13].

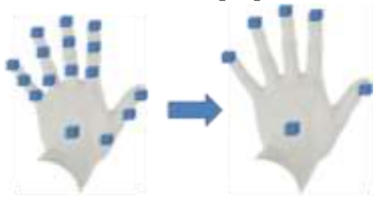

Figure 1. Placement of magnetic hand motion capture receivers.

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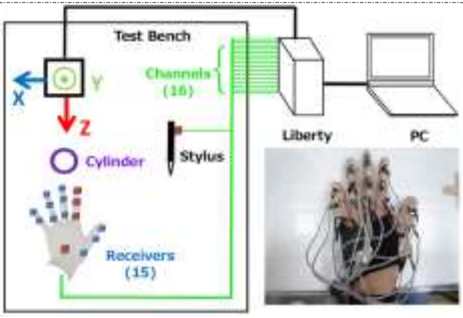


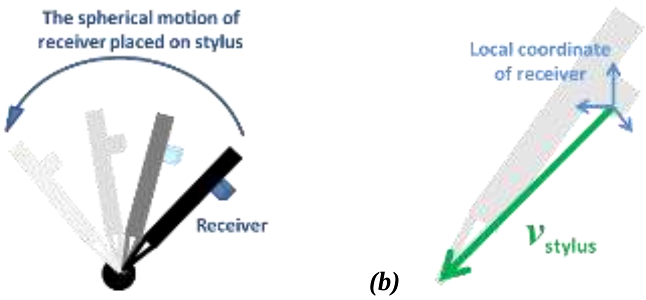
Figure 2. A sample of placement of receivers and block diagram of experimental system.

II. EXPERIMENTAL SYSTEM AND METHODS

System overview

Our experiment system consists of a PC, Polhemus™ Liberty system, one transmitter, and sixteen magnetic receivers. Figure 2 shows a sample of the placement of receivers and a block diagram of the experimental system. The magnetic field from a transmitter generates the induced electromotive force to the coils in the receivers. By analyzing the induced electromotive force, the relative position and posture of receivers from the transmitter can be calculated, and automatically recorded. There are fifteen receivers placed on hand and one attached on a stylus, a self-made position measuring device, which will be discussed later. In order to fit the shape of finger segments, the receivers (RX1-D) were processed into a teardrop shape, with a specially thinned cable. For each receiver on the finger bones, a special kind of toupee tape that is thinner, but with more strength was applied. In addition, kinesiology tape was used to wrap the receivers onto the finger bones. As skin on the dorsum of hand extends and contracts while moving, we used a special fingerless glove to reduce skin movement, instead of using toupee tape and kinesiology tape.

The cylinder used in the grasping motion is a PVC pipe 26 cm high and 3.8 mm in diameter. In addition, the cylinder is fixed on the table, so there is neither significant movement nor shape changes. One special self-made positioning device that will be introduced is the stylus. The stylus is a device for measuring position, with one receiver fixed on the thicker end of a pencil that is like wood. In order to get the calibration data of the stylus, the sharper end point is fixed on the test bench, and movement of the other end point is of a sphere surface. Figure 3 shows the motion for the stylus and the end point calculation method. Figure 3(a) shows the motion for calibration and Figure 3(b) shows the calculation method for the end point of the stylus. From the stylus calibration data, the sharper point of the other end could be calculated by sphere fitting [14]. Once the vector ($\boldsymbol{v}_{\text{stylus}}$) between the receiver and the sharper end point is determined in the local coordinate of a receiver, the position of the sharper end point could be calculated from motion data. Because the distribution of the magnetic field generated by the transmitter is very important for a correct reading, anything that influences the distribution of the magnetic field, like other metals, should be removed from the test space. Therefore, we used a 1-centimeter-thick acrylic plate as a test bench, and our measurements were executed in a wooden house.



(a) *(b)*

Figure 3. Motion for calibration and end point estimation method for stylus. (a) Motion for calibrating stylus. (b) Calculation method of end point.

Construction method of skeletal finger model from motion capture data

We used the AJPE calculation method, which cannot determine the position of single-axis joints [5]. Therefore, we took three steps to calculate the position of joint centers and to construct a skeletal finger model. Figure 4 shows the joint center estimation method from motion capture data.

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- Rotation axis estimated from grasping motion

Figure 4(a) shows the estimation method for rotation axis from a grasping motion. This step used AJPE to calculate points from the data of a number of grasping motions. This allows us to obtain a set of points for each joint, which are different points on the rotation axis of a finger joint. Then, the axis of the grasping motion was calculated by linear fitting of the points calculated above.

- Joint center estimation at reference posture

Figure 4(b) shows the joint center estimation method at reference posture. In this paper, postures are represented by Euler angle (yaw pitch roll). The reference posture is the posture for defining the Euler angle of finger segments. With the stylus, the position of the midpoint on the skin could be measured. The normal vector of the sagittal plane is the same as the X axis of coordinates of the transmitter. Therefore, with the midpoint on the DIP and PIP joint, it was possible to determine the sagittal plane of a finger. We defined the intersection of the joint axis and sagittal plane as the joint center for the DIP and PIP joint. To reduce calculation costs, we also used the same method as applied to the DIP and PIP joint on the metatarsophalangeal joint (MP joint). Although the MP joint is not biometrically a single-axis joint, there is a rotation axis in the grasping motion.

- Construction of skeletal finger model

Figure 4(c) shows the construction of a skeletal finger model. The finger skeletal model is constructed by $\boldsymbol{v}_{drm}$, $\boldsymbol{v}_{trd}$, l_1 and l_2. l_1 and l_2, which was calculated from the DIP, PIP, and MP joint estimates. Meanwhile, $\boldsymbol{v}_{drm}$ and $\boldsymbol{v}_{trd}$ were calculated from position and posture data of a receiver placed on a fingertip and the dorsum of the hand.

Calibration method for magnetic receiver placed on fingertip

After placing receivers on finger segments, the postures of the magnetic motion receivers are different from the posture of finger segments. For ordinary CG animation, the difference between reference posture and motion capture data are ignorable. However, in surgical training or practice, this difference may be significant. Therefore, it is necessary to have an accurate calibration of receiver posture. In this paper, two postures were used for calibration. Figure 5 shows the posture calibration method for a receiver placed on a fingertip. Figure 5(a) shows the hand posture for calculating the Y axis of a receiver placed on the fingertip, which is calculated from vectors $\boldsymbol{v}_{pd}$ and $\boldsymbol{v}_{pm}$. In order to determine the posture of a fingertip, one more axis is needed. Figure 5(b) shows the posture for determining the X axis of the receiver. We used the vector from the DIP joint to the PIP joints at the reference posture as the X axis of the receiver. With the posture of a fingertip, the relationships with data from the receivers were calculated, and the postures of the receiver were calibrated.

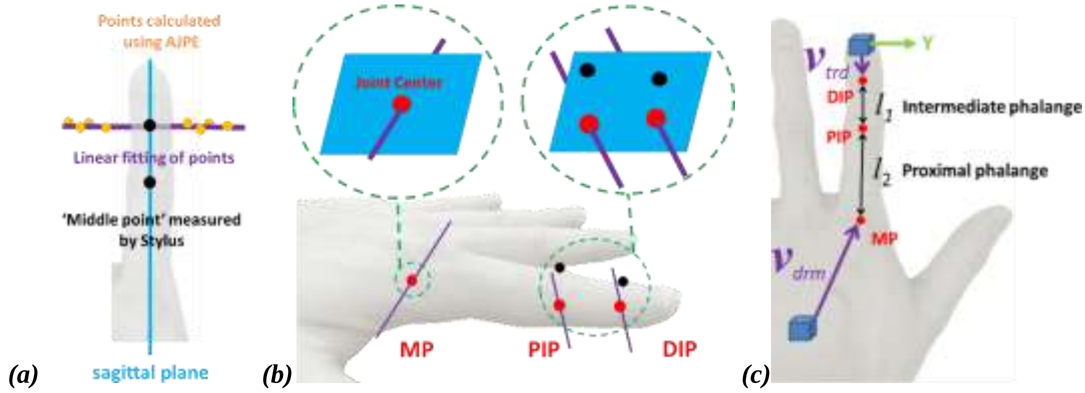

Figure 4. Construction method for skeletal finger model. (a) Calculation method for sagittal plane and axis of rotation. (b) Joint center estimation method. (c) Construction of skeletal finger model.

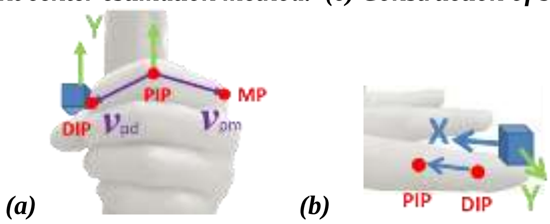

Figure 5. Posture calibration method for receiver placed on fingertip. (a) Posture for calculating Y axis. (b) Posture for calculating X axis.

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Inverse kinematic method for estimating finger segments without receivers

Figure 6 shows the inverse kinematic method for estimating finger segments without receivers. In our method, there are two kinds of conditions. Figure 6(a) shows the method for flexion, which is the main movement of a grasping motion. Figure 6(b) shows the method for over extension, which commonly happens when stretching the fingers, but is usually not taken into consideration. We made a condition judging vector $\boldsymbol{v}_{co}^{i}$, which is the cross product of $\boldsymbol{v}_{dt}^{i}$ and $\boldsymbol{v}_{dm}^{i}$. By comparing the $\boldsymbol{y}_i$ local coordinate of the receiver placed on the fingertip with $\boldsymbol{v}_{co}^{i}$, the finger pose condition is determined. At flexion posture, $\boldsymbol{v}_{co}^{i}$ is in the same direction of $\boldsymbol{y}_i$, and would be in a reversed direction with an over extension posture. With the corresponding calculation method, the joint center could be calculated. By importing a skeletal hand model, the position of the DIP and MP ($\boldsymbol{p}_{dip}^{i}$, $\boldsymbol{p}_{mp}^{i}$) joints can be calculated from the motion data of the receivers placed on the fingertips and dorsum of a hand. Our method is shown in pseudo-code in algorithm 1.

Algorithm 1. Joint center estimation method

Input motion data (#position (*x,y,z*) and posture (*yaw, pitch, roll*) of receivers placed on fingertips and dorsum of the hand)
Input $\boldsymbol{v}_{drm}$, $\boldsymbol{v}_{trd}$, l_1, l_2 (#skeletal hand model)
for all frame *i* **do**
  calculate $\boldsymbol{p}_{mp}^{i}$, $\boldsymbol{p}_{dip}^{i}$, $\boldsymbol{v}_{dt}^{i}$, $\boldsymbol{v}_{dm}^{i}$
  if $|\boldsymbol{v}_{dm}^{i}| \geq l_1 + l_2$ **then** (#Hand at stretching posture. Sometimes, l_1, l_2 and $\boldsymbol{v}_{dm}^{i}$ did not form a triangle. This situation is neither flexion nor over extension).
    $\theta^i = 180°$
  else
    $\beta_i = \arccos(\frac{{l_1}^2 + |\boldsymbol{v}_{dm}^{i}| + {l_2}^2}{2 l_1 \boldsymbol{v}_{dm}^{i}})$
    $\boldsymbol{v}_{co}^{i} = \boldsymbol{v}_{dt}^{i} \times \boldsymbol{v}_{dm}^{i}$ (#Left hand coordinate)
    calculate $\boldsymbol{y}_i$ (#The y-axis vector of local coordinate of receiver placed on fingertip)
    if $\boldsymbol{v}_{co}^{i}$ and $\boldsymbol{y}_i$ are in the same direction **then**
      $\theta^i = \alpha^i + \beta^i$ (#Flexion)
    else
      $\theta^i = -(\alpha^i + \beta^i)$ (#Over extension)
    end if
  end if
  calculate $\boldsymbol{n}_{dp}^{i}$ (#Unit vector of $\boldsymbol{v}_{dp}^{i}$ from rotating $\boldsymbol{v}_{dt}^{i}$ by θ_i about $\boldsymbol{y}_i$)
  calculate $\boldsymbol{v}_{dp}^{i}$ (#Change the length of $\boldsymbol{n}_{dp}^{i}$ to l_1)
  calculate $\boldsymbol{p}_{pip}^{i}$ (#The position of PIP by translating $\boldsymbol{p}_{dip}^{i}$ with $\boldsymbol{v}_{dp}^{i}$)
end for

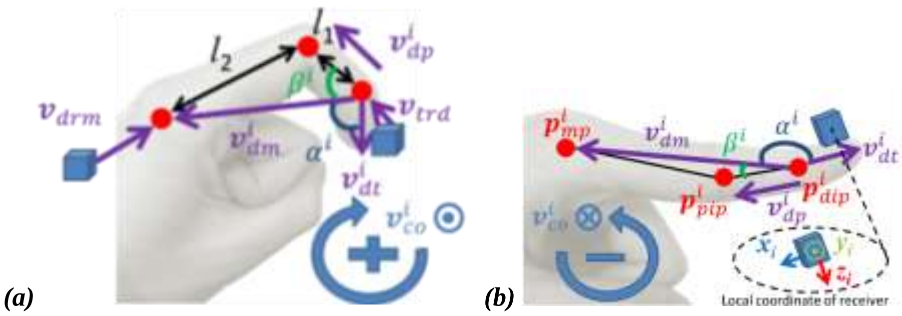

Figure 6. Finger segment position estimation method for flexion and over extension posture. (a) Flexion. (b) Over extension.

III. Results

In order to evaluate the reliability of the proposed joint center estimation method, the distance between two joints (segment length) were calculated from the data of a grasping motion. Figure 7 shows finger segment length and joint angle during a grasping motion. The horizontal axis represents time, and the first vertical axis represents

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joint angle and the second vertical axis represents the length of segments. Although the angle of the PIP joint is changing (from about -20 degrees to 80 degrees) during grasping, the lengths of intermediate and proximal phalange remain stable. Table 1 shows the mean and standard deviation (SD) of segment lengths for each subject. The mean lengths of intermediate phalanges according to subjects are from 23.3 mm to 27.4 mm, and the mean lengths of proximal phalanges are from 34.8 mm to 44.0 mm. All standard deviations of estimated segment lengths are under 0.4 mm, which means almost no variation on segment lengths during grasping. Figure 8 shows the trajectories of joint centers of an index generated by the method using a full set of four receivers (4R method) and the proposed method with only two receivers (2R method) during one grasping motion that is described in a 3D space. The origin of this space is the local coordinate of the receiver placed on the dorsal side. The red trajectory represents the center of a PIP joint, and yellow represents a MP joint. Meanwhile, the green and blue trajectory represents the center of a PIP and MP joint generated by the 4R method. The trajectory of a PIP joint generated by the 2R method (red) are coincident with the trajectory generated by the 4R method (green). On the one hand, the trajectory of the MP joint generated by the 2R method are gathered as a point, while the trajectory of the MP joint generated by the 4R method are in an arc shape.

Figure 9 shows each component of position (X, Y, Z) during ten grasping motions that were analyzed. The horizontal axis represents time and the vertical axis represents the position of center of a PIP joint. The red lines represent the components that are generated by the 2R methods, and positions generated by the 4R method are in green. The red lines are visually well polymerized to the corresponding green lines, indicating that the 2R methods are visually reliable.

For a statistical evaluation, we also calculated the Pearson correlation coefficient of the lines in green and red. Table 2 shows the Pearson correlation coefficients between the center of the PIP joints generated by the 2R method and 4R method. For the Y component, the lowest correlation coefficient is 0.82, which showed a strong correlation. For the X and Z components, the lowest correlation was 0.97, and both showed a very strong correlation. Table 3 shows the mean and standard deviation of the distance between joint centers generated by the 2R method and 4R method. The mean distance of the PIP and MP joint are under 3.4 mm, and the corresponding standard deviations are under 2.6 mm. In the inverse kinematics method, the calculation of PIP joints uses the position of a MP joint, and the standard deviation of PIP joints was greater than for MP joints in most cases. The standard deviation of MP joints are under 1.1 mm.

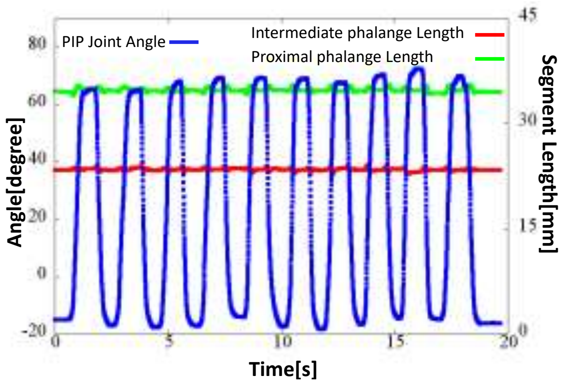

Figure 7: Segment length and joint angle during grasping motion.

Table 1: Mean and standard deviation of segment length

Subjects	Mean (SD) of segment length [mm]	
	Intermediate Phalange	Proximal Phalange
A	25.2 (0.2)	38.5 (0.4)
B	25.2 (0.2)	34.8 (0.2)
C	26.5 (0.2)	43.4 (0.3)
D	27.4 (0.4)	44.0 (0.4)
E	23.3 (0.2)	40.3 (0.2)
F	24.7 (0.2)	42.3 (0.4)

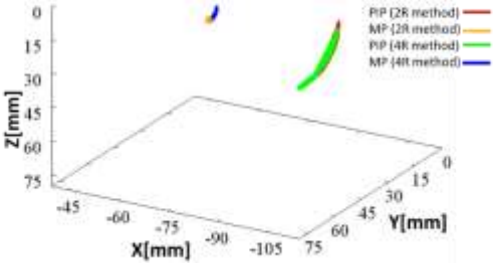

Figure 8: One sample of the trajectories generated by 2R method and 4R method during one grasping motion.

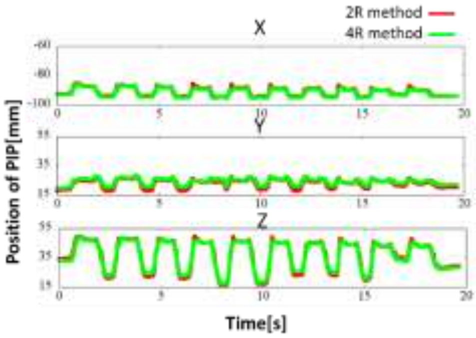

Figure 9: Each component of position during grasping motion.

Table 2: Pearson correlation coefficients between the center of PIP joints generated by 2R method and 4R method

Subjects	Pearson correlation coefficients		
	x	y	z
A	0.99	0.99	0.99
B	0.98	0.99	0.99
C	0.99	0.82	0.97
D	0.97	0.93	0.97
E	0.98	0.97	0.99
F	0.99	0.98	0.99

Table 3: Mean distance between joint center of generated by 2R method and 4R method

Subjects	Mean (SD) distance [mm]	
	PIP joint	MP joint
A	2.6 (1.1)	2.9 (1.0)
B	1.6 (0.6)	1.8 (0.6)
C	3.4 (2.6)	2.1 (0.6)
D	2.8 (2.0)	1.9 (1.1)
E	2.3 (1.0)	2.3 (0.8)
F	1.4 (0.9)	1.6 (0.6)

IV. DISCUSSION

This paper proposed a method for estimating the joint center from the intersection of the joint axis and sagittal plane. Each finger joint that was estimated was aligned in a straight line when a finger was in a stretched posture, which means the finger motion that is generated is more natural. For segment length estimation made by Zong-Ming Li, the standard deviation of intermediate phalanges and proximal phalanges were 1.2 mm and 1.6 mm [5], while the standard deviation of finger segment lengths in our results were under 0.4 mm for both intermediate phalanges and proximal phalanges. In the future, this segment length estimation method can also be used in musculoskeletal systems for moment prediction [15].

The mean distance between our 2R method and a 4R method joint was smaller compared to past research. For the PIP joint, the mean distance of our method was about 2.4 mm while past research [5] achieved about 5 mm (2.6 mm in X, 4.8 mm in Y, 3.6 mm in Z). In addition, our method can also be applied when a finger is over extended, which until now has not been considered by other methods.

V. CONCLUSION

By constructing a skeletal finger model from magnetic motion capture data, we were able to estimate the finger segment position of the index finger with two receivers. We proposed, introduced, and validated a calibration method for a magnetic receiver placed on the fingertip and an inverse kinematic method for estimation. In the evaluation part, which included motion capture data from six subjects, we compared the finger segment position estimated by our method with a full set of four receivers. The standard deviation on length in our results were under 0.4 mm for intermediate phalanges and proximal phalanges. The Pearson correlation coefficients between the center of PIP joints generated by our method with two receivers and a method using a full set of four receivers were all strong (over 0.82).

Our future research will focus on three steps. Firstly, we will apply our method to other fingers, especially the thumb. Secondly, we will make some laparoscopic instruments with non-metal handlers for experiments and training. Lastly, we will develop a measurement method for the contact surface of the hand and laparoscopic instruments.

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