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CALCULATING POSITIONS OF THE FINGER JOINTS CENTERS OF ROTATIONS IN FLEXION-EXTENSION MOVEMENT FROM REFLECTIVE MARKERS

Tamara Grujic Supuk[1], *William Harwin*[2], *Vlasta Zanchi*[1]

[1] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[2] School of Systems Engineering, Department of Cybernetics, University of Reading, Reading, United Kingdom

ABSTRACT

The aim of this paper is to describe the algorithm for calculating the positions of finger centres of rotation in flexion-extension movement from reflective surface markers. The method presents the simplified version of the kinematic modelling of human motion, developed by various researchers as X. Zhang, S.W. Lee, P. Braido, [1] and Ouerfelli, Kumar, Harwin, [2]. Proposed method uses the mathematical model which connects the fingers internal centres of rotations with the surface markers, positioned on the skin, above the observed joints. An optimisation routine, which minimise the difference between the estimated values of finger segments lengths and these lengths expressed by the distance between surface markers, is employed. As results, the positions of internal centres of rotations were obtained. The efficacy of the proposed algorithm is tested by using data measured during the flexion-extension movement of index finger. Results were compared with the data obtained and published by X. Zhang, S.W. Lee, P. Braido, [1].

1. INTRODUCTION

Increasing interest in hand biomechanics emphasized various problems relating to kinematic modelling of hand movement. The human hand is extremely versatile in its interactions with the environment, demonstrating skills that designers of dexterous robot hands would like to emulate in their designs, [3]. It is a highly complex structure which includes 27 bones, 18 joints and more than 20 degrees of freedom, [4]. Different methods for capturing and analysing of hand movements, including prehension and grasping, were developed, [5]. Among them, surface techniques are the most convenient, due to its non-invasive nature. Such techniques apply surface markers or sensors, attaching them to the surface landmarks, most often above the joints of interest. Despite to its conveniently usage, surface markers methods usually do not best represent the underlying human skeletal structure, [1]. For example, positions of fingers joint's centres of rotation can not be simply substituted by positions of surface markers attached on the skin above them. The technique for determining the fingers centres of rotation using surface markers has to be developed.

2. METHODS

Five subsequent measurements were performed on a single healthy male subject, with no known neurological or musculosceletal disorders. The subject's age, weight and height were 30years, 64kg and 170cm, respectively. The subject was asked to perform the movement starting with natural full extension and finishing with natural full flexion of all four digits, excluding the thumb. Passive hemispherical retro-reflective markers, 6mm in diameter were attached to the subject's skin on the dorsal side of the hand and 10mm in diameter markers were attached to the subject's wrist. Markers, whose coordinates were studied in this work, were positioned on the following landmarks on the digit 2 (the index finger): finger tip (TIP2), distal interphalangeal joint (DIP2), proximal interphalangeal joint (PIP2) and metacarpophalangeal joint (MCP2), Fig.1. Markers used for the calculation of the local, wrist-hand coordinate system were positioned on metacarpophalangeal joint of the middle finger, MCP3, and on the radial styloid process (RWRA) and ulnar styloid process (RWRB), Fig.1.
A four-cameras motion capture system (512 Vicon Motion System, Oxford, UK) was used to capture 3D coordinates of the markers at the sampling frequency of 120 Hz. The recorded data were preprocessed by Vicon software and then exported into an ASCII file for the further analysis using Matlab. Data gaps, caused by fingers overlapping, which makes markers invisible to the cameras, were filled using cubic spline interpolation.

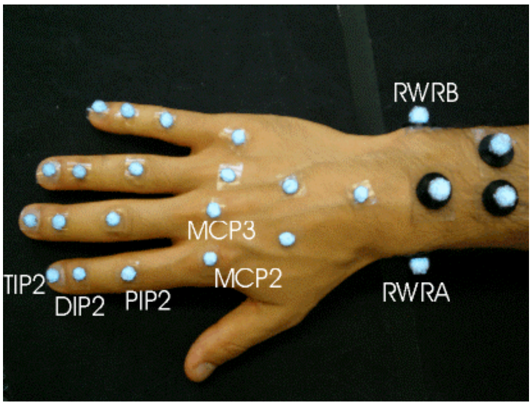

Fig.1. Retro-reflective markers attached to the dorsal side of the hand. The study described in this paper used the markers positioned at the joints of index finger: TIP2, DIP2, PIP2, MCP2 and markers for defining the wrist-hand coordinate system: RWRA, RWRB and MCP3.

2. 1. MATHEMATICAL MODEL

The markers coordinates, measured in the global (laboratory) coordinate system, {o}, were transformed in a local wrist-hand coordinate system, denoted as {w}. Local coordinate system was defined according to the notation described in [6], Fig. 2.: The origin of the frame was defined as the mid point between RWRA and RWRB points, and is denoted as MID. The **z** axis was defined as unit vector passing through RWRA and RWRB. The **x** axis was created as perpendicular to the plane defined by RWRA, RWRB and MCP3, and the **y** axis was calculated from the vector product of **z** and **x**. The flexion-extension movement of the hand was described as rotation about the **z** axis. The coordinates of the four markers attached to the index finger, in the wrist frame, were projected onto the x-y plane, in which the finger flexion-extension movements occur. Thus, the method for the calculation of the joints centres of rotations, JCORs, can be performed in 2D.

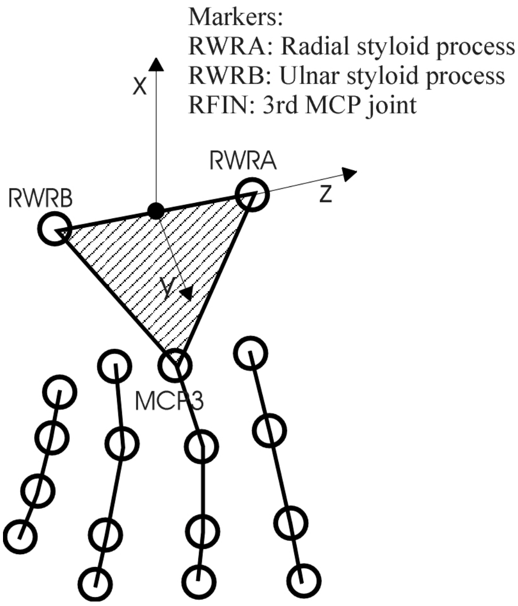

Fig. 2: Wrist-hand coordinate system

The calculation of markers coordinates in wrist-hand coordinate system was performed using the expression which describes the general transformation mapping of a point (vector) from its description in one frame to a description in a second frame [7]:

$$ {}^{\{w\}}P = {}^{\{w\}}_{\{o\}}T\, {}^{\{o\}}P \tag{1} $$

where:

${}^{\{w\}}P$ is the marker point observed in wrist-hand coordinate system, {w}

${}^{\{o\}}P$ is the same point observed in global frame, {o}

${}^{\{w\}}_{\{o\}}T$ is the transformation matrix from the global frame {o} to the wrist frame {w}

${}^{\{w\}}_{\{o\}}T$ can be expressed as:

$$ {}^{\{w\}}_{\{o\}}T = {}^{\{o\}}_{\{w\}}T^{-1} \tag{2} $$

We first calculated ${}^{\{o\}}_{\{w\}}T$ as follows:

$$ {}^{\{o\}}_{\{w\}}T = \left[\begin{array}{ccc|c} & {}^{\{0\}}_{\{w\}}R & & {}^{\{o\}}P_{\{w\}\mathrm{ORG}} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \tag{3} $$

where:

${}^{\{0\}}_{\{w\}}R$ is the rotation matrix which describes relative rotation of the frame {w} with respect to the global frame {o}.

${}^{\{o\}}P_{\{w\}\mathrm{ORG}}$ is the vector that locates {w}'s origin relative to {o}.

Rotation matrix can be calculated as follows:

$$ {}^{\{0\}}_{\{w\}}R = \begin{bmatrix} \hat{x}_w\hat{x}_o & \hat{y}_w\hat{x}_o & \hat{z}_w\hat{x}_o \\ \hat{x}_w\hat{y}_o & \hat{y}_w\hat{y}_o & \hat{z}_w\hat{y}_o \\ \hat{x}_w\hat{z}_o & \hat{y}_w\hat{z}_o & \hat{z}_w\hat{z}_o \end{bmatrix} \tag{4} $$

where $\hat{x}_o$, $\hat{y}_o$ and $\hat{z}_o$ are unit vectors of the global frame, {o}, and $\hat{x}_w$, $\hat{y}_w$ and $\hat{z}_w$ are unit vectors of the wrist-hand frame, {w}.

Vector ${}^{\{o\}}P_{\{w\}\mathrm{ORG}}$, in our case, points at MID point, and therefore can be presented as:

$$ {}^{\{o\}}P_{\{w\}\mathrm{ORG}} = \begin{bmatrix} x_{MID} \\ y_{MID} \\ z_{MID} \end{bmatrix} \tag{5} $$

where x_{MID}, y_{MID} and z_{MID} are 3D coordinates of MID point, the origin of the {w} frame.

Figure 3. shows movement of index finger in wrist-hand coordinate system, for one flexion-extension movement trial.

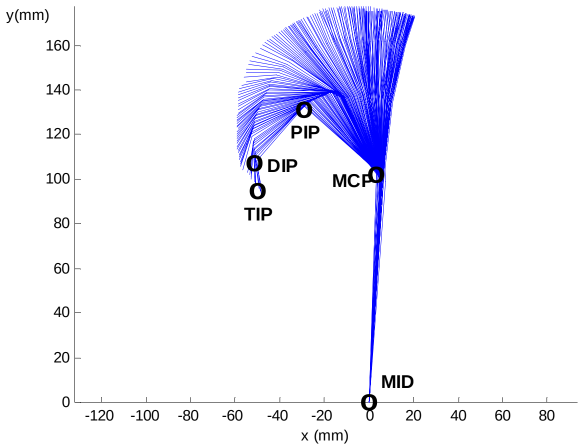

Fig.3: Flexion-extension trial of index finger in wrist-hand coordinate system

The model which establishes the geometrical relationship between the surface markers and joint centres of rotations, CORs, is proposed and presented on Figures 4. and 5. In this model four surface markers M_i, i=0,..,3, attached to the finger TIP, DIP, PIP and MCP joint, respectively, are connected by surface link vectors $\boldsymbol{l}_i$, i=1,2,3. Centres of rotation, C_i, are connected by internal link vectors $\boldsymbol{L}_i$. Centers of rotation are connected to adjoining surface markers by vectors $\boldsymbol{d}$i. During the extension-flexion movement, $\boldsymbol{l}_i$ changes its length and orientation, while $\boldsymbol{d}_i$ and $\boldsymbol{L}_i$ change the orientation and maintain a constant length.

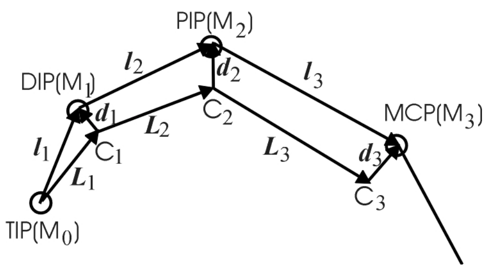

Fig. 4. The geometrical model of the finger with the attached surface markers: relationship between markers (Mi) and internal centres of rotation (C_i)

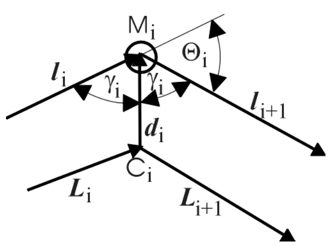

Fig. 5. Surface marker M_i and center of rotation C_i with adjoining vectors and angles, during flexion

The basic assumption we made is that the vector $\boldsymbol{d}_i$, pointing from the i-th centre of rotation, C_i to the adjoining surface marker M_i, equally divides the angle defined by surface link vectors which connect markers adjacent to the observed marker, Fig.5:

$$\gamma_i = \angle(\boldsymbol{l}_i, \boldsymbol{d}_i) = \angle(-\boldsymbol{l}_{i+1}, \boldsymbol{d}_i) \tag{6}$$

Further more, angle γ_i is defined by flexion-extension angle Θ_i for segment i, in following manner:

$$\gamma_i = \frac{\pi - \Theta_i}{2} \qquad \text{(for flexion)} \tag{7}$$

$$\gamma_i = \frac{\pi + \Theta_i}{2} \qquad \text{(for extension)} \tag{8}$$

Vector $\boldsymbol{d}_i$ is determined by its length, $|\boldsymbol{d}_i|$, which is the unknown variable, and by its orientation which depends on angle γ_i. In order to determine the orientation of vector $\boldsymbol{d}_i$, the unit vector in its direction, $\boldsymbol{d}_i$_unit will be calculated in following manner:
According to Fig. 5, the scalar products between vectors are:

$$dot(\boldsymbol{l}_i, \boldsymbol{d}_i\_unit) = \begin{bmatrix} l_i\_x & l_i\_y \end{bmatrix} \begin{bmatrix} d_i\_unit\_x \\ d_i\_unit\_y \end{bmatrix} = |l_i| \cos\gamma_i \tag{9}$$

$$dot(-\boldsymbol{l}_{i+1}, \boldsymbol{d}_i\_unit) = \begin{bmatrix} -l_{i+1}\_x & -l_{i+1}\_y \end{bmatrix} \begin{bmatrix} d_i\_unit\_x \\ d_i\_unit\_y \end{bmatrix} = |l_{i+1}| \cos\gamma_i \tag{10}$$

where l_i_x, d_i_unit_x and l_i_y, d_i_unit_y are horizontal and vertical component of vectors $\boldsymbol{l}_i$ and $\boldsymbol{d}_i$_unit, respectively.
Expresions (9) and (10) can be written in the matrix form:

$$\begin{bmatrix} l_i\_x & l_i\_y \\ -l_{i+1}\_x & -l_{i+1}\_y \end{bmatrix} \begin{bmatrix} d_i\_unit\_x \\ d_i\_unit\_y \end{bmatrix} = \begin{bmatrix} |\boldsymbol{l}_i| \cos\gamma_i \\ |\boldsymbol{l}_{i+1}| \cos\gamma_i \end{bmatrix} \tag{11}$$

From the above, the expression for calculating the components of unit vector $\boldsymbol{d}_i$_unit follows:

$$\begin{bmatrix} d_i\_unit\_x \\ d_i\_unit\_y \end{bmatrix} = \begin{bmatrix} l_i\_x & l_i\_y \\ -l_{i+1}\_x & -l_{i+1}\_y \end{bmatrix}^{-1} \begin{bmatrix} |\boldsymbol{l}_i| \cos\gamma_i \\ |\boldsymbol{l}_{i+1}| \cos\gamma_i \end{bmatrix} \tag{12}$$

The relationship between link vectors, at any time sample, can be expressed as follows, Fig 4:

$$\boldsymbol{L}_i(t) = \boldsymbol{l}_i(t) + \boldsymbol{d}_{i-1}(t) - \boldsymbol{d}_i(t) \tag{13}$$

In order to obtain the positions of JCORs, we used the optimisation routine, presented in [1] which minimizes the variation of internal link lengths over the entire movement:

$$J = \sum_{i=1}^{3} \left\{ \sum_t \left(|\boldsymbol{L}_i| - |\boldsymbol{l}_i(t) + \boldsymbol{d}_{i-1}(t) - \boldsymbol{d}_i(t)| \right)^2 \right\} \tag{14}$$

The above cost function contains known variables $\boldsymbol{l}_i$(t) and unknown variables $|\boldsymbol{L}_i|$ and $\boldsymbol{d}_i$(t). The lengths of vectors $\boldsymbol{d}_i$(t) and $\boldsymbol{L}_i$(t), $|\boldsymbol{d}_i|$ and $|\boldsymbol{L}_i|$ are time-constant variables and will be determined by optimisation process. The orientation of $\boldsymbol{d}_i$(t) is determined by the orientation of the unit vector, $\boldsymbol{d}_i$_unit, calculated according to (12).
The constrained nonlinear optimisation which uses the Sequential Quadratic Programming (SQP) method was used. This method represents state-of-the-art in nonlinear programming and does not require the calculation of the gradient of the optimisation function.
In solving the optimisation problem, the constraints incorporated in order to make the solution search more efficient, were: the lower bounds were set to zero, the upper

bounds for $|\boldsymbol{d}_i|$ were set to corresponding joints thickness, and the upper bounds for $|\boldsymbol{L}_i|$ were set to index finger length. The $|\boldsymbol{d}_0|$ was set to zero.
The data analysis, including the optimisation routine, was performed using Matlab and Matlab's Optimisation Toolbox (The Mathworks, Inc.).

3. RESULTS

Table 1. presents the results of optimisation routine, obtained for all 5 measurements.

	Joint			Estimated segment's lengths		
	DIP	PIP	MCP			
	$\|d_1\|$ (mm)	$\|d_2\|$ (mm)	$\|d_3\|$ (mm)	$\|L_1\|$ (mm)	$\|L_2\|$ (mm)	$\|L_3\|$ (mm)
1	4.48	8.80	14.92	14.28	27.02	37.51
2	4.65	8.74	11.05	14.31	27.18	37.93
3	5.48	8.42	11.37	14.44	26.94	37.59
4	4.56	8.59	14.64	14.27	27.31	37.72
5	5.06	8.33	9.16	14.33	27.09	37.72
av	**4.48**	**8.58**	**12.23**	**14.33**	**27.11**	**37.69**
sd	0.41	0.20	2.47	0.06	0.14	0.16

Table 1. Statistics obtained for index finger (all 5 measurements): distances between surface markers and joints centres of rotation, $|d_i|$ and estimated lengths of segments, $|L_i|$.

Table 2. presents the average magnitudes of vectors $\boldsymbol{d}_i$, obtained and published by Zhang, Lee and Braido, [1]. Their study comprised 24 subjects (12 males and 12 females), with the average (±st. dev) age, body weight and height: 24 (±5) years, 65.1 (±8.9) kg and 168.3 (±11.9) cm, respectively.

	Joint		
	DIP	PIP	MCP
	$\|d_1\|$ (mm)	$\|d_2\|$ (mm)	$\|d_3\|$ (mm)
average	**5.25**	**8.87**	**13.39**
st.dev	2.38	1.76	1.16

Table 2. Average distances between surface markers and joints centres of rotation, $|d_i|$, obtained by Zhang, Lee and Braido, [1]

Insight into Tables 1. and 2. shows that results obtained by applying our method on a single subject (Table 1.) are comparable to the results obtained on the larger test group (Table 2.). Average values of the $|\boldsymbol{d}_i|$ for all three joints from Table 1. fall into the interval $|\boldsymbol{d}_i|$±st.dev from the Table 2, which confirms the results obtained by our method as valid.

4. CONCLUSION

The algorithm described in this article presents the simplification of the JCORs calculating method developed by Zhang, Lee and Braido, [1], and, as seen in the previous section, still produces efficient results.
The algorithm calculates fingers centres of rotation in two dimensions. Future investigations will be focused on extending the proposed algorithm in order to calculate JCORs into 3D.

The method presented in the article may be usable in different applications such as the assessment of joint range of movements, the investigations of different grasp configurations and to improve the techniques for estimation of joint torques and forces. Further more, the method can be applied as a design mechanism to assist in exoskeleton design.

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Authors:
MSc. Tamara Grujic Supuk, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Rudjera Boskovica bb, 21000 Split, Croatia, phone: ++38521305817, fax:++38521463877, email: tamara.grujic@fesb.hr

Dr. William Harwin, School of System Engineering, Department of Cybernetics, University of Reading, Whiteknights, Reading RG66AY, United Kingdom, phone: ++441189316792, fax:++441189318220, email: w.s.harwin@reading.ac.uk

Prof. Dr. Vlasta Zanchi, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Rudjera Boskovica bb, 21000 Split, Croatia, phone:++38521305817, fax:++38521463877, email: vzanchi@fesb.hr