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Manipulability analysis of human thumb, index and middle fingers in cooperative 3D rotational movements of a small object

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SUMMARY

The combined motion of the human thumb, index and middle fingers while rotating a small object across the extended, intermediate and flexed planes with respect to the fingers was analyzed. Auto reflective markers were attached on the fingers to track their motion across three postures and planes via a 3D motion capture system. Central, right and left rotation postures were considered in each plane for investigation and the rotation experiments were performed with 30 healthy subjects. The obtained data were used to compute the finger joint angles. Based on the three criteria of (i) manipulability measure, (ii) major axis direction angle of the manipulability ellipsoid and (iii) ratio of the minor over major axis lengths, the collective behavior of the fingers was studied. It has been found after analysis that the thumb and middle finger were active, while the index finger operated passively when manipulating small objects in cooperative rotational motion across the three planes. Activeness refers to the independence of a digit in controlling the motion of an object whereas passiveness denotes its dependence on other digits. An active finger governs the motion of an object whereas a passive finger simply supports it. The results of this investigation are of great importance in planning treatment for rehabilitation and for designing controllers for robotic therapists, finger exoskeletons and prostheses.

KEYWORDS: Cooperative rotation motion; Manipulability; Finger motion analysis.

1. Introduction

In the last two decades there has been a lot of interest in using the principles of robotics to study biomechanics and neuromuscular control of the human fingers. Several authors such as Valero-Cuevas *et al.*,[1–4] Yokogawa and Hara[5,6] and several others have used the principles of robotics to analyze finger motion. The concept of using manipulability ellipsoids to study robotic linkage systems was first proposed by Yoshikawa.[7] A set of fingertip velocities realized by the input unit sphere of joint angular velocities represents a manipulability ellipsoid in the Euclidean space. For all joint velocities inside a unit sphere, the major axes direction of the ellipsoid gives the direction along which a finger can move easily, while the minor axes give an indication of directions in which the fingers cannot move easily. The human hand has five digits (four fingers and a thumb) to manipulate different objects essential to many activities in daily living. Activities such as translating a small object in the tip-pinch motion only require the thumb and index finger. However, rotating a small object requires the coordination of three fingers: the thumb, middle and index fingers. Due to the intricate finger kinematics associated with many complex ways in which an object can be rotated, the coordination of these three fingers for a task requires greater understanding. In this paper our focus is to use the principles of robotics to study the cooperative behavior of three fingers (the thumb, middle and index fingers) for performing a simple cooperative motion such as rotating a small object. The results obtained would enable us to understand more about the relative activeness of these three fingers during cooperative motion and also be useful in the control of finger exoskeletons and rehabilitation therapy.

Human finger motion has been analyzed by several researchers who have focused on the (a) kinematics of multi-finger motion, (b) coordination between different fingers while performing tasks, (c) using principles of robotics to understand finger motion and (d) trying to use human data to control robots to enable them to behave like humans. In the following paragraphs, we discuss each of these separately. The detailed literature survey enables us to place our work in perspective with respect to the existing research in the biomechanics of human finger motion. Cobos *et al.*[8] proposed efficient human finger linkage models using Denavit–Hartenberg (DH) parameters that are suitable for manipulation tasks. Two simplified hand descriptions with 9 and 6 Degrees of Freedom (DOF) have been compared. Ingram *et al.*[9] analyzed the kinematics data of different subjects' right hand as they go about their daily routine using a vision system. Principle component analysis of the joint angular velocities showed that the first two components were highly conserved. Specifically the thumb was found to be the most independent of the digits and the index finger the most independent of the fingers. Tung *et al.*[10] provided quantitative evidence of kinematics and functional

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difference among different graded trigger fingers based on Froimson's classification. Metcalf and Nutley[11] proposed a kinematics measurement technique using a reduced surface marker system to calculate hyperextension of the MetaCarpoPhalangeal (MCP) joint. The algorithm provides a valid method for calculating hand kinematics. Leijnse *et al.*[12] accurately determined the kinematics and variability of the coupled interphalangeal joint motion for clinical and finger model validation applications. Kuo *et al.*[13] presented a quantitative method for measuring the functional workspace of the human hand. They found that the functional workspace of the precision thumb – finger grasps as the range of all possible positions in which the thumb tip and each fingertip can contact each other. Friedman and Flash[14] compared the trajectories of the index finger during grasping movements and compared the trajectories predicted by three optimization methods. They proved that finger trajectories are planned primarily on the joint level kinematics considerations.

Several researchers[15–18] have studied human multi-finger coordination while performing tasks of daily living. Martin *et al.*[16] characterized the finger interactions by enslaving and synergy of finger forces in voluntary and involuntary phases during pressing task. Synergic effects and enslaving were observed during both voluntary and involuntary phases. The mechanical factors affecting finger forces, such as latency between the lifted and non-lifted fingers, reflex responses, enslaving and synergy during the pressing task, are discussed in Martin *et al.*'s[16] study. Sun *et al.*[17] showed that the digit forces and digit coordination (synergic effects) during steady holding of an object secured to a handle is highly persistent and history-dependent. They observed from the results that the central nervous system could distinguish the holding of a half-full glass and a half-empty glass through digit coordination.

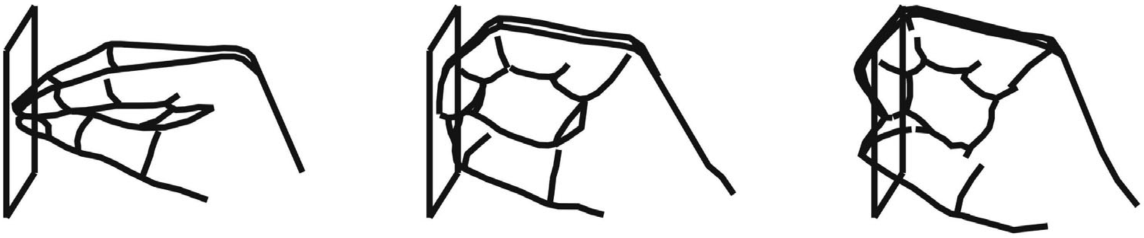
Humans perform different tasks by moving the fingers in coordination. The ease of moving a finger in a particular direction can be examined by analyzing the properties of its manipulability ellipsoid. The ellipsoid gives an indication of the transformation from the finger joint velocities to the tip velocities. Several earlier researchers have used the finger ellipsoid to analyze its biomechanical motion characteristics. Yokogawa and Hara[5] investigated the combined manipulability of the index finger and thumb in translation motion along the flexion/extension plane of the index finger. They concluded that the thumb worked passively to support the active index finger in object translation. Yokogawa and Hara[6] investigated the distribution of fingertip forces using the manipulability analyses by studying different subjects. Hara *et al.*[19] studied the static characteristics of a human finger using a linkage model involving force manipulability sets. They considered asymmetric joint angular velocities for transmission from muscle force to the finger tip force. Valero-Cuevas[2] reported the significance of the MCP finger joint modeling through the manipulability ellipsoid. Later, they investigated the overall kinematics of a 2-dimensional (2D) biomechanical model of the finger from muscle contraction to finger tip velocity.[3]

Kim[20] developed a joint motion-planning algorithm based on a biomimetic approach for human-like finger motion. Liu and Zhang[21] developed an algorithm for mapping from human hand motion to dexterous robotic hand to enable a robot to emulate human motion. Prattichizzo *et at.*[22] analyzed the kinematics and force manipulability properties of under actuated robotic hands, considering the ratio of the task space performance to the input joint space effort for computing the manipulability index. Liu[23] examined human manipulation skills and tried to embed them in robotic hands for object manipulation with the same dexterity and ease as the human hand.

In our daily lives we use the three-jaw pinch grip for performing several tasks such as opening the cap of a bottle, rotating a coin etc. Lambercy *et al.*[24] developed robotic rehabilitation aids for manipulation in which the rotation motions of the three fingers are in the intermediate (ITP) plane (central plane as shown in Fig. 1). As most rotation motions take place in this plane, we selected this particular plane as the starting plane in our work. As the human fingers' workspace for precision manipulation is quite large as reported by Kuo *et al.*[13] and ranges from the extended to the flexed finger position, we also added two extreme planes – extended plane (ETP) and flexed plane (FXP) – in our study. Hence, our results represent the complete workspace, although in three discrete planes. In this paper, the subjects used the three-jaw chuck to pinch the two sides of a coin with their three digits. The three planes have been further explained in Fig. 1, showing a coordinate system for the rotation of an object in the Y–Z plane. The frames assigned to other joints are as shown in Fig. 2. Since manipulability depends on the degrees of freedom, link length and configuration of linkage digits, manipulability of the thumb with 5 DOF,[25] and the index and middle fingers with 4 DOF each,[26] will vary due to physiological differences between them.

Here we consider rotating a small object in both clockwise (Fig. 1(e)) and counterclockwise directions (Fig. 1(f)) on each of the following planes. The ETP plane is the Y–Z plane (Fig. 1(d)) in which it is assumed that the three digits (fingers) are in their fully extended configuration. The FXP plane is parallel to the ETP plane, wherein the digits are in their almost completely flexed configuration. The ITP plane is the central plane positioned approximately half way between the ETP and FXP planes. On this plane, most manipulations, such as rotation, are expected to take place. All planes are parallel to the plane containing the palm of the hand. It is assumed that each of the three planes is formed by rotating the line, formed by connecting the tips of the index and middle fingers, about the axis (x-axis) normal to the plane of the palm. The tips of the fingers have coordinates with reference to a global coordinate system fixed on the wrist of the subject (Fig. 2). This ensures that even if the arm moves, the relative positions of the fingers do not get disturbed. The three planes are treated to be at fixed distances (x_{ETP}, x_{ITP} and x_{FXP}) along the x-axis. Even though being discrete, the ETP, ITP and FXP planes are representatives of the entire workspace.

On each plane, there exist three different rotation postures, namely, central rotation (CR), left rotation (LR) and right rotation (RR) postures. In all experiments performed, a thin plate like object is rotated from CR to RR and then from RR to LR postures. The orientation of the vector joining the tips



(a) ETP plane (b) ITP plane (c) FXP plane

(d) Central rotation posture (e) Right rotation posture (f) Left rotation posture

Fig. 1. Three planes and postures considered for coordinated finger motions in object rotation.

of middle and index fingers about the axis normal to the palm describes these postures quantitatively.

As a study on the combined rotation motion has not been performed earlier, this is the main motivation for this paper. In Section 2, the method and measurement procedures of the finger joint positions using a 3D motion capture system are explained. In Section 3, the experimental results are detailed. These are interpreted and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Methods

The manipulability analysis was performed using a three-finger kinematics model as shown in Fig. 2. The index and middle fingers were modeled as open chains with 4 DOF each. Joints such as a universal joint at the MCP joint and hinges at the Proximal-InterPhalangeal (PIP) and Distal-InterPhalangeal (DIP) joints[5–7,19] were used. As per Valero-Cuevas,[4] the thumb was modeled using a 5-DOF open chain with two universal joints each at the CarpoMetacarpal joint

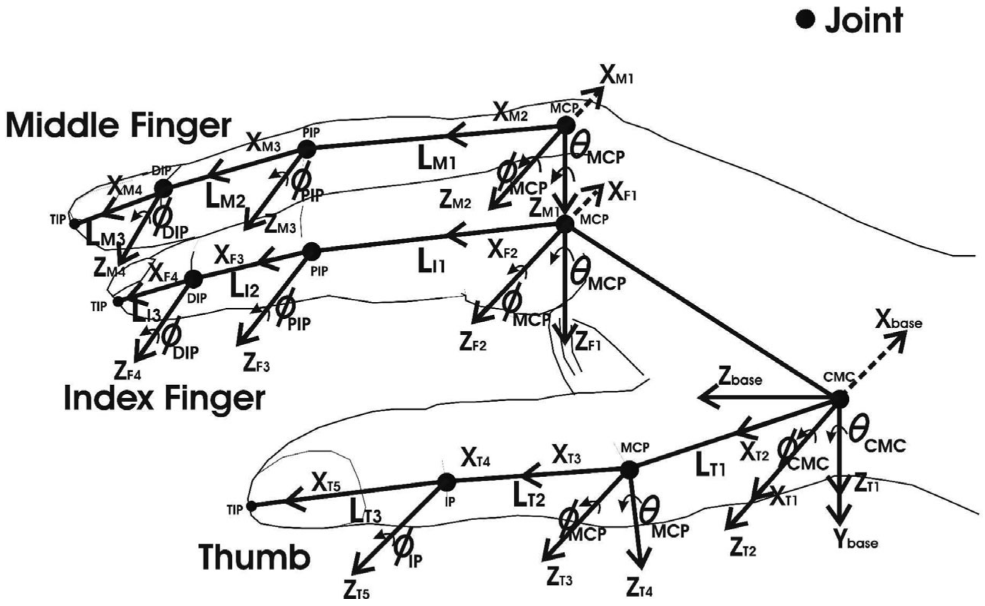


Fig. 2. Link models of the thumb, index finger and middle finger.

(CMC) and MCP joints, and a hinge at the InterPhalangeal (IP) joint (Fig. 2). The two major components of the movements of the thumb CMC joint as reported by Hollister *et al.*[25] are flexion/extension and abduction/adduction, and hence the CMC joint was modeled with the flexion/extension and abduction/adduction axes of rotation. Also, the complete movements of the thumb, as in opposition, can be modeled by the motion occurring about the two axes of rotation of the CMC joint, two axes of rotation of the MCP joint and the single axis of rotation about the IP joint. Variables θ_i (i = CMC, MCP) and ϕ_i (i = CMC, MCP, PIP, DIP and IP) at the finger joints denote the abduction/adduction and flexion/extension degrees of freedom of the fingers and the thumb respectively. The base coordinate reference frame was set at the thumb's CMC joint. All local coordinate frames are related to this base frame.

We have represented the coordinate frames in each joint with respect to the base coordinate frame to compute the manipulability ellipsoids.

The fingertip position vectors $I_{\mathrm{TIP}} = [x_I, y_I, z_I]^T$, $M_{\mathrm{TIP}} = [x_M, y_M, z_M]^T$ and $T_{\mathrm{TIP}} = [x_T, y_T, z_T]^T$ were expressed as

$$I_{\mathrm{TIP}} = I_{\mathrm{MCP}} + {}^{\mathrm{MCP}}_{\mathrm{PIP}}R\left[I_{\mathrm{PIPwrtMCP}} + {}^{\mathrm{PIP}}_{\mathrm{DIP}}R \bullet I_{\mathrm{DIPwrtPIP}} + {}^{\mathrm{DIP}}_{\mathrm{TIP}}R \bullet I_{\mathrm{TIPwrtDIP}}\right], \tag{1}$$

$$M_{\mathrm{TIP}} = M_{\mathrm{MCP}} + {}^{\mathrm{MCP}}_{\mathrm{PIP}}R\left[M_{\mathrm{PIPwrtMCP}} + {}^{\mathrm{PIP}}_{\mathrm{DIP}}R \bullet M_{\mathrm{DIPwrtPIP}} + {}^{\mathrm{DIP}}_{\mathrm{TIP}}R \bullet M_{\mathrm{TIPwrtDIP}}\right], \tag{2}$$

$$T_{\mathrm{TIP}} = {}^{\mathrm{CMC}}_{\mathrm{MCP}}R\left[T_{\mathrm{MCP}} + {}^{\mathrm{MCP}}_{\mathrm{IP}}R \bullet T_{\mathrm{IPwrtMCP}} + {}^{\mathrm{IP}}_{\mathrm{TIP}}R \bullet T_{\mathrm{TIPwrtIP}}\right], \tag{3}$$

where I_{TIP} is for the index finger tip, M_{TIP} is for the middle finger tip and T_{TIP} is for the thumb tip; suffixes I, M, T represent the index and middle fingers and thumb respectively. Rotation matrices ${}^{i}_{j}R$ (ith frame relative to the jth frame) with Euler angles along with the link lengths L_{Ii}, L_{Mi}, L_{Ti} as shown in Fig. 2 ($i = 1, 2, 3$ indicates joint numbers) were used to obtain the fingertip positions.

The objective was explained *a priori* to the 30 healthy subjects aged 20 to 30 years. The finger joint positions were recorded using a motion capture system MAC3D system (Motion Aalysis,. Inc.) at a sampling frequency of 200 Hz. A sample of errors recorded for this calibration for a 200-mm wand length was 0.16 mm and 3D errors in x, y and z directions had a mean of 0.4 mm and a standard deviation of 0.14 mm. Figure 3 shows 15 markers attached to a subject's hand (thumb (4 markers), index finger (4 markers) and middle finger (4 markers)) at the DIP, PIP and MCP joints. Near the wrist three markers are attached on the top surface of the hand to fix the orthogonal coordinate system. The coordinate system markers ensure that we calculate only the position of the joints without the motion of the wrist.

The distances between the joint positions for all intermediate finger configurations were measured and averages were taken to represent the finger link lengths. The mean and standard deviation of the total link lengths of the thumb, index and middle fingers are 105.0 mm (±8.0 mm), 114.0 mm (±9.0 mm) and 103.0 mm (±6.0 mm) respectively. The experimental results therefore are valid over a wide range of lengths of the three digits. The subjects were requested to perform two separate independent motions: Motion I, from CR posture to RR posture, and Motion II, from RR posture to LR posture in each of the ETP, ITP and FXP planes. The CR posture represents the initial confirmation of the three digits holding the object to be rotated. The RR posture denotes the configuration when the three digits rotated the object in a clockwise direction. Finally, the LR posture indicates the three digits' configuration when the held object is rotated in the counterclockwise direction. The configuration of the three digits holding the object in the CR posture is considered as the first (start) posture. The RR and LR denote respectively the second and third postures. The subjects were given enough training to perform the rotation movement. They were asked to rotate a coin from the CR posture (Fig. 1(d)) to the right (Fig. 1(e)) and then from the right to the left posture in 3 seconds. These two independent motions are classified as Motion I and Motion II in this study. We compared the three criteria for these two independent motions among the three digits to determine the activity of the fingers.

Fig. 3. (Colour online) A subject with auto reflective markers attached to the finger joints holding a small object (coin).

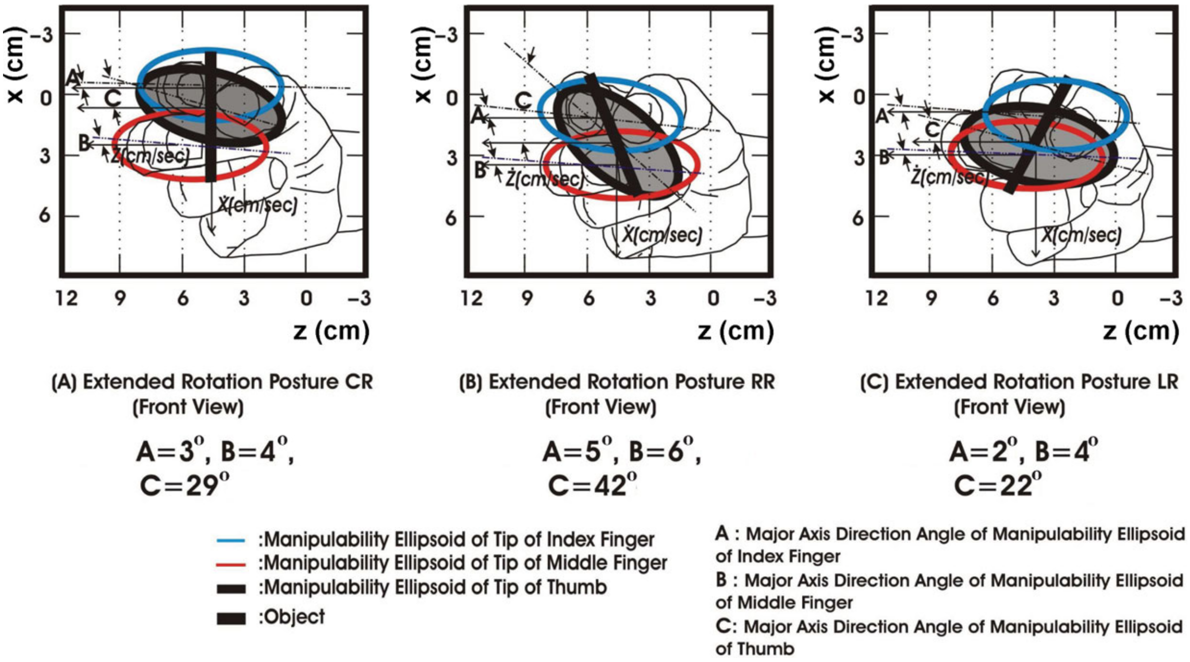
A set of all possible angular velocities of a finger can be accommodated in an ellipsoid in Euclidean space. The physical significance of this is that in the direction of the major axes of the ellipsoid, the finger can move at high speeds. If the ellipsoid is a sphere, then the fingertip can move with equal speed in all directions. Hence, this manipulability index gives us a quantitative measure of the ease of finger motion in particular directions. The general fingertip velocities (Eq. (4)) are obtained by taking the time derivatives of the finger tip positions given by Eqs. (1)–(3).

$$\dot{\boldsymbol{I}}_{\mathrm{Tip}} = \boldsymbol{J_I}\dot{\boldsymbol{q}}_{\boldsymbol{I}} \tag{4}$$

such that $\dot{I}_{\mathrm{Tip}} = [\dot{x}_{\boldsymbol{I}}, \dot{y}_{\boldsymbol{I}}, \dot{z}_{\boldsymbol{I}}]^{\boldsymbol{T}}$,

$$\dot{\boldsymbol{q}}_{\boldsymbol{I}} = [\dot{\phi}_{\mathrm{MCP\_}\boldsymbol{AA\_I}}, \dot{\phi}_{\mathrm{MCP\_}\boldsymbol{FE\_I}}, \dot{\phi}_{\mathrm{PIP\_}\boldsymbol{I}}, \dot{\phi}_{\mathrm{DIP\_}\boldsymbol{I}}]^{\boldsymbol{T}},$$

where $\boldsymbol{J_I}$ is a 3 × 4 Jacobian matrix and is obtained by the partial derivatives of the fingertip position given by Eq. (1) with respect to the joint angle vector $\boldsymbol{q_I}$.



(A) Extended Rotation Posture CR (Front View)

A=3°, B=4°, C=29°

(B) Extended Rotation Posture RR (Front View)

A=5°, B=6°, C=42°

(C) Extended Rotation Posture LR (Front View)

A=2°, B=4° C=22°

Fig. 4. (Colour online) ETP plane rotation ellipsoids of a subject participating in the experiment.

The set of all index fingertip velocities is realized by the index finger joint velocities such that the Euclidean norm of $\dot{\boldsymbol{q}}_{\boldsymbol{I}}$ is unity, that is

$$\|\dot{\boldsymbol{q}}_{\boldsymbol{I}}\| = \sqrt{(\dot{\phi}^2_{\mathrm{MCP\_}\boldsymbol{AA\_I}} + \dot{\phi}^2_{\mathrm{MCP\_}\boldsymbol{FE\_I}} + \dot{\phi}^2_{\mathrm{PIP\_}\boldsymbol{I}} + \dot{\phi}^2_{\mathrm{DIP\_}\boldsymbol{I}})} \leq 1, \tag{5}$$

which is equivalent to[7]

$$\dot{\boldsymbol{i}}^{\boldsymbol{T}}_{\mathrm{TIP}}(\boldsymbol{J}^+_{\boldsymbol{I}})^{\boldsymbol{T}}\boldsymbol{J}^+_{\boldsymbol{I}}\dot{\boldsymbol{i}}_{\mathrm{TIP}} \leq 1. \tag{6}$$

Here $\boldsymbol{J}^+_{\boldsymbol{I}}$ represents the pseudo inverse of the Jacobian matrix $\boldsymbol{J}_{\boldsymbol{I}}$. The manipulability ellipsoid of the finger is given by Eq. (6). This indicates the mapping of the unit input sphere of finger joint angular velocities given by Eq. (5) into the manipulability ellipsoid given by Eq. (6).[7] Using the singular value decomposition of the Jacobian matrix $\boldsymbol{J}_{\boldsymbol{I}}$, the principal axes of the manipulability ellipsoid are found as

$$\boldsymbol{J}_{\boldsymbol{I}} = \boldsymbol{R}\sum \boldsymbol{S}^{\boldsymbol{T}}, \tag{7}$$

where R and S are orthogonal matrices, and $\sum$ is a 3×4 matrix given as

$$\sum = \begin{bmatrix} \sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_2 & 0 & 0 \\ 0 & 0 & \sigma_3 & 0 \end{bmatrix}, \ \sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0.$$

The scalars $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$ and $\boldsymbol{\sigma}_3$ are the singular values of $\boldsymbol{J}_{\boldsymbol{I}}$. Let $\boldsymbol{r}_{\boldsymbol{i}}$ be the ith column vector of $\boldsymbol{R}$, then the principal axes of the manipulability ellipsoid are $\boldsymbol{\sigma}_1\boldsymbol{r}_1$, $\boldsymbol{\sigma}_2\boldsymbol{r}_2$, $\boldsymbol{\sigma}_3\boldsymbol{r}_3$. Also, the length of the major and minor axes are $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_3$ respectively.

The three criteria for evaluating manipulability considered here are (i) major axis direction angle of the ellipsoid, (ii) ratio of minimum radius/maximum radius of the ellipsoid and (iii) manipulability measure (volume of the ellipsoid). These three criteria are calculated based on the singular-value decomposition of the Jacobian matrix of each digit. The major axis direction angle criterion is calculated from the horizontal (X–Y plane in Fig. 1(d)) representing the front view of the three digits with the object. The major axis direction angle measurement is based on the weak sense (e.g., projecting the 3D major axis onto the 2D plane of object rotation).[7] This major axis direction angle, computed clockwise from the positive z-axis in rotation motion (angles A, B, C in Fig. 4), was used to investigate the posture (orientation) of the ellipsoid.

The ratio of the minimum/maximum radii of the manipulability ellipsoid given by $\boldsymbol{\sigma}_3/\boldsymbol{\sigma}_1$ represents its shape. If this ratio is one, the ellipsoid is spherical and hence the fingertip can move uniformly in all directions. But if this ratio is close to zero, then the ellipsoid tends to be a straight line, which denotes a singular configuration of the finger. The volume of the manipulability ellipsoid is given by $\boldsymbol{w} = \sqrt{|\boldsymbol{J}_{\boldsymbol{I}}\boldsymbol{J}^{\boldsymbol{T}}_{\boldsymbol{I}}|}$. Since the unit input condition was considered, the manipulability measure values are dimensionless. The above-mentioned three indices were separately obtained for all 30 subjects.

The analyses were performed by obtaining joint angles from the experiment data where all the joint positions of the three fingers are known. For the index and middle fingers, the angles between the links are calculated as follows:

$$\boldsymbol{\theta}_{F,\,C,\,\mathrm{A/A}} = \sin^{-1}\left(\frac{V_{1,\,F,\,C,\,\mathrm{A/A}} \times V_{2,\,F,\,C,\,\mathrm{A/A}}}{|V_{1,\,F,\,C,\,\mathrm{A/A}}||V_{2,\,F,\,C,\,\mathrm{A/A}}|}\right), \tag{8}$$

$$\boldsymbol{\theta}_{F,\,C,\,\mathrm{F/E}} = \sin^{-1}\left(\frac{V_{1,\,F,\,C,\,\mathrm{F/E}} \times V_{2,\,F,\,C,\,\mathrm{F/E}}}{|V_{1,\,F,\,C,\,\mathrm{F/E}}||V_{2,\,F,\,C,\,\mathrm{F/E}}|}\right), \tag{9}$$

where

A/A = Abduction/adduction,
F/E = Flexion/extension,
F = Index finger and middle finger,
C = [MCP, PIP, DIP joints, tip],
D = [CMC, MCP, IP joints, tip],
$V_{1,F,C,A/A}$ = Position vector given by $(C(i+1)x, yt - C(i)x, yt)$,
$V_{2,F,C,A/A}$ = Position vector given by $(C(i+1)x, yt+1 - C(i)x, yt+1)$,
$V_{1,F,C,F/E}$ = Position vector given by $(C(i+1)y, zt - C(i)y, zt)$,
$V_{2,F,C,F/E}$ = Position vector given by $(C(i+1)y, zt+1 - C(i)y, zt+1)$,
$i = 1, 2, 3$ are the joint numbers,
t = Instantaneous frames of motion of the three fingers.

Here, for $i = 1$, for the first joint (MCP) of the finger, the rotation angle is obtained by considering the vector of the next joint (PIP). Hence, $C(i+1)y, zt+1$ implies finger's PIP joint position vector $[0\ y\ z]^T$ at $(t+1)$th frame of motion.

The mean and standard deviation of the three criteria under study were then used to first assess the cooperative rotational motion. The estimation of significant difference ($p < 0.05$) in every criterion of each digit among the 30 healthy subjects was performed using 3-way Analysis of Variance (ANOVA) with the subjects, rotational postures representing the two motions and the planes as the three factors. The analysis is performed with no replication. Two interactions, one between the subjects and the rotational postures and the other between the subjects and the planes are considered. Because the main objective of this study was to find how the human subjects affect the manipulability criteria of the three digits in each motion represented by the postures of each plane, the subjects were considered as one of the factors. The null hypothesis was that each of the criteria was not influenced by the subjects. Multi-comparison by the Bonferroni method in Matlab was utilized to compute the subject pairs contributing the significant difference in the data analysis when there was significant difference in each criterion of any of the digits.

3. Results

The results were segregated for Motion I and Motion II separately as performed in each of the three planes. The manipulability ellipsoids of one subject are shown in Fig. 4 that correspond to the rotation postures representing Motions I and II in the ETP plane. Figure 4 shows the ellipsoid at three postures for one sample subject. Although we performed the study in three discrete planes, we expected that the results would also hold for the case in-between the planes.

The statistical analysis of the data obtained from the rotation experiments is described next by considering the interaction between the factors: subjects and rotational postures representing the motions (Motion I and II). The orientation of the major axis of the manipulability ellipsoid was first investigated in all the three planes. The significant difference describes the difference between the criterion value of interest and the mean value. The significant difference was considered for the criterion values of all the 30 subjects in (a) each posture (CR, RR or LR), (b) between the postures (CR–RR and RR–LR) and (c) between the planes. There existed significant difference ($p = 0.0177$ in ETP, 0.0021 in ITP and 0.0019 in FXP) in the major axis direction angle criterion of the index finger among the subjects within each posture. The pairs of subjects with significant differences from the mean of all the subjects in the major axis direction angle criterion are subjects (7, 18) and (7, 27) in ETP, subjects (6, 7), (6, 17) and (6, 27) in ITP and subjects (4, 23) and (13, 23) in FXP.

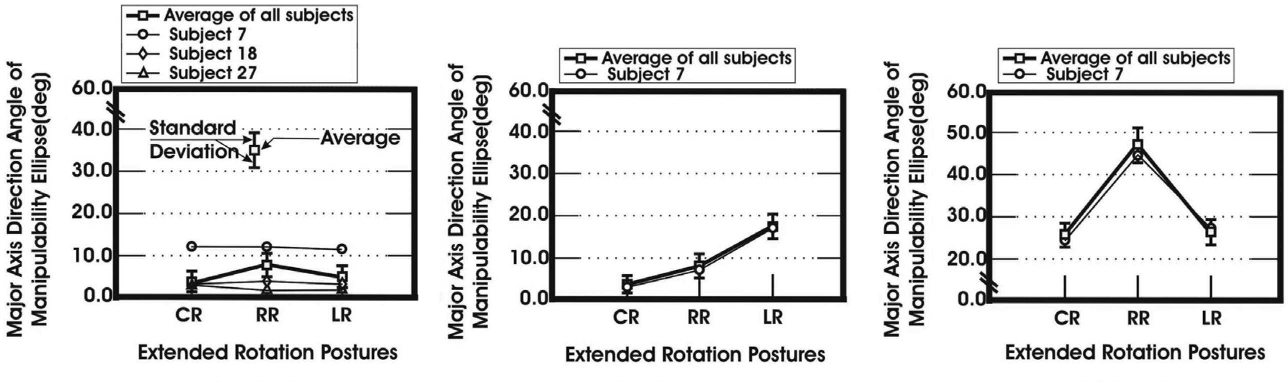
There existed no significant difference ($p = 0.0823$ in ETP, 0.09 in ITP, 0.07 in FXP for middle finger, and $p = 0.1528$ in ETP, 0.0604 in ITP, 0.0523 in FXP for thumb) in the major axis direction angles of the middle finger and thumb across all the subjects within each posture. Thus, the major axis direction angle of the manipulability ellipsoid of the index finger was influenced by the subjects. For each digit, there existed significant difference ($p < 0.05$) in the major axis direction angle criterion among the three postures.

Next, the shapes (minimum/maximum radii ratio) of the manipulability ellipsoids were investigated. There were significant differences from the mean within each posture ($p = 0.0017$ in ETP, 0.0019 in ITP, 0.0055 in FXP) in the minor/major axis lengths of the manipulability ellipsoids of the index finger of all the subjects, whereas there were no significant differences in the minimum/maximum radii ratio of the middle finger ($p = 0.0731$ in ETP, 0.07 in ITP, 0.08 in FXP) and thumb ($p = 0.0564$ in ETP, 0.0523 in ITP, 0.1682 in FXP). The pairs with significant differences in the ratio criterion of the index finger were subjects (11, 16) and (11, 29) in ETP, (12 14) and (12, 20) in ITP and (15, 3), (15, 4) and (15, 12) in FXP.

Among the postures for every digit, there existed significant difference ($p < 0.05$) in the ratio criterion as shown in Figs. 5–7. Lastly, the manipulability measures were examined. Due to significant difference in the ellipsoid volume criterion of the index finger ($p = 0.0084$ in ETP, 0.02 in ITP, 0.0197 in FXP) within each posture, the ellipsoid volume criterion was influenced by subjects (18, 6), (18, 20) and (18, 21) in ETP, (14, 25) and (14, 27) in ITP, and (13, 25) and (13, 27) in FXP.

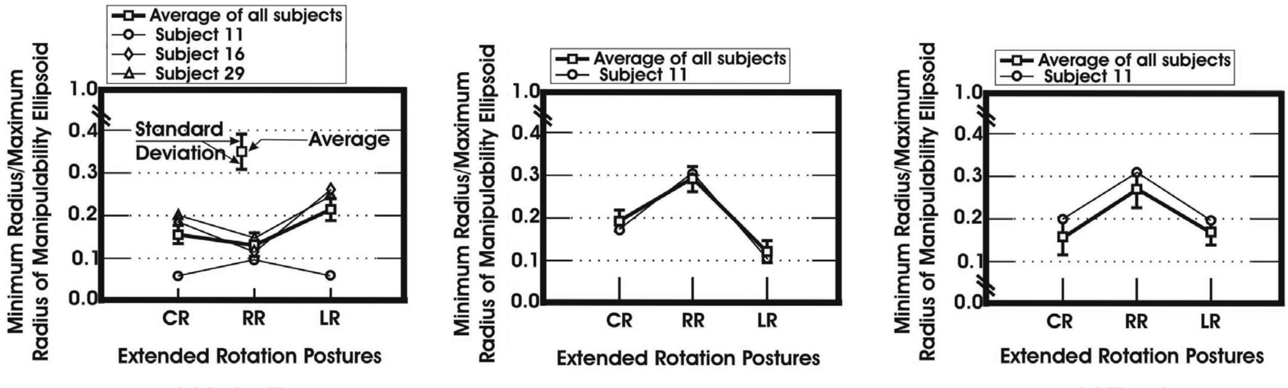
There were no significant differences within the postures in the ellipsoid volume of the middle finger ($p = 0.0853$ in ETP, 0.077 in ITP, 0.064 in FXP) and thumb ($p = 0.2237$ in ETP, 0.1851 in ITP, 0.1640 in FXP). Hence, the ellipsoid volumes of the middle finger and the thumb were not influenced by the subjects. Also, among the postures, there were significant differences ($p < 0.05$) in this ellipsoid volume criterion of each digit. As shown in Figs. 6 and 7, the activeness of both thumb and middle finger are explicitly depicted as per the rotation results given in Fig. 5.

In the interaction between the factors, i.e., subjects and planes, for the major axis orientation of the manipulability ellipsoid criterion, there existed significant difference in the rotational posture LR among the planes for the index finger ($p = 0.0096$ with the subject pairs (2, 6), (13, 6), (19, 6) and (26, 6)). No significant difference was found in the LR posture for the middle finger and the thumb ($p = 0.0906$ and 0.0731 respectively). For CR and RR postures separately, there existed no significant difference ($p > 0.05$) across



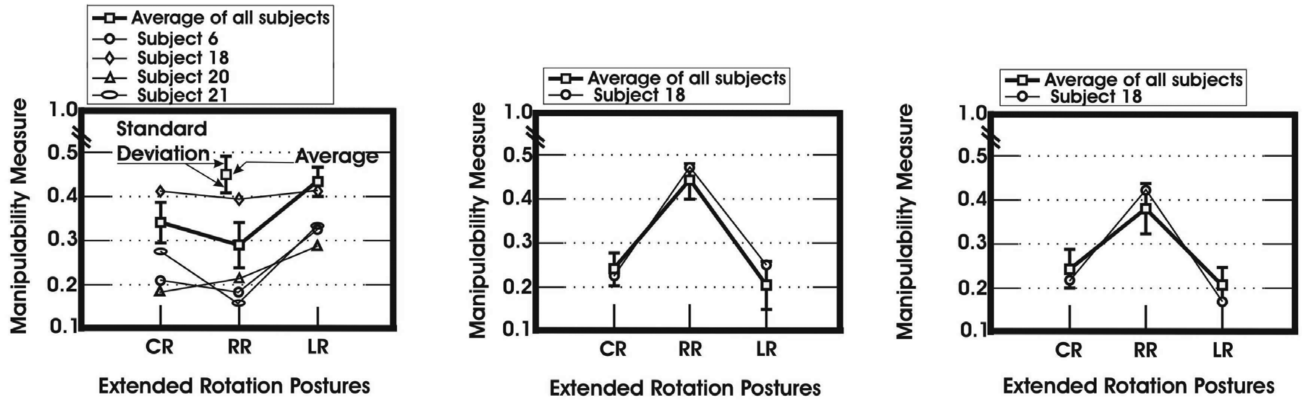
(a) Index Finger (b) Middle Finger (c) Thumb

(i)



(a) Index Finger (b) Middle Finger (c) Thumb

(ii)



(a) Index Finger (b) Middle Finger (c) Thumb

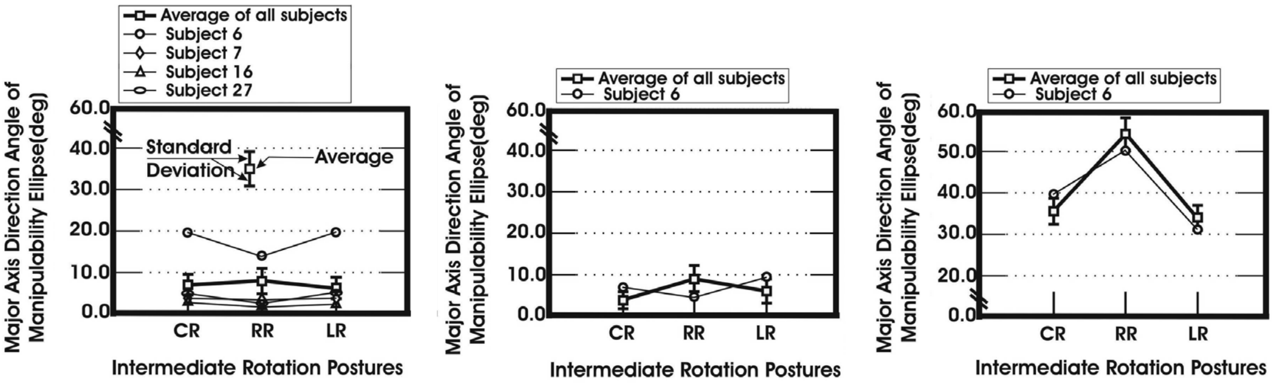
(iii)

Fig. 5. Numerical values of the three criteria for manipulability ellipsoids obtained using rotational experiments in ETP plane with 30 subjects. (i) Major axis direction angle; (ii) ratio of minimum radius/maximum radius; (iii) manipulability measure.

the subjects for this orientation criterion for the three digits among the three planes.

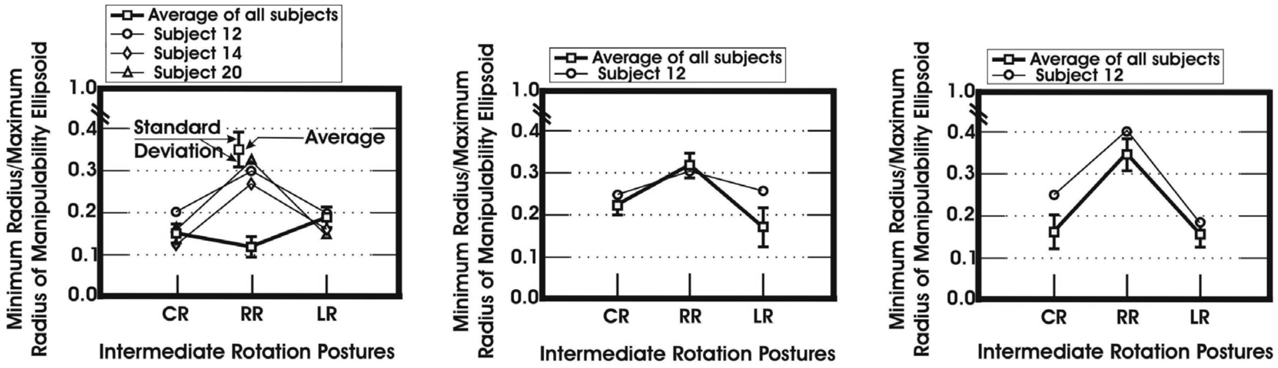
In case of the shapes of the manipulability ellipsoids criterion, for the rotational posture LR, there existed significant difference among the planes for all the three digits. For the index finger, middle finger and the thumb, the significant differences were $p = 0.002$ with the subject pairs (1, 11), (5, 11), (12, 11), (28, 11) and (30, 11), $p = 0.0313$ with the subject pairs (4, 3), (9, 3) (26, 3) and $p = 0.0023$ with the subject pairs (2, 6), (13, 6), (26, 6) respectively. For the CR and RR postures, no significant differences ($p > 0.05$) existed in this criterion for the three digits among the planes across the subjects.

Finally, in the volume of the manipulability criterion, again all the three digits exhibited significant differences (index finger: $p = 0.0078$ with the subject pairs (2, 18), (11, 18), (15, 18) and (20, 10), (middle finger: $p = 0.0356$ with the subject pairs (1, 22) and (6, 22)) and (thumb: $p = 0.0011$ with the subject pairs (1, 30), (9, 30) and (20, 30)) in the RR posture among the planes. For the CR and LR postures, there were no significant differences ($p > 0.05$) in the criterion of the three digits among the planes. Thus, in the interaction



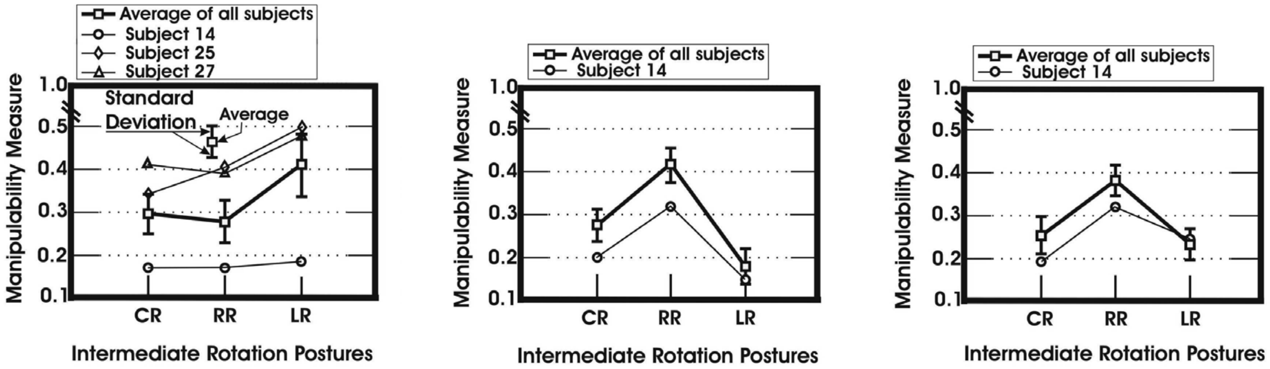
(a) Index Finger (b) Middle Finger (c) Thumb

(i)



(a) Index Finger (b) Middle Finger (c) Thumb

(ii)



(a) Index Finger (b) Middle Finger (c) Thumb

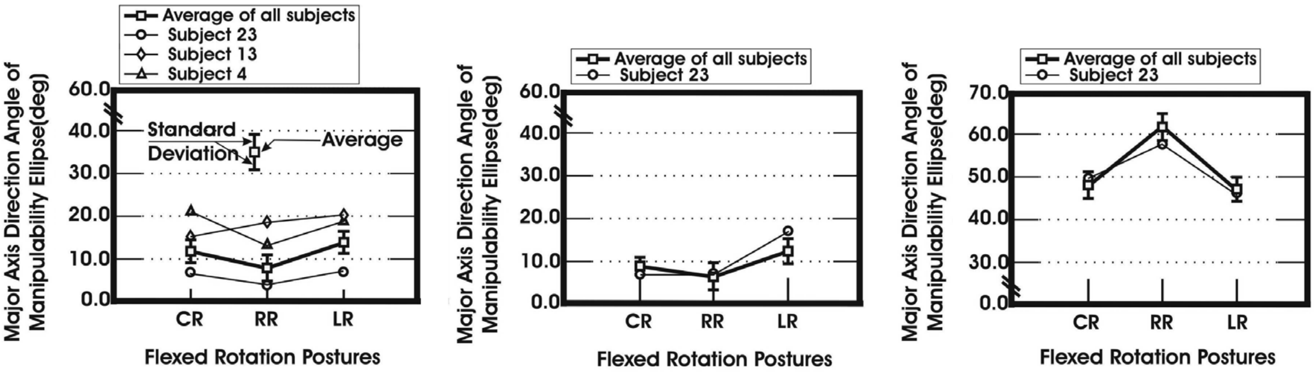
(iii)

Fig. 6. Numerical values of the three criteria for manipulability ellipsoids obtained using rotational experiments in ITP plane with 30 subjects. (i) Major axis direction angle; (ii) ratio of minimum radius/maximum radius; (iii) manipulability measure.

between the factors i.e., subjects and planes, the influence of the subjects on the index finger is explicit.

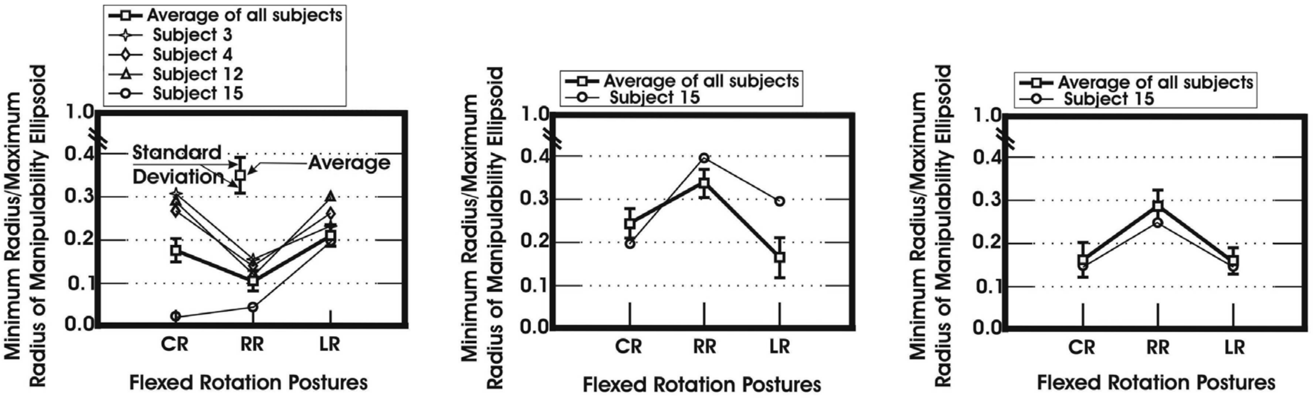
Tables I and II show the three parameters studied for Motion I and Motion II. The manipulability measure corresponds to the normalized ellipsoid volume and therefore no unit is specified.

In Table I we see that the thumb has the maximum value for the major axis direction angle for the three planes, while the ellipsoid volume is maximum for the middle finger in ETP and ITP planes. The index finger has the least value in all cases. In Table II we find that the thumb has the maximum value for the ellipsoid major axis direction angle in the three planes, while the middle finger has the maximum value for the other two criteria in ETP and FXP planes. Again, the index finger has the least value of the three criteria for the three planes. Based on these results for the rotation postures in all the three planes for Motion I and Motion II we conclude that the thumb and middle finger work actively whereas the index finger works passively to perform object rotation. Since the thumb is not confined to move only within the flexion/extension plane of the index and middle fingers, the thumb is more active than the middle finger. Also, the non-influence of the subjects on the criteria of the thumb and middle finger makes them



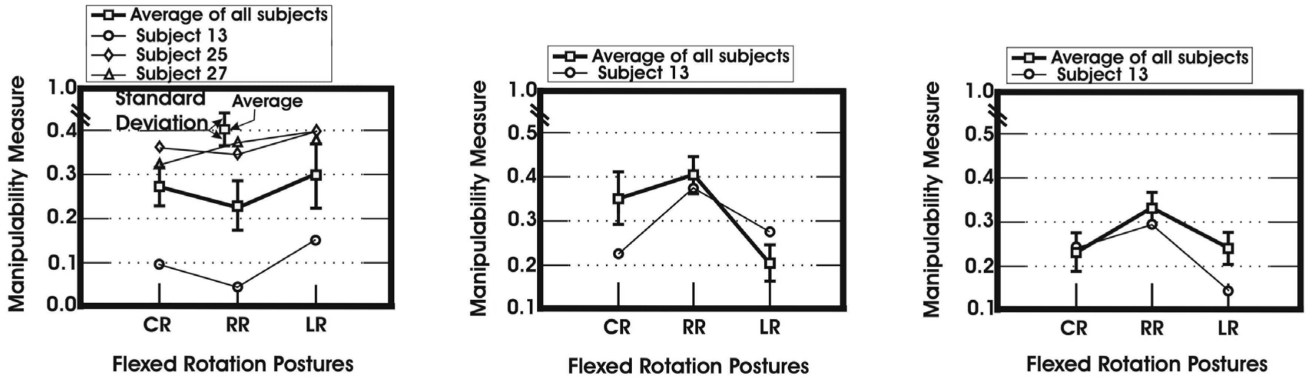
(a) Index Finger (b) Middle Finger (c) Thumb

(i)



(a) Index Finger (b) Middle Finger (c) Thumb

(ii)



(a) Index Finger (b) Middle Finger (c) Thumb

(iii)

Fig. 7. Numerical values of the three criteria for manipulability ellipsoids obtained using rational experiments in FXP plane using 30 subjects. (i) Major axis direction angle; (ii) ratio of minimum radius/maximum radius of the ellipsoid; (iii) manipulability measure.

active digits in the performed rotation motions in all the three planes.

Variations in the manipulability ellipsoids will be greater if there is greater movement of the fingertip. We designed the experiments for two motions (I and II) so that the distances moved in the two cases are different. Hence, the average distances (computed by the distance formula for the two extreme points representing each motion) traveled by the three digits of all the 30 subjects in each plane have been also analyzed and are given in Tables III and IV. It is seen that the average distances traveled by the index finger in Motion I and Motion II separately are less than the distances traveled by the other two fingers in all the respective cases. This further reinforces the conclusion we have drawn regarding the activity of the thumb and middle finger.

4. Discussion

Based on the three criteria of major axis direction angle, minimum/maximum radii and volume of the manipulability ellipsoids, the functionality of the thumb, index and middle fingers is investigated across 30 healthy subjects for the

Table I. Criteria differences in Motion I of the three fingers in all the planes.

	Motion I								
	ETP			ITP			FXP		
Variation in criteria	Thumb	Index	Middle	Thumb	Index	Middle	Thumb	Index	Middle
Major axis direction angle (deg)	20.00 (± 3.50)	4.00 (± 1.00)	5.00 (± 2.00)	20.00 (± 3.00)	2.00 (± 1.00)	5.00 (± 2.00)	13.00 (± 2.00)	4.00 (± 1.00)	2.00 (± 1.00)
Minimum/maximum radii	0.10 (± 0.02)	0.02 (± 0.01)	0.10 (± 0.01)	0.18 (± 0.02)	0.03 (± 0.01)	0.10 (± 0.02)	0.13 (± 0.02)	0.08 (± 0.02)	0.09 (± 0.02)
Ellipsoid volume	0.13 (± 0.05)	0.05 (± 0.01)	0.20 (± 0.01)	0.12 (± 0.02)	0.02 (± 0.01)	0.13 (± 0.01)	0.10 (± 0.04)	0.06 (± 0.03)	0.05 (± 0.06)

Table II. Criteria differences in Motion II of the three fingers in all the planes.

	Motion II								
Variation in criteria	ETP			ITP			FXP		
Major axis direction angle (deg)	Thumb	Index	Middle	Thumb	Index	Middle	Thumb	Index	Middle
	19.00 (± 3.0)	3.00 (± 1.00)	8.00 (± 1.00)	22.00 (± 4.00)	3.00 (± 1.0)	4.00 (± 1.0)	14.00 (± 1.00)	5.00 (± 1.0)	5.00 (± 1.00)
Minimum/maximum radii	0.09 (± 0.03)	0.08 (± 0.01)	0.17 (± 0.02)	0.18 (± 0.02)	0.07 (± 0.03)	0.14 (± 0.04)	0.13 (± 0.02)	0.10 (± 0.01)	0.18 (± 0.02)
Ellipsoid volume	0.18 (± 0.05)	0.14 (± 0.03)	0.25 (± 0.04)	0.14 (± 0.01)	0.13 (± 0.03)	0.23 (± 0.01)	0.11 (± 0.02)	0.08 (± 0.02)	0.20 (± 0.01)

coordinated rotation of small objects. Even though there are numerous possibilities to rotate an object grasped by three fingers, we consider a small subset of these in our study. After prior instructions and training, the subjects perform rotations in two independent motions: Motion I and Motion II, each in three different planes (ETP, ITP and FXP). Based on Tables I–IV and the inferred observations, our new results suggest that both thumb and middle finger are more active than the index finger in cooperative rotational motion. More precisely, the index finger behaves as a passive digit whereas the thumb and middle finger actively impart rotational movement to the object about the index finger. Finger activity for cooperative rotational motion is studied for the first time. We performed the Bonferroni test through multi-comparison to understand which subject pairs have significant effect on the mean of each of the parameters that we measured. As the finger lengths across the population are different, the data recorded during the experiments for each parameter would also vary based on finger lengths, holding postures etc. Hence, there will be variation in the values of each parameter and the Bonferroni test gives the corresponding pairs of subjects. Even though there is variation, the results are valid for every subject in each plane, and this proves our hypothesis. The variation of pairs (due to different finger lengths, postures etc) will be analyzed in the future.

Several researchers studied the grasping tasks involving two or more digits.[14,27–31] Those who studied the participation of a single digit in a grasping task did not comment on its functionality in comparison with other digits.[14,31] The joint coordination of a digit[32] and capability of human grasp trajectory prediction[14] are investigated in their works. While studying planned coordinated motion such as grasping, finger joint motions are found to be highly organized and correlated. It is these correlations of human fingers that are required to be mimicked through exoskeletons to provide rehabilitation and physical therapy. As mentioned by Kapur *et al.*[15] and Grinyangin *et al.*,[30] the joint coordination is partially due to finger biomechanics. The activation of flexor muscles causes the coordination of the MCP, PIP and DIP joints to vary in grasping. In our coordinated rotation motions, the motion range is significantly less compared with that of a grasping task. The PIP and DIP joints move less compared with the MCP joint of the digits. Further, it seems that the thumb is more likely

Table III. Average distance traveled by the three digits in Motion I in all the three planes.

	Motion I in mm (SD)		
Digit	ETP	ITP	FXP
Thumb	5.74 (± 0.96)	5.77 (± 1.01)	3.68 (± 0.77)
Index finger	4.17 (± 0.98)	4.40 (± 0.96)	3.44 (± 0.96)
Middle finger	6.76 (± 1.09)	6.67 (± 1.03)	6.68 (± 1.02)

Table IV. Average distance traveled by the three digits in Motion II in all the three planes.

	Motion II in mm (SD)		
Digit	ETP	ITP	FXP
Thumb	10.82 (± 1.27)	10.87 (± 1.25)	8.48 (± 1.57)
Index finger	7.77 (± 1.34)	7.63 (± 1.16)	6.13 (± 0.73)
Middle finger	12.04 (± 1.99)	11.61 (± 1.68)	11.00 (± 1.17)

to undergo ad-abduction, while the middle finger probably flexes and extends more to cause rotations.

Lin *et al.*[31] performed the 3D analysis of all the thumb joints in six different gripping tasks, thereby covering the most gripping tasks performed in daily life. They quantified the participation of each thumb joint and correlated the relationship between the range of motion, maximum joint angle and phalanx lengths. In addition to describing the experimental observation of a stereotypical human grasping trajectory, Friedman and Flash[14] designed a model based on optimization to replicate the trajectory. They considered only the index finger in their study. They found that the model derived from only the kinematics information (minimum joint angular jerk) rather than that involving dynamics (the center of mass of the phalanx and the density in the inertia matrix calculation) is suitable to predict the human grasping trajectory. Since it is observed by Friedman and Flash[14] that the finger trajectories can be planned based on the joint level kinematics considerations, we also utilized the kinematics-based model in our work for the finger behavior analysis in rotation manipulation of small objects. Unlike Lin *et al.*[31] and Friedman and Flash,[14] we involved three fingers, including thumb, to perform coordinated object rotation, which we consider as more complex.

For two-fingertip-pinch translation motion,[5] it is observed that the index finger is active due to significant difference in the manipulability criteria among the translation postures. As the thumb's manipulability index does not vary much, it is concluded that the thumb supports the combined flexion/extension translation motion passively. The anatomical reason is that the thumb is confined to move within the flexion/extension plane of the index finger. Based on the differences in the values of these criteria, conclusions are quantitatively inferred in terms of activeness and passiveness of a digit. Both cooperative translation and rotation manipulation results reveal important properties of the dexterity of digits. The role of the thumb and index finger in cooperative translation is significantly different from that in cooperative rotation. While the thumb tip is suggested to be passively following the trajectory of the index fingertip in cooperative translation,[5] in cooperative rotation we find that the thumb tip traverses primarily on its ad-abduction plane. Cooperative rotation is lot easier to perform in the ITP plane than in the ETP and FXP planes. This study and that in Yokogawa and Hara[5] individually predict contradictory roles of the thumb and index fingers for two different manipulation goals. However, the two studies collectively provide a near comprehensive result on how the three fingers might function in object manipulations.

Kapur *et al.*[15] tested the two hypotheses that shear force components may show features such as unintended force production by non-task finger in the direction opposite to the instructed force and also unintended force in the direction orthogonal to the instructed direction. Also, strong multi-finger synergies would be observed stabilizing both magnitude and direction of the total force vector. Both the hypotheses were found to be true in that the index finger induced the smallest unintended forces in non-task finger whereas multi-finger synergy indices reflected strong covariation in the space of finger modes. This reduces variability of the total applied force magnitude. Although we did not study the fingertip forces applied, we still found that there exist similar synergies between the thumb, index and middle fingers for rotation tasks. In this case the thumb and middle finger were more active than the index finger but all three participated in the rotation of the object.

The assumptions made to compute manipulability in the present study are (i) single point contact without friction between the fingertips and the object, and (ii) unit size of the input joint angular velocity. Our present investigation is limited only to the tip-pinch-based cooperative rotational movements. Our conclusions, therefore, may be different due to following: Differences in positions and orientations of the target planes and postures during the experiment were permitted to accommodate anatomical variations in the finger/palm sizes of the subjects. In a real case the object may not rotate exactly in one plane because rotation involves coordination of multiple degrees of freedom of the hand. We have analyzed two motions (I and II) in which the CR posture is not assumed to be the center, i.e., CR is not symmetrical about the LR and RR postures. Also, from our results it is not possible to establish if human clockwise and counterclockwise motions are identical in terms of the finger degrees of freedom involved. Factors such as friction, elasticity and fingertip forces were ignored in our study.

Although the subjects perform coin rotation in three different planes (ETP, ITP and FXP), we realize that this motion is not quite restricted to these planes. We analyzed the motion data of different subjects and realized that the fingertip velocities (dx/dt) perpendicular to these planes (parallel Y–Z plane) are not exactly zero. The motion of the coin could therefore be considered in three dimensions due to which we choose to analyze the finger activity through the manipulability ellipsoids. One could also assume the coin motion to be restricted to these planes, set dx/dt to zero to obtain manipulability ellipses on the Y–Z plane and analyze them. Accordingly, we obtained the Y–Z manipulability ellipses for all 30 subjects manipulating the coin in the ETP plane. We find that our observations based on the ellipsoids are not significantly different from those garnered from the manipulability ellipses. This could be because the out-of-plane angle of the major axes of ellipsoids when projected on the horizontal plane averages close to 9° for all subjects.

We still work with the assumption that static equilibrium is always maintained between the fingers and the coin (thin plate). We perform the analysis with the assumption of the tip-pinch contact, although, in reality, the thumb and fingers are in "pad-contact" with the object. In case of the latter, the analysis with the manipulability ellipsoid (or with the manipulability ellipse) will no longer be valid. We assume that the pad area of contact is close to zero such that the conditions of equilibrium and no slip are just about satisfied. We assume that the fingers do not exert extraneous gripping forces, which contribute to increase in the pad area of contact. We note that even a two-finger grip (thumb and index or middle finger) is adequate to manipulate an object in rotation. We only consider three rotation postures (CR, RR and LR) in each of the three planes, although in postures between them the coin may deviate out of plane marginally. As previously mentioned, we choose to study manipulability ellipsoids over manipulability ellipses realizing that the motion of the coin is not quite restricted to rotation about an axis.

The new results obtained in this paper are important from the mechanical design and control, ergonomic and also clinical perspectives. In the design of the most existing exoskeleton devices for finger rehabilitation/therapy, the thumb is considered as passive. Hence, such designs are only for open–close grasping of objects. We have shown that in order to manipulate an object in rotation, the thumb must have additional degrees of freedom that are actively controlled. Any manipulation may be considered as a combination of translation and rotation, hence an active thumb is a necessity. At present we are developing a three-finger exoskeleton based on the above results.[32,33] In terms of ergonomics, our study clearly shows that for rotating objects the index finger does not move much, while the middle finger and thumb control the rotation. This ensures that fatigue or strain of these two fingers will be more as compared with the index finger. In clinical therapy most rehabilitation devices[24] dealing with finger coordination could use this knowledge to activate the fingers differentially.

The major advantage of the study lies in the fact that the investigation has been performed on a wide number (30) of healthy human subjects. The advantages of using a linkage system to simulate the thumb involves obtaining an optimal posture by incrementing the flexion/extension degrees of freedom by 1° toward the full range of the CMC, MCP and IP joints with the abduction/adduction degrees of freedom neutral in the lateral tip-pinch task.[34] Also, considering the CMC and MCP joint axes as the non-orthogonal and non-intersecting axes of rotation with the DH parameter notations will help the researchers and clinicians to understand the restoration and clinical problems regarding the thumb functionality.[35]

However, it has to be emphasized that the obtained results may differ if the non-orthogonal and non-intersecting joint axes of rotation representing the MCP and CMC[35] joints of the digits are considered due to the condyloid and saddle shapes of joints. The assumption of unit joint velocity as input is used in our study, but the tendon-driven system may not be using this assumption because the inputs are the combination of different muscle coordination patterns.[1] The main disadvantage of the kinematics model of the thumb used in our study with the orthogonal and intersecting joint axes of rotation at the CMC and MCP joints model is that our model may not accurately represent the net joint torque transformation into thumb tip forces of the human anatomical thumb.[4]

The main experimental or application drawbacks are that these experiments were carried out slowly (in 3 seconds) by the subjects compared to a normal real-time action in daily life, and hence it is assumed that the object motion is quasi-static. Therefore, the results could vary under dynamic conditions of object rotations. The fingertip motion has been recorded by an eight-camera motion capture system and each measurement may be associated with a small, negligible error due to camera calibration etc. Also, the study is limited to only one particular movement although the human hand is capable of infinite movements. Hence, the direct application of the results of this study to robotic hand control for multi-finger manipulation would be challenging.

5. Conclusion

In the present investigation, experiments using a 3D motion capture system involving the thumb, index and middle fingers were performed. The joint angle variations were studied for cooperative object rotation motions. From the results it has been found that the thumb and middle finger actively control the rotation of small objects, which are passively supported by the index finger. The findings of this study are important in assessing injury and in planning therapy for the thumb, index and middle fingers-related functions. A useful guidance for designing controllers for rehabilitation devices, prosthetic hands and robotic therapist can also be obtained from these results.

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