Characterization of Multijoint Finger Stiffness: Dependence on Finger Posture and Force Direction

Theodore E. Milner* and David W. Franklin

***Abstract*— The two-dimensional static stiffness of the index finger was measured with the interphalangeal joints in flexed and extended postures. The stiffness of the relaxed finger was compared with the stiffness when voluntary force was exerted in different directions. The finger stiffness was found to be anisotropic, with the direction of greatest stiffness being approximately parallel to the proximal phalange of the finger. This direction was relatively unaffected by finger posture or direction of finger force. Finger stiffness was more anisotropic when the interphalangeal joints were extended than flexed. The stiffness was most anisotropic when the interphalangeal joints were extended and force was being exerted in the direction of pointing, while it was least anisotropic when the interphalangeal joints were flexed and force was being exerted in directions normally associated with pinching and tapping actions. The stiffness of the individual finger joints was computed and the relation between stiffness and joint torque was examined. Previous studies, which examined single finger joints in isolation, had found that joint stiffness varied in a linear fashion with net joint torque. In contrast, we did not find a monotonic relation between joint stiffness and net joint torque, which we attributed to the need to vary the amount of cocontraction of antagonistic muscles when controlling the direction of finger force.**

***Index Terms*—Extension, finger, flexion, stiffness ellipse.**

I. Introduction

KNOWLEDGE of how the mechanical impedance of the fingers varies when voluntary force is being applied to an object is of interest in areas such as medical robotics, rehabilitation, and design of force-reflecting interfaces for teleoperation. The manipulation of objects by prosthetic hands and dextrous medical robots might be improved if the natural mechanical behavior of human fingers could be mimicked by the dextrous manipulator. Similarly, control parameters for functional electrical stimulation (FES) of paralyzed finger muscles could be chosen so that the mechanical impedance produced by FES more closely matched that occurring during normal central nervous system control. Mechanical interfaces designed to provide haptic feedback to human operators about the forces being applied to a remotely manipulated object must be mechanically stable when coupled to the hand of the human operator. Achieving stability might require adaptive modulation of the mechanical impedance of the interface in response to natural modulation of the mechanical impedance of the fingers.

The finger consists of three joints, the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints. In most published studies of finger stiffness to date, motion of the finger has been constrained about a single joint, namely, the DIP joint in the case of the thumb or the MCP joint in the case of the index finger [1]–[6]. These studies have shown that joint stiffness increases with the level of muscle activation, i.e., the joint torque, or with the degree of voluntary stiffening of the joint by cocontraction of flexor and extensor muscles. However, in most actions, finger movement is not restricted to a single joint. Fingers have parallel axes of rotation at the DIP, PIP, and MCP joints, subserving flexion and extension and an orthogonal axis of rotation at the MCP joint, subserving abduction and adduction. Flexion and extension predominate in many finger actions, e.g., grasping, pinching, tapping, pushing, and poking. Abduction and adduction come into play more during exploratory and manipulative actions. The muscles which abduct and adduct the MCP joint are also flexors of the MCP joint. Whenever they are activated during finger flexion, they will stiffen and stabilize the MCP joint around the adbuction/adduction axis.

The mechanical impedance of multijoint structures, such as fingers, will vary according to the direction of displacement. This has been shown recently, in relation to the stiffness of the thumb and index finger during a grasping task [7]. Studies of the impedance of the human arm indicate that directional differences in stiffness can be as large as an order of magnitude [8]. Consequently, it is critical in applications such as those referred to earlier, where displacement can occur in more than a single direction, that directional properties of mechanical impedance be quantified. The aim of the present study was to describe and quantify the directional properties of multijoint finger stiffness.

Mussa-Ivaldi *et al.* [9] developed a technique to measure two-dimensional (2-D) static stiffness characteristics of the human arm. They displaced the hand in different directions by small amounts from a stable equilibrium posture and determined the components of the resulting force vector. In general, they found that the force vector did not point in the same direction as the displacement, indicating that the stiffness was not uniform in all directions. The endpoint

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stiffness of the arm was represented by an ellipse whose major axis was oriented along the direction of the larger of the two eigenvectors associated with a 2×2 symmetric stiffness matrix. The shape of the ellipse was determined by the ratio of the two eigenvalues. They showed that the long axis of the ellipse was oriented along a line joining the hand and shoulder and that the ellipse became more elongated as the elbow approached full extension. Stiffening the arm by cocontracting flexor and extensor muscles while producing zero net torque at the joints, resulted in an increase in the size of the stiffness ellipse without significantly altering its orientation or shape.

Although the dependence of orientation and shape of the endpoint stiffness of the arm on the arm posture is well-documented [8]–[11], much less attention has been given to the possible dependence of these parameters on the direction of voluntary force. Dolan *et al.* [11] reported no change in orientation, shape, or size of the stiffness ellipse with the direction of voluntary force. However, the forces which they used were very small (<3% of maximum). McIntyre *et al.* [12], employing a 20-fold greater force range, did find substantial increases in the magnitude of the eigenvalues (size) and changes in eigenvalue ratio (shape) when the force became large, although their study was limited to one arm posture and two force directions. While some general principles regarding the dependence of limb endpoint stiffness on posture emerge from studies of the arm, these cannot be applied directly to the finger because the anatomical arrangement of finger muscles leads to activation synergies, which are different from those of muscles which span the shoulder and elbow joints.

The finger is controlled by two sets of muscles: the extrinsic muscles which exert primary forces and the intrinsic muscles which serve coordinating and stabilizing functions. Almost all of these muscles are bi- or triarticular. The geometrical arrangement of some muscles is such that they flex one joint while extending another. Consequently, cocontraction of finger flexor and extensor muscles occurs frequently [13]. Such cocontraction would result in a less systematic relation between joint stiffness and joint torque for the finger than for the arm.

The objective of the present study was to examine the effects of finger posture and direction of finger force on finger stiffness for tasks involving flexion and extension of the finger. In particular, we wanted to confirm that the ellipse representing the 2-D stiffness of the finger, like that of the arm, would be more elongated for extended than flexed postures. We also wanted to determine whether the orientation of the stiffness ellipse was related in a simple manner to the finger geometry, as had been found for the arm. Finally, we wanted to establish whether force direction affected the shape of the stiffness ellipse in a consistent manner. We adapted the procedure of [9] to measure the 2-D stiffness of the finger for flexed and extended postures and for several different force directions. The results of this study establish qualitative and quantitative features of finger stiffness which provide a basis for understanding adaptive modulation of mechanical impedance by humans and can be applied to selecting appropriate mechanical impedances for haptic interfaces and dextrous manipulators.

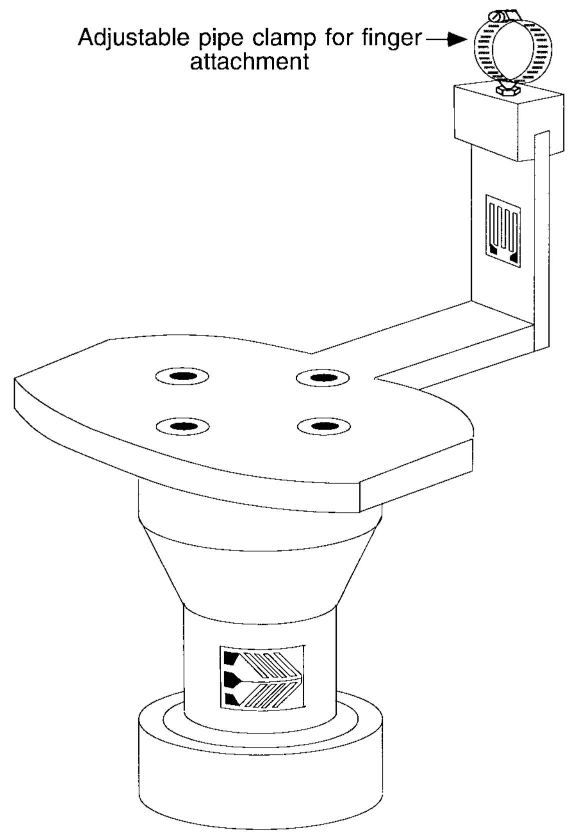

Fig. 1. Apparatus used to displace the finger and measure the resulting force. Location of strain gauges and finger clamp are shown. The finger clamp was locked in position, thereby constraining the orientation of the distal phalange of the finger.

II. Methods

A. Apparatus

The apparatus consisted of a torque motor coupled to a rigid manipulandum bar which projected 8.24 cm radially from the center of the motor shaft. The coupling between the motor shaft and the bar was instrumented with a transducer to measure the torque applied by the motor. This could be converted to tangential force at the end of the bar by dividing by the radial distance from the center of the motor shaft to the end of the bar, i.e., by the moment arm. A second transducer fixed to the end of the bar was oriented to measure the force applied along the radial direction. An adjustable pipe clamp attached to the force transducer served to clamp the fingertip and hold it in a fixed orientation (Fig. 1). A strip of athletic tape wrapped around the fingertip provided sufficient friction that the fingertip did not slip when forces were exerted along the barrel of the pipe clamp.

We adapted the technique developed in [9] to measure the finger stiffness in the plane defined by flexion and extension of the finger joints. Using a single torque motor, we applied controlled displacements to the finger in one of two directions. By repositioning the hand and rotating the manipulandum we were able to achieve eight different displacement directions (Fig. 2).

During measurement of finger stiffness, the subject's wrist and forearm were placed in a custom-molded orthopedic splint

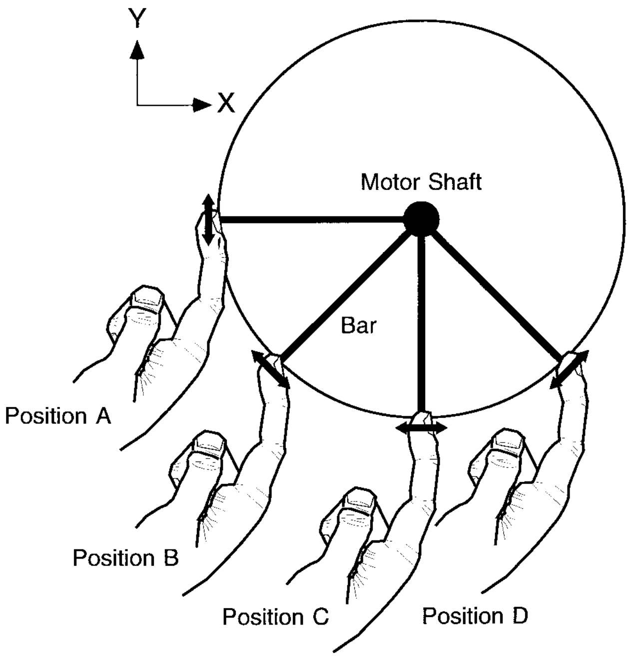

Fig. 2. Orientation of the eight directions of finger displacement with respect to the fingertip. The Cartesian coordinate system for finger displacement, shown in the upper left, is identical to that for the voluntary force, shown in Figs. 5 and 6. The fingertip was kept in the same orientation with respect to the coordinate system at all four positions.

that was sufficiently rigid to prevent wrist movement. The splint was bolted to a platform that supported the forearm. The platform and the subject were repositioned each time the orientation of the manipulandum was changed (Fig. 2) to maintain the same posture of the finger and the same orientation of the hand and arm with respect to the apparatus. The finger joint angles were preserved by superimposing a transparent template over the subject's finger. The template consisted of dots at the joint centers and line segments, at the appropriate angles, joining the dots. A separate template was made for each subject, customized for the lengths of the subject's finger segments. The position of the platform was adjusted until the alignment of the finger matched that of the template. Alignment of the template with a mark on the cast also preserved the forearm orientation. The orientation of the pipe clamp was adjusted each time in order to maintain a fixed orientation of the fingertip with respect to the external coordinate frame.

Angular displacement and velocity of the motor were measured with a potentiometer and tachometer, respectively, which were aligned along the axis of rotation of the motor. Angular displacements of approximately 3° were used. Consequently, the linear displacement and velocity of the end of the bar were directly proportional to their angular counterparts. Although the end of the bar followed a curved path during the displacement, the curvature was negligible since the radius of curvature was more than 16× the arc length.

B. Protocol

Five healthy male subjects between the ages of 23 and 29, all right-handed, participated in this study. The experimental protocol conformed to the guidelines of the Helsinki convention and was approved by the University Ethics Committee. Subjects gave informed consent to the procedure.

TABLE I
MAXIMUM VOLUNTARY FORCE (N)
MEANS AND STANDARD DEVIATIONS ($n = 5$)

Force Direction	Finger Extended	Finger Flexed
$+x$	10.6 [1.5]	11.2 [1.8]
$+y$	31.0 [5.6]	10.9 [2.5]
$-x$	49.7 [4.9]	45.2 [9.5]
$-y$	26.9 [7.4]	49.6 [19.4]

To study the effect of finger posture and finger force on the static finger stiffness, measurements were made on the right index finger. The finger was held either in an extended or flexed posture while the subject relaxed or exerted a force in one of four target directions. The finger postures and force directions are shown in Figs. 5 and 6. In all cases, the proximal phalange of the finger was flexed 20° at the MCP joint with respect to the long axis of the metacarpal bone (Fig. 2). This corresponded to an angle of about 60° with respect to the x-axis of our coordinate system, which was arbitrarily chosen to correspond to one of the displacement directions, as shown in Fig. 2. In the extended posture, the PIP joint angle was flexed 27° with respect to the long axis of the proximal phalange and the DIP joint angle was flexed 15° with respect to the long axis of the middle phalange. In the flexed posture, these angles were 80° and 50°, respectively. The target force directions were chosen to be roughly parallel or perpendicular to the long axis of the distal phalange.

The maximum isometric force (MVC) which the subject could exert at the fingertip was first determined for each of the four target directions for both the flexed and extended finger postures. We then measured the finger stiffness while the subject relaxed the finger and while the subject exerted a target force of 20% MVC in each of the four directions. The MVC varied considerably with both force direction and finger posture. The mean MVC values for the five subjects are listed in Table I.

The motor operated in a position servo mode with a servo stiffness of approximately 90 N/cm. The force was displayed on a computer screen as a polar plot, showing the direction and magnitude of the target force vector and the instantaneous voluntary force vector. The subject was required to maintain the voluntary force within a narrow target window (target force direction ±5°, target force magnitude ±5%) for a period of at least 2 s. The experimenter then triggered a servo displacement of the fingertip by means of a keyboard press. The timing of the keyboard press was unpredictable, which prevented the subject from anticipating the exact time of onset of the displacement. The fingertip was rapidly displaced by 4 mm (in approximately 50 ms) and held in the displaced position for a period of 1 s. The subject was instructed not to respond to the displacement. Five consecutive displacements were applied in each direction.

In a separate experiment, we placed small active bipolar surface electrodes (bandpass 50–500 Hz) over the flexor digitorum superficialis (FDS), first dorsal interosseus (FDI), first palmar interosseus (FPI), extensor digitorum communis (EDC), and lumbrical (LUM) muscles of one subject. The EMG was recorded at 2 kHz while the subject applied isometric force in each of the four target directions. Force was measured with a six-axis force-torque transducer. Ten isometric contractions of 1 s duration were performed for each direction with the finger in either the flexed or the extended posture. The rms EMG of each 1–s record was computed and averaged for the ten trials for each force direction and finger posture. Background "noise" was also recorded from each electrode while the muscles were relaxed and its rms value was subtracted from the rms EMG.

C. Analysis

The Cartesian coordinate system used for representing the displacement and force vectors is shown in relation to the finger in Fig. 2. The x and y components of the displacement vector were easily computed from the motor shaft angle and length of the bar. Computation of the x and y components of the force vector required that the motor torque first be converted into tangential force by dividing the torque by the length of the bar. The tangential force was then expressed in terms of its x and y components based on the motor shaft angle. The same was done for the radial force. Finally, the corresponding x and y force components were summed.

The static force and displacement vectors prior to the servo displacement were computed by finding the mean position and force during the 50-ms period immediately preceding the onset of displacement. They were again computed following the end of the displacement. Although the servo command to the motor lasted only 30 ms, the damping in the servo-controller prevented the velocity from reaching zero immediately. Measurements were made only after the velocity had stabilized at zero. The mean position and force were computed in successive 20-ms intervals, beginning 70 ms after the onset of the servo command. An example of the raw data recorded from the force, torque and displacement transducers for one displacement direction is illustrated in Fig. 3.

Displacement and force difference vectors $\Delta\boldsymbol{r}$ and $\Delta\boldsymbol{F}$ were computed for each 20-ms interval from the difference in mean position and mean force with respect to the initial values prior to displacement. These difference vectors were used to compute the coefficients of a 2×2 stiffness matrix $\boldsymbol{K}$ from the vector equation $\Delta\boldsymbol{F} = \boldsymbol{K}\Delta\boldsymbol{r}$. Expressed in matrix notation this becomes

$$\begin{bmatrix}\Delta F_x \\ \Delta F_y\end{bmatrix} = \begin{bmatrix}K_{xx} & K_{xy} \\ K_{yx} & K_{yy}\end{bmatrix}\begin{bmatrix}\Delta x \\ \Delta y\end{bmatrix}. \tag{1}$$

Forty pairs of difference vectors, comprising the eight displacement directions and the five repetitions for each direction, were used in determining the coefficients of the stiffness matrix for each subject for a given target force direction. The standard errors of the regression coefficients were determined, as well as the square of the multiple correlation coefficient (R^2).

The stiffness matrix was then decomposed into symmetric and antisymmetric components, as shown below, to separate contributions from conservative and nonconservative components of force

$$\begin{bmatrix}K_{xx} & K_{xy} \\ K_{yx} & K_{yy}\end{bmatrix} = \begin{bmatrix}K_{xx} & (K_{xy}+K_{yx})/2 \\ (K_{xy}+K_{yx})/2 & K_{yy}\end{bmatrix} + \begin{bmatrix}0 & (K_{xy}-K_{yx})/2 \\ (K_{yx}-K_{xy})/2 & 0\end{bmatrix}. \tag{2}$$

When multiplied by the displacement vector $\Delta\boldsymbol{r}$ the symmetric component of the stiffness matrix represents the force contribution of conservative forces while the antisymmetric component represents the contribution of nonconservative forces [9]. For a force field to be conservative its curl must be equal to zero. In the case of a 2-D elastic force field, as above, this implies that the off-diagonal elements of the stiffness matrix must be equal

$$K_{xy} = \frac{\partial F_x}{\partial y} = \frac{\partial F_y}{\partial x} = K_{yx}. \tag{3}$$

It is clear from this constraint that conservative forces can arise only from the symmetric component of the stiffness matrix. If the elastic force field of the finger were conservative, then the work done in displacing the finger in one direction would be equal and opposite to that done in returning it to its original position, resulting in zero net work. In general, the net work is not zero because some nonconservative forces are present.

The eigenvalues and eigenvectors of the symmetric component of the stiffness matrix were computed and used to define shape, orientation, and size parameters for an ellipse that provided a graphical representation of the 2-D finger stiffness. The ratio of force contributed by the symmetric and antisymmetric components was then computed for the eight displacement directions to provide a measure of the relative contribution of conservative and nonconservative forces. Since spring-like mechanical behavior is purely conservative, this ratio provided a measure of the degree to which the mechanical behavior of the finger was spring-like in nature.

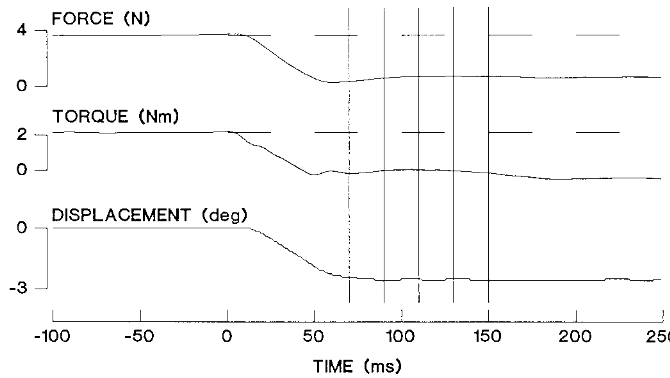

Fig. 3. Example of raw data collected from the force and torque strain gauges and the motor shaft potentiometer. The first trace represents the force acting along a radial line through the center of rotation of the motor. The second trace represents the torque on the motor shaft, which is directly proportional to the tangential force. The third trace represents the angular displacement of the motor shaft, which is directly proportional to the linear displacement of the finger. The four intervals used in computing the static stiffness are indicated by the vertical lines.

The 3×3 joint stiffness matrix was computed from the finger stiffness matrix, using the following relation

$$\boldsymbol{K}_{\theta} = J^T \boldsymbol{K} J + \frac{\partial J^T}{\partial \theta} \boldsymbol{F}. \quad (4)$$

The diagonal elements of $\boldsymbol{K}_{\theta}$ gave the single joint stiffness of the MCP, PIP, and DIP joints.

The coefficients of the stiffness matrix were tested for significance by applying a Student t-test and requiring that $P < 0.05$. A similar criterion was applied when comparing one stiffness coefficient with another, obtained from the same data set. The two were considered not to be significantly different if $2P > 0.05$. When comparing stiffness coefficients or eigenvalues obtained under different conditions, i.e., different target force directions or different finger postures, the difference in the stiffness coefficient or the eigenvalue between the two conditions was computed for each subject and a t-test for paired comparisons ($P < 0.05$) was used to determine whether the difference across subjects was significantly greater or less than zero.

Regression analysis was used to identify factors that might be responsible for variations in the parameters of the stiffness ellipse across the five subjects. Ellipse size, shape, orientation, or maximum eigenvalue was the dependent variable. Finger force, relaxed size, relaxed shape, relaxed orientation, and/or finger length were independent variables. From cross-correlation analysis it was established that the independent variables were uncorrelated with each other. The set of data points used in the regression did not include the values of a dependent variable measured under relaxed conditions since these were used as independent variables. Linear regression was first carried out with a single independent variable. A second and third independent variable were then added in a multiple linear regression analysis to determine whether more of the variance could be explained with additional independent variables. The coefficient of determination or coefficient of multiple determination r^2 was used to quantify the explained variance. The level for statistical significance was set at $P < 0.05$.

The variance due to intersubject variability across the eight conditions (four force directions $\times$ two finger postures) was compared with the intrasubject variance due to force direction (with finger posture constant) or finger posture (with force direction constant). The stiffness parameters tested in this way were ellipse size, ellipse shape, and maximum eigenvalue. Ellipse shape and maximum eigenvalue were adjusted by dividing by force magnitude to minimize its contribution to the variance.

III. Results

An example of the raw data recorded from the strain gauges and the potentiometer encoding the motor shaft angle is shown in Fig. 3. The data were transformed, as explained in Section II, to obtain the Cartesian forces and displacements. An example of the Cartesian forces and displacements for all eight displacement directions, along with the resulting stiffness ellipse is shown in Fig. 4. The displacement and force were sufficiently stable within 70 ms of the displacement onset that the static stiffness could be computed. The stiffness coefficients computed in consecutive 20-ms intervals (70–90 ms, 90–110 ms, 110–130 ms, and 130–150 ms following displacement onset), illustrated in Fig. 3, did not differ significantly ($2P > 0.05$). Since finger position was more stable the greater the elapsed time from the onset of displacement, the stiffness coefficients for the 130–150-ms interval, identified in Fig. 4, were used for all subsequent analysis.

A. Stiffness Matrix

The mean coefficients of the stiffness matrices for the extended and flexed finger postures are listed in Table II. The mean of the squared multiple correlation coefficient for K_{xx} and K_{xy} was 0.95 [S.D. 0.05], while for K_{yx} and K_{yy} it was 0.91 [S.D. 0.07]. This indicates that the mechanical response of the finger was well modeled by the equations of a 2-D spring element. The ratio of nonconservative forces to conservative forces was less than 0.15 in 44/50 cases. In most of the remaining cases it was less than 0.2. The relatively small contribution of nonconservative forces to the total force (<15%) indicates that the static mechanical behavior of the finger was predominantly spring-like. In general, the K_{xy} and K_{yx} terms of the stiffness matrix were not significantly different from each other (42/50 cases). When a significant difference between K_{xy} and K_{yx} was found, it was indicative of a contribution to the total force by nonconservative forces of more than 15%.

The diagonal terms of the stiffness matrix were always significantly greater than zero ($P < 0.001$). The off-diagonal terms were also significantly greater than zero ($P < 0.05$) with two exceptions. For three of the five subjects, neither the K_{xy} nor the K_{yx} coefficient was significantly different from zero when the target force was in the $+y$ direction with the finger flexed. This also occurred in the case of the K_{xy} coefficient for four of the five subjects, when the target force was in the $-x$ direction. These were the two situations in which the finger stiffness was most isotropic (see below).

B. Stiffness Ellipse

The ellipses drawn in Figs. 5 and 6 are representations of the eigenvectors and eigenvalues of the symmetric (spring-like) component of the stiffness matrix. The two axes of an ellipse are aligned with the directions of the eigenvectors. They indicate the directions of maximum and minimum finger stiffness. The lengths of the axes are proportional to the corresponding eigenvalues and, hence, indicate the relative magnitudes of the maximum and minimum finger stiffness. The five ellipses shown in each figure are drawn to the same scale. Thus, their size indicates the relative stiffness of the finger for the different target force directions.

We characterized the stiffness ellipses with three parameters: orientation, size, and shape. The orientation was represented by the angle of the long axis of the ellipse, i.e., the direction of greatest stiffness, with respect to the $+x$ axis. The size was quantified by determining the area of the ellipse and provided an integrated measure of the stiffness of the finger over all directions. The shape was quantified as the ratio of

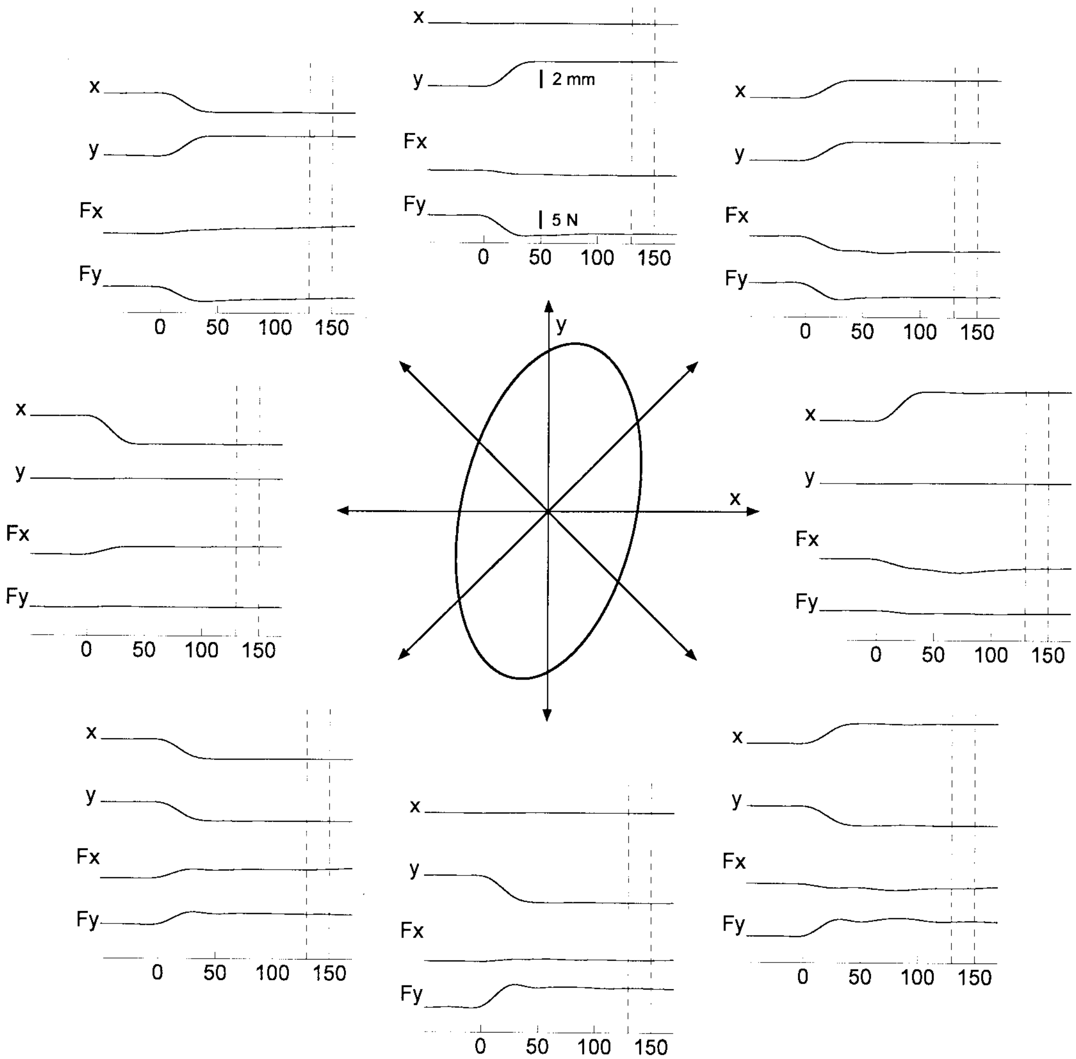

Fig. 4. Single-trial data for one force direction, showing displacements and forces in Cartesian coordinates for all eight displacement directions. The finger was in the extended posture and the target force was 10.7 N in the $-x$ direction. The corresponding stiffness ellipse is shown in the center. Subject 1.

TABLE II
STIFFNESS COEFFICIENTS (N/cm)
MEANS AND STANDARD DEVIATIONS ($n = 5$)

Force Direction	K_{xx}	K_{xy}	K_{yx}	K_{yy}
EXTENDED FINGER				
Relaxed	2.83 [1.13]	2.02 [1.34]	2.77 [1.86]	7.07 [4.14]
$+x$	6.30 [2.22]	4.91 [1.58]	5.23 [2.82]	16.49 [6.24]
$+y$	5.17 [1.93]	5.56 [1.64]	6.14 [2.33]	26.12 [6.88]
$-x$	10.13 [1.93]	3.44 [1.34]	0.85 [2.68]	23.40 [7.50]
$-y$	10.53 [1.64]	6.07 [0.80]	5.80 [1.06]	18.26 [6.00]
FLEXED FINGER				
Relaxed	2.65 [0.68]	0.78 [0.44]	1.35 [0.46]	3.60 [0.92]
$+x$	4.73 [1.11]	1.70 [0.37]	2.50 [0.66]	6.69 [1.20]
$+y$	5.45 [1.10]	0.28 [0.56]	1.49 [0.55]	8.98 [1.71]
$-x$	10.48 [2.03]	0.61 [1.01]	0.50 [1.09]	13.21 [2.53]
$-y$	12.66 [3.23]	4.22 [0.72]	4.16 [0.48]	16.87 [4.91]

the maximum eigenvalue to the minimum eigenvalue, i.e., the ratio of lengths of the axes of the ellipse, which provided an indication of the anistropy of the stiffness. The greater this value, the more anisotropic the stiffness. The means of the ellipse parameters are listed in Table III.

1) Size: The size of the stiffness ellipse was smaller when the finger was relaxed than when the subject produced a 20% MVC in any of the four target force directions. In general, the size of the ellipse increased as the force increased, regardless of the force direction. This is evident from comparison of the force magnitudes in Table I with the size parameters corresponding to the same force directions in Table III.

The magnitude of the finger force accounted for the largest proportion (50%) of the variance in ellipse size across subjects ($P < 0.001$). Including relaxed size as an independent variable in a multiple linear regression analysis of ellipse size, accounted for an additional 28% of the variance ($P < 0.001$). Including any of the other independent variables did not result in a significant increase in the explained variance.

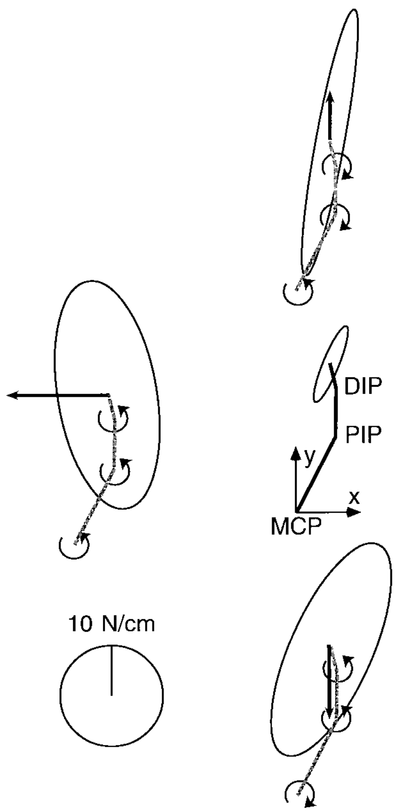

Fig. 5. Modulation of finger stiffness with the direction and magnitude of voluntary force applied with the finger extended. The voluntary force directions are indicated by the heavy arrows. The length of each arrow is proportional to the magnitude of the force applied in that direction. The circular arrows indicate the direction of net isometric torque at each joint prior to measuring stiffness. The size, shape, and orientation of the ellipse centered at the fingertip indicate the magnitude and directionality of the stiffness. The central ellipse represents the stiffness of the relaxed finger. All ellipses are drawn to the same scale, shown in the bottom-left corner. Subject 2.

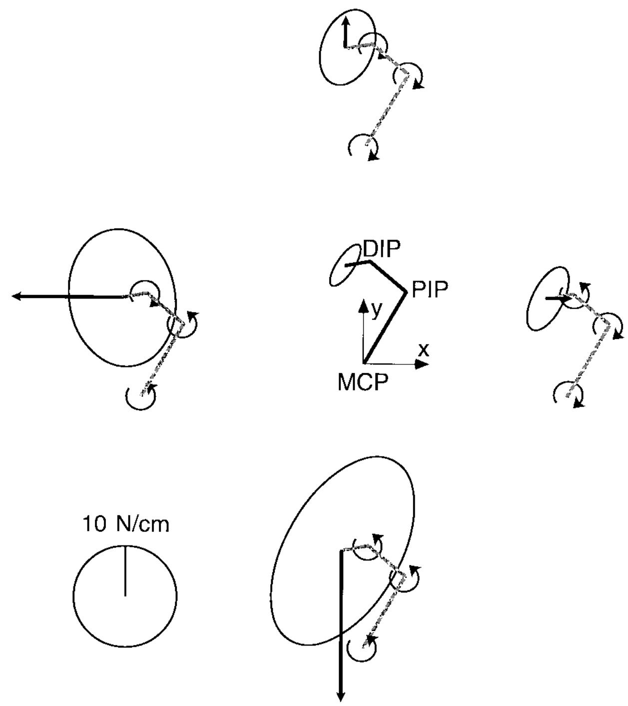

Fig. 6. Modulation of finger stiffness with the direction and magnitude of voluntary force applied with the finger flexed. Force and stiffness are represented on the same scale as in Fig. 5. Subject 2.

TABLE III
STIFFNESS ELLIPSE PARAMETERS
MEANS AND STANDARD DEVIATIONS ($n = 5$)

Force Direction	λ_{max} (N/cm)	Orientation	Size	Shape $\lambda_{max}/\lambda_{min}$
EXTENDED FINGER				
Relaxed	8.2 [4.8]	65.3^0 [4.0]	50 [42]	4.48 [1.41]
$+x$	18.6 [7.1]	67.6^0 [4.6]	265 [172]	4.41 [0.47]
$+y$	27.8 [7.1]	75.1^0 [4.6]	324 [164]	8.03 [1.32]
$-x$	23.9 [7.7]	80.8^0 [6.3]	753 [361]	2.45 [0.49]
$-y$	21.6 [5.5]	60.2^0 [6.9]	510 [266]	3.03 [0.30]
FLEXED FINGER				
Relaxed	4.3 [1.2]	57.3^0 [3.4]	27 [12]	2.23 [0.42]
$+x$	8.1 [1.5]	57.9^0 [5.2]	88 [31]	2.44 [0.26]
$+y$	9.3 [1.4]	75.6^0 [10.9]	154 [53]	1.86 [0.25]
$-x$	13.6 [2.3]	76.8^0 [19.5]	442 [171]	1.37 [0.12]
$-y$	19.5 [4.9]	57.9^0 [4.6]	654 [358]	1.99 [0.18]

2) Shape: It is evident in comparing Figs. 5 and 6 that the finger stiffness became more isotropic when the joints were flexed. This was expected since displacements in different directions produce more uniform joint displacements when the finger is in a flexed posture than an extended posture. The isotropy of the stiffness is quantified by the shape parameter in Table III. The closer to unity the shape parameter, the more isotropic the stiffness. In both the extended and flexed postures, the finger stiffness was most isotropic when the target force was in the $-x$ direction. This is the direction in which force is most commonly exerted during pinching and tapping tasks. The modulation of stiffness isotropy with the direction of target force was much greater, though, for the extended posture of the finger than for the flexed posture. In particular, the stiffness ellipse became very elongated when force was exerted in the $+y$ direction, the direction associated with poking.

As might be expected, relaxed shape accounted for a significant ($P < 0.001$) proportion (26%) of the variance in ellipse shape across subjects. Including relaxed orientation as an independent variable in a multiple linear regression analysis of ellipse shape, accounted for an additional 8% of the variance ($P < 0.05$). Including any of the other independent variables did not result in a significant increase in the explained variance.

3) Orientation: With the finger relaxed, for both extended and flexed postures, the direction of greatest stiffness was approximately parallel to the most proximal phalange of the finger. This was generally also the case when force was exerted in any of the four target directions. For a given force direction, there was little change in the direction of greatest stiffness between the extended and flexed postures. This may have been because the orientation of the proximal phalange of the finger was the same in the two postures.

On the other hand, orientation was influenced by the direction of the target force. While it changed little, compared with that of the relaxed finger, when target force was in the $+x$ or $-y$ directions, the orientation rotated by 10°–20° when the target force was in the $-x$ or $+y$ directions, shifting in the direction of the target force. These force directions are those associated with pinching, tapping, and poking. Although this change in orientation occurred both when the finger was extended and when it was flexed, the variability among subjects was much greater in the flexed posture. This greater variability may have been largely due to the shape being close to unity (isotropic stiffness). As the shape approaches unity, the ellipse degenerates, becoming a circle, and the orientation cannot be defined. Consequently, the more isotropic the stiffness, the larger the error in determining the direction of greatest stiffness.

Relaxed orientation was the only independent variable which could account for a statistically significant ($P < 0.05$) proportion of the variance in the orientation across subjects. However, it explained only 8% of the variance.

4) Maximum Eigenvalue: The maximum eigenvalue represents the magnitude of the stiffness along the direction of greatest stiffness. Like the size, the maximum eigenvalue tended to increase with the magnitude of the finger force. However, it is also evident from a comparison of the values in Table III for any given force direction, that the maximum eigenvalue was significantly greater in the extended posture than in the flexed posture ($P < 0.05$), even for those force directions with lower MVC, i.e., $+x$ and $-y$. Extending the finger apparently amplified stiffness by a factor of almost two. In two directions where force magnitude was comparable ($+x$ and $-x$), the maximum eigenvalue was twice as large when the finger was extended as flexed. In a third direction, where the force of the extended finger was only half that of the flexed finger ($-y$), the maximum eigenvalues were nearly equal. Force direction also had a powerful effect on the maximum eigenvalue, but it is less clear how best to quantify this effect. We chose to compare maximum eigenvalues for opposite force directions. In going from the positive to the negative force direction, the maximum eigenvalue increased with force magnitude, but the increase was generally one-half to one-third of the proportion of the increase in force magnitude, i.e., the gain between stiffness and force was attenuated.

Relaxed shape accounted for most (64%) of the variance in maximum eigenvalue across subjects ($P < 0.001$). The strong dependence on relaxed shape followed from the observation that for any target force direction, the maximum eigenvalue, like the shape, was consistently greater when the finger was extended than flexed. Including finger force as an independent variable in a multiple linear regression analysis of maximum eigenvalue, accounted for an additional 18% of the variance ($P < 0.001$). Including any of the other independent variables did not result in a significant increase in the explained variance.

IV. Inter- and Intrasubject Variance

To establish whether the effect of changing force direction or finger posture was greater than intersubject variability, the intersubject variance was compared with the intrasubject variance due to force direction or finger posture. In the case of ellipse size, there was little difference between the intersubject variance (43.8) and the intrasubject variance due to force direction (41.2), but intrasubject variance due to finger posture was about five times as great (236). On the other hand, for the maximum eigenvalue intrasubject variance due to force direction (0.230) was about three times as great as intersubject variance (0.0750), while the intrasubject variance due to finger posture (0.748) was about ten times as great. The difference between intrasubject and intersubject variance was even greater for the ellipse shape. The intrasubject variance due to force direction (0.118) was about 15 times as great, while that due to finger posture (0.612) was about 60× as great as the intersubject variance (0.007 83).

TABLE IV
Net Joint Torque and Stiffness. Means: ($n = 5$)

Force Direction	MCP Torque Nm	MCP Stiffness Nm/rad	PIP Torque Nm	PIP Stiffness Nm/rad	DIP Torque Nm	DIP Stiffness Nm/rad
EXTENDED FINGER						
$+x$	-0.16	3.10	-0.75	1.00	-0.03	0.19
$+y$	0.14	1.95	-0.02	0.59	-0.02	0.08
$-x$	0.80	7.25	0.37	1.48	0.14	0.20
$-y$	-0.11	6.30	0.16	1.88	0.02	0.35
FLEXED FINGER						
$+x$	-0.12	1.69	-0.03	1.03	0.01	0.15
$+y$	-0.03	1.64	-0.12	1.05	-0.05	0.18
$-x$	0.52	3.37	0.12	1.33	-0.02	0.13
$-y$	0.09	5.08	0.36	2.48	0.16	0.28

V. Joint Stiffness

We investigated the relative stiffness of the individual finger joints by transforming the finger stiffness matrices for each subject to joint stiffness matrices, using (3). The single-joint contributions to joint stiffness are represented as diagonal terms in the joint stiffness matrix. The relation between single-joint stiffness and joint torque was not monotonic, i.e., the stiffness was sometimes lower for higher values of joint torque. This can be seen in Table IV where the mean values of joint stiffness and net joint torque are tabulated. For example, when the finger was flexed and force was exerted along the $-x$ direction, the torque at the MCP joint was over five times that when force was exerted along the $-y$ direction, but the stiffness was 30% lower. A similar inverse relation between torque and stiffness was seen for the PIP joint, e.g., force exerted along the $+x$ direction for the extended finger compared with the flexed finger, and the DIP joint, e.g., force exerted along the $-y$ direction for the flexed finger compared with the extended finger.

VI. Muscle Activation

Figs. 7 and 8 show the relative muscle activation of the five finger muscles whose activity could be recorded with surface EMG electrodes. The muscles have been classified according

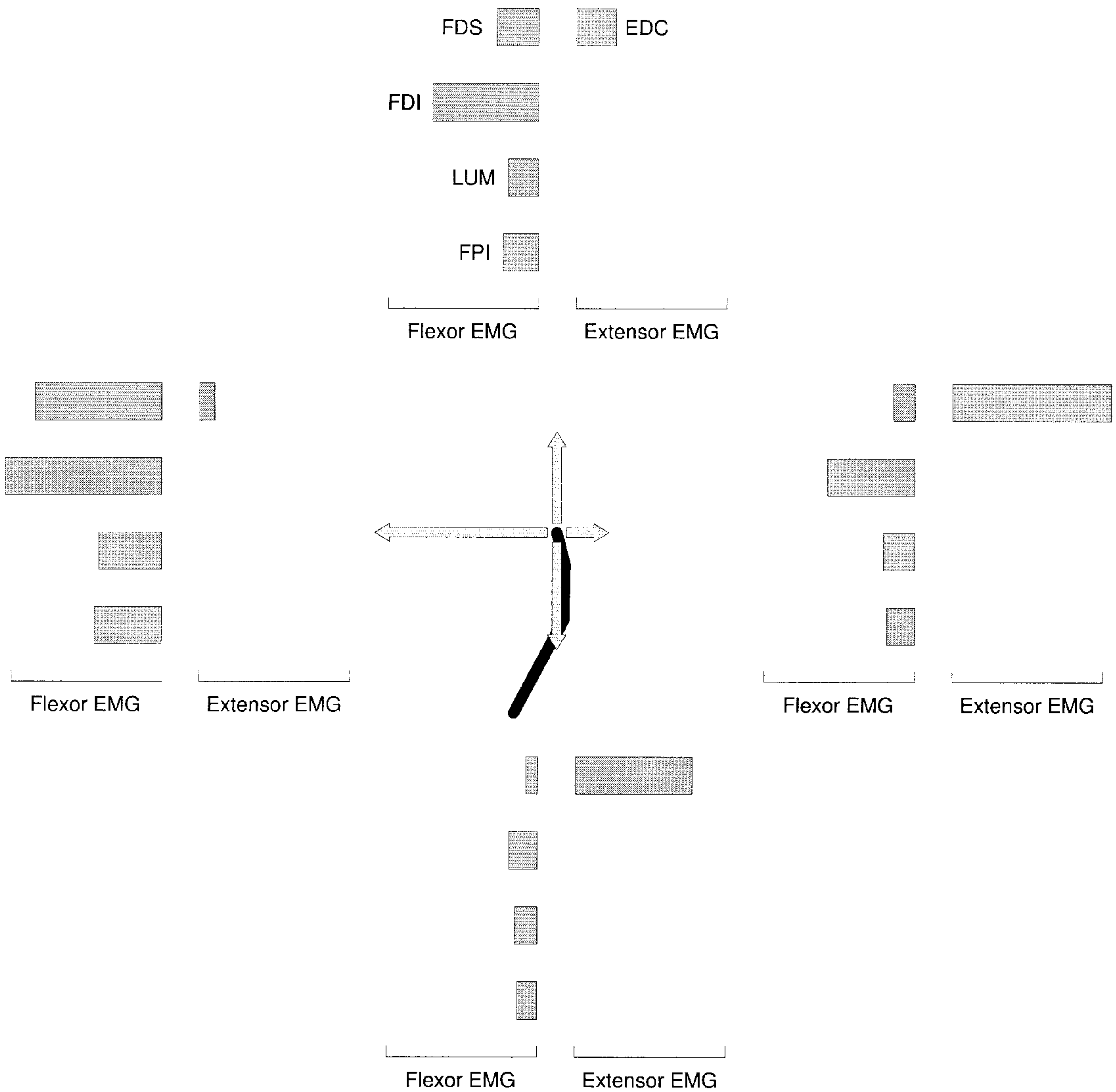

Fig. 7. Relative activity of finger muscles for Subject 3 in the extended posture. Each bar represents the mean rms EMG of ten trials, all of 1-s duration. Scales are arbitrary, intended only for comparison of the relative activity of each muscle in different force directions. Relative forces in the four directions are indicated by the length of the arrows at the fingertip. Muscles are classified according to their action at the MCP joint [flexor digitorum superficialis (FDS), first dorsal interosseus (FDI), lumbrical (LUM), first palmar interosseus (FPI), and extensor digitorum communis (EDC)].

to their action at the MCP joint. The principal objective is to illustrate that muscles are frequently activated even when they produce torque in a direction opposite to the direction of net torque required at a joint.

First, consider the extended finger (Fig. 7). FDI and FPI, both flexors of the MCP joint and extensors of the PIP joint, are most strongly activated when force is applied in the $-x$ direction, which requires flexor torque at all three joints. Consequently, their extensor action at the PIP joint constitutes effective cocontraction with the FDS, which is a flexor of all three joints. The FDI is also quite active when force is applied in the $+x$ direction. In this case, its flexor action at the MCP joint constitutes effective cocontraction with the EDC, an extensor of all three joints.

In the case of the flexed finger (Fig. 8), there are several other clear cases of flexor/extensor cocontraction. LUM, a flexor of the MCP joint, is more active when force is applied in the $+x$ and $+y$ directions, which require MCP extensor torque, than in the $-y$ direction, which requires MCP flexor torque. Its cocontraction with EDC in the $+x$ and $+y$ directions will stiffen the MCP joint. Similarly, EDC is as active when force is applied in the $-y$ direction, which requires flexor torque at all three joints, as in the $+y$ direction, which requires extensor torque at all three joints. Clearly, EDC cocontracts with the finger flexors, stiffening all three joints when force is applied in the $-y$ direction.

VII. Discussion

In this study, we examined the mechanical response of the finger to static displacement in the plane of flexion/extension when the finger was positioned in flexed and extended postures

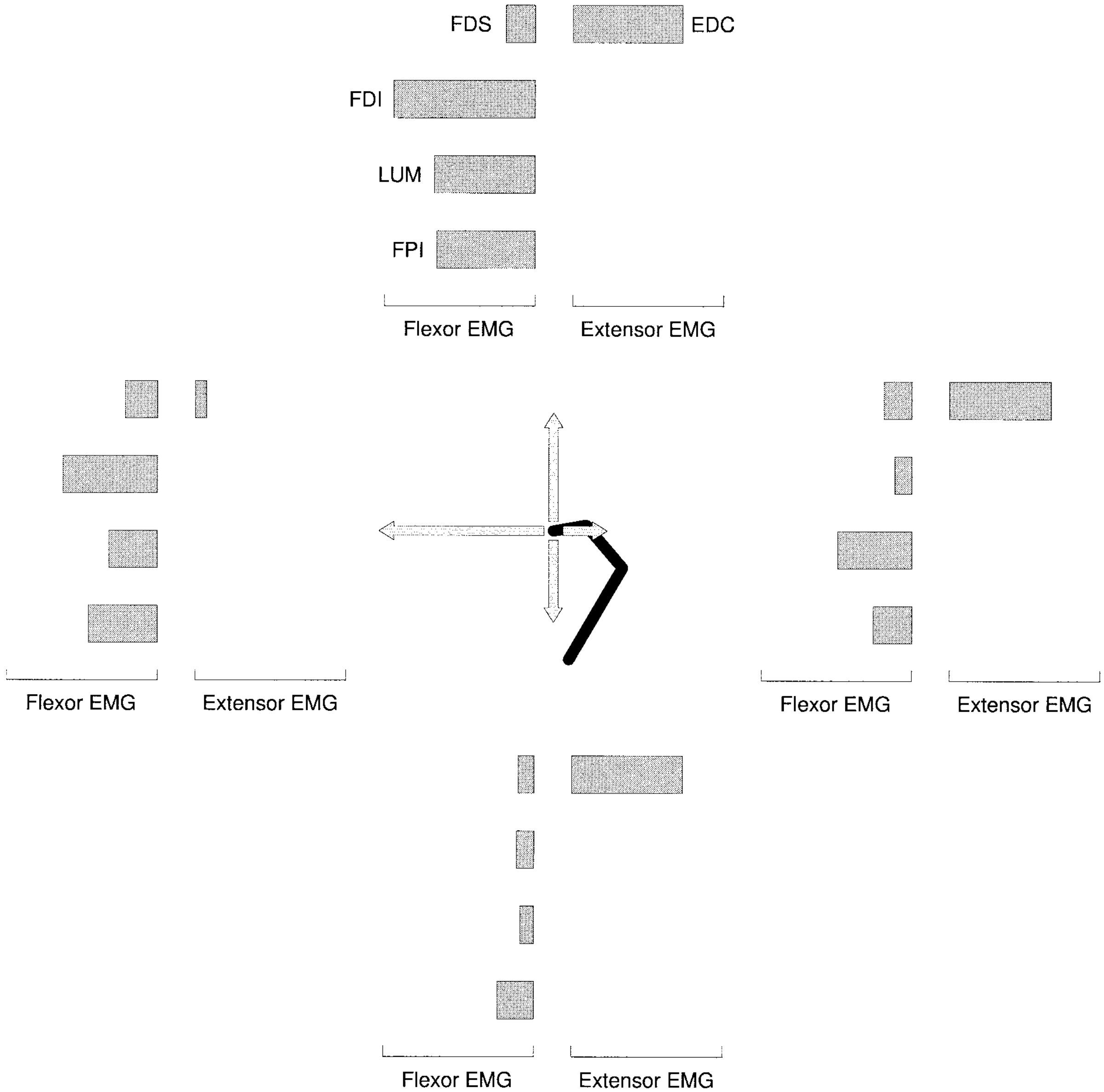

Fig. 8. Relative activity of finger muscles for Subject 3 in the flexed posture, represented as in Fig. 7.

and when the target force direction was varied. Like the arm [9], the mechanical behavior of the finger was predominantly spring-like. The conservative component of the force field was modeled well by equations representing the mechanics of a 2-D linear spring. The finger stiffness was found to be anisotropic, with the direction of greatest stiffness being approximately parallel to the proximal phalange of the finger. The anisotropy varied considerably, being greatest when the interphalangeal joints were extended and force was being exerted in the direction of pointing and least when the interphalangeal joints were flexed and force was being exerted in directions normally associated with pinching and tapping.

VIII. Stiffness Isotropy

We established that the finger stiffness, like arm stiffness [9], was not uniform, but varied with displacement direction. In all cases, stiffness was higher in the direction parallel to the proximal phalange of the finger than in the perpendicular direction. Isotropy, quantified as the ratio of greatest stiffness to least stiffness, varied over a five-fold range, from approximately 1.5–8.0.

The variance of ellipse shape due to force direction or finger posture was more than an order of magnitude greater than the intersubject variance, clearly indicating that both had a very powerful effect on stiffness isotropy. Stiffness was more isotropic when the finger was flexed than when it was extended. However, for either posture, the uniformity of finger stiffness varied with the direction of finger force. In particular, stiffness was most isotropic when force was exerted in directions associated with pinching and tapping, while it was most anisotropic when the finger was extended and force was exerted along the direction of pointing.

IX. Stiffness Magnitude

The magnitude of the finger force appeared to be the primary determinant of the size of the stiffness ellipse. Since ellipse size is an integrated measure of stiffness over all displacement directions, it was to be expected that it would reflect the greater muscle activation associated with larger forces and would be relatively independent of geometrical factors. On the other hand, the maximum eigenvalue, which is a measure of stiffness in a specific direction, was more highly correlated with a geometric factor, the shape under relaxed conditions, than with the finger force. The maximum eigenvalue would seem to be a more useful measure of stiffness magnitude than ellipse size, in the context of interface design or finger impedance control, because it represents the upper limit of stiffness for any displacement direction. An average measure, like size, would underestimate the effects of stiffness anisotropy. The choice of maximum eigenvalue as the more appropriate measure of stiffness magnitude is also supported by the greater relative variation due to force direction and finger posture than that due to intersubject variability.

Although force magnitude was not varied independently of force direction in the present study, we can infer that the maximum eigenvalue (stiffness) and force magnitude should vary more or less linearly [12]. Increasing force magnitude while keeping force direction constant is likely to be achieved by a proportional increase in torque at each joint [13], which would result in simple scaling of the joint stiffness matrix. Thus, doubling the finger force in a given direction should effectively double the nonpassive portion of finger stiffness. Given that forces of 20% MVC resulted in maximum eigenvalues two to four times those of the relaxed finger, stiffness is likely modulated over at least a five-fold range between the relaxed state and MVC. The effect of changing finger posture had a much smaller effect, modulating stiffness over only a two-fold range. The effect of force direction on stiffness appeared to be similar to or slightly stronger than that of finger posture, although considerably less than that of force magnitude.

X. Stiffness Orientation

We found that maximum finger stiffness, like arm stiffness, seems to maintain a relatively fixed orientation with respect to specific anatomical landmarks. For the arm, this was a line running from the shoulder to the hand [9]. In the case of the finger, the direction of greatest stiffness was oriented parallel to the axis of the proximal phalange of the finger. Orientation never deviated by more than about 20°, but when it did change, it appeared always to rotate in the direction of the finger force. Variations in orientation among subjects did not appear to be due to differences in force magnitude or factors thought to reflect differences in muscle geometry. They may have been due to differences in muscle activation patterns among subjects. The results of [13] indicate that for the same force magnitude and direction, the strength of the correlation of activity between different finger muscles varies widely among subjects. This variation would likely be sufficient to account for the relatively small differences in stiffness orientation across subjects. Uncertainty in the orientation may have been the prime factor responsible for the greater variances in the two force directions where the stiffness was most isotropic. It should be noted that uncertainty in the direction of greatest stiffness is not a drawback if the stiffness is nearly isotropic since the stiffness will be nearly equal in all directions.

Because the direction of maximum stiffness varied little, compared with the 180° range which is theoretically possible, the orientation of maximum stiffness could be approximated relatively well by the orientation of the proximal phalange of the finger. Rotating the orientation by 10° in the direction of the applied force might provide an even better approximation, particularly when the finger is extended and the stiffness is more anistropic. However, some caution should be exercised in generalizing these results to other finger postures since they are based on only two finger postures, both of which incorporated the same MCP joint angle.

XI. Nonconservative Effects

Nonconservative forces contributed less than 15% of the total force response to static displacement. Muscle viscosity, as well as friction in joints and tendon sheaths are dissipative and, hence, nonconservative, resulting in a force field with nonzero curl. Another less obvious contributor to nonzero curl is asymmetric reflex stiffness. The change in muscle force due to reflex responses is generally not symmetric for displacements in opposite directions [14], thereby contributing to the nonconservative component of the force field.

XII. Joint Stiffness

When single finger joints have been studied, a monotonic relation has been found between joint stiffness and joint torque [1]–[6]. This was not the case when the finger was considered as a multijoint structure. The lack of a systematic relation between joint stiffness and joint torque is at least partly due to the geometry of muscle attachment at the three joints. Five of the seven finger muscles span both the MCP and PIP joints. Two of these muscles, the interossei, act as flexors of the MCP joint, but extensors of the PIP joint [15]. Clearly, any time that all of the muscles with a flexor function at the MCP joint are activated, there must be flexor/extensor cocontraction at the PIP joint. This will increase the stiffness of the PIP joint without a corresponding increase in the net joint torque. However, we found several other clear examples where cocontraction of flexor and extensor muscles occurred, not only at the PIP joint, but at the MCP and DIP joints, as well. A recent study which examined all seven muscles of the index finger during pinching, has shown that the activity of all five MCP flexor muscles is positively correlated with pinch force [13], indicating that they are coactivated during pinching. Coactivation of both MCP extensor muscles was also reported, although it was not modulated with the magnitude of the pinch force.

We can make a qualitative comparison of our results with those of [6] for the extended posture of the finger. In that study the stiffness, viscosity, and inertia about the MCP joint were estimated during the first 20 ms of a rapid displacement, rather than after the displacement was complete, as in our study. The direction of displacement in [6] corresponded approximately to the direction of minimum stiffness in Fig. 5 and the direction of the applied force corresponded to the $-x$ direction. The mean eigenvalue along this direction which we obtained for our five subjects was 9.7 [S.D. 1.9] N/cm. The mean force exerted by our subjects was approximately 10 N. From Fig. 5 in [6], the mean dynamic stiffness appears to be about 5 N/cm (500 N/m) for a force of 10 N. This is approximately half the value which we obtained.

The stiffness estimates in [6] were more akin to dynamic stiffness than to the static or steady-state stiffness which we measured. Dynamic stiffness is dominated by the stiffness inherent in attached cross-bridges. In addition, changes in sarcomere length, muscle moment arm, and the passive elastic properties of muscle and tendon will contribute to dynamic stiffness to varying degrees. They will also contribute to steady-state stiffness, once displacement has stopped, although in a different proportion than during the displacement. The changes in cross-bridge length produced by finger displacement are not likely to persist sufficiently long to contribute significantly to steady-state stiffness, due to cross-bridge cycling. On the other hand, stretch-induced force enhancement and changes in muscle activation due to reflexes will contribute to the steady-state stiffness, but not to the dynamic stiffness estimated during the first 20 ms of a displacement. While the steady-state stiffness, inclusive of reflex stiffness, could be larger than the dynamic stiffness [3], we would not have expected it to be twice as large. We would suggest instead that the magnitude of the dynamic stiffness in [6] was underestimated. This conclusion is based on our observation that they estimated the effective mass of the finger to be about 6 g. The center of mass of the finger could not be less than 40% of the distance from the MCP joint to the fingertip. Using their estimate of effective mass, the real mass of the finger could not be greater than 15 g. However, in a study on index finger movement, the mass of the proximal phalanx alone was reported be in the range of 17g to 30 g [16], the lower value presumably for female subjects. This would suggest that the mass in [6] was underestimated by at least a factor of three. In an earlier report of the work presented in [6], presumably based on the same data, the estimates of finger mass were three to four times as large and the corresponding stiffness estimates were about twice as large [17]. Those results were more in line with our findings.

XIII. APPLICATIONS

The variation in isotropy of finger stiffness has implications for the design of force-reflecting interfaces. If the force-reflecting device is capable of moving in two or three dimensions, then a change in finger posture or finger force direction will affect the amount by which the finger is displaced by the reflected force. This may be critical in applications where precision is important. In addition, changes in stiffness isotropy can affect the mechanical stability of the human–machine interface. To accommodate these modulations in the mechanical impedance of the finger, design parameters can take into account the range of variation of the impedance in different directions or the interface can be adaptively controlled to avoid undesirable behavior in selected directions. If it is important that finger stiffness be as isotropic as possible, then the interface should be designed to keep the finger flexed with force being applied more or less along the long axis of the distal phalange.

The direction of maximum stiffness appears to be predictable, always oriented within 20° of the proximal phalange of the finger. Therefore, by constraining the orientation of the proximal phalange, a fixed orientation between the direction of highest (or lowest) finger stiffness and the direction of motion of a machine interface can easily be achieved. Furthermore, by changing the direction of the applied finger force or the finger posture, the stiffness along that direction can be amplified or attenuated.

The most important characteristic of natural finger stiffness that might be implemented in the control of a dextrous manipulator is a direct variation in endpoint stiffness with applied force. Whether or not stiffness anisotropy would be a desirable feature of a dextrous manipulator is likely to depend on the application. For example, if it is important that the manipulator not be deflected in a direction perpendicular to the direction of the applied force, then endpoint stiffness could be made anisotropic with the direction of greatest stiffness perpendicular to the direction of applied force. In the case of FES of finger muscles, stiffness magnitude is likely to be appropriately modulated with finger force because of the natural modulation of muscle stiffness with muscle force. Stiffness anistropy can be most easily achieved by changing finger posture, not only because the control of force direction is more difficult to achieve with FES, but because finger posture has an effect which is more robust and generally greater in magnitude than that of force direction.

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