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Finger joint impedance during tapping on a computer keyswitch

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Abstract

We studied the dynamic behavior of finger joints during the contact period of tapping on a computer keyswitch, to characterize and parameterize joint function with a lumped-parameter impedance model. We tested the hypothesis that the metacarpophalangeal (MCP) and interphalangeal (IP) joints act similarly in terms of kinematics, torque, and energy production when tapping. Fifteen human subjects tapped with the index finger of the right hand on a computer keyswitch mounted on a two-axis force sensor, which measured forces in the vertical and sagittal planes. Miniature fiber-optic goniometers mounted across the dorsal side of each joint measured joint kinematics. Joint torques were calculated from endpoint forces and joint kinematics using an inverse dynamic algorithm. For each joint, a linear spring and damper model was fitted to joint torque, position, and velocity during the contact period of each tap (22 per subject on average). The spring-damper model could account for over 90% of the variance in torque when loading and unloading portions of the contact were separated, with model parameters comparable to those previously measured during isometric loading of the finger. The finger joints functioned differently, as illustrated by energy production during the contact period. During the loading phase of contact the MCP joint flexed and produced energy, whereas the proximal and distal IP joints extended and absorbed energy. These results suggest that the MCP joint does work on the interphalangeal joints as well as on the keyswitch.
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Keywords: Finger; Typing; Keyswitch; Impact; Mechanical properties

1. Introduction

Computer keyboard use is a complex motor control task that has been associated with upper extremity musculoskeletal disorders (MSDs; BLS, 1998; Faucett and Rempel, 1994; Gerr et al., 2002; Hales et al., 1994). Since injury mechanisms appear to be related to the specific loading patterns of the internal tissues (Rempel et al., 1992), we seek to understand how the individual joints of the finger behave, and mechanically distribute forces and energy through the musculoskeletal system during the task of tapping. As a first step towards our goal, we sought to characterize joint kinematics and dynamics during single finger tapping.

Vertical forces and the motions of the metacarpal-phalangeal (MCP) and the interphalangeal (IP) joints have been measured during typing (Gerard et al., 1999; Nelson et al., 2000; Sommerich et al., 1996; Yun et al., 2002). However, the dynamic relationship between joint kinematics and endpoint forces during tapping has not been described. Finger joint motions may be coupled due to the complex anatomy of the hand (Landsmeer, 1958; Spoor and Landsmeer, 1976). Consequently, we tested the hypothesis that during the contact period of tapping, finger joints act similarly in terms of kinematics, torque, and energy production.

Hajian and Howe (1997), Milner and Franklin (1998), and Becker and Mote (1990), have used mechanical impedance (i.e. a lumped parameter, mass-damper-spring model) to describe the dynamic behavior of the finger under different isometric loads and different directions (i.e. flexion/extension or abduction/adduction). Becker and Mote (1990) and Hajian and Howe (1997) showed that a lumped-parameter model could successfully describe the impedance characteristics of fingers when perturbed from isometric loading conditions. Although lumped-parameter models can describe finger mechanics under many conditions, specific stiffness measurements depend on applied loads, direction of perturbations and the postures of the finger. We

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tested the hypothesis that a simple lumped-parameter model can describe joint impedance during the potentially complex, dynamic task of tapping.

2. Methods

Fifteen subjects (8 male, 7 female), ages 20–35 (mean $= 28 \pm 5$ SD) participated in the study. Subjects gave informed consent prior to experiments, and experimental procedures were approved by the Human Subjects Committee at the Harvard School of Public Health. Subjects sat beside the experimental apparatus, rested their right arm on a wooden platform directly in front of the force sensor, and adjusted their chair to a comfortable elbow and shoulder position with the elbow at approximately 90° of flexion and the shoulder relaxed. The subjects rested the palm of their hand on the surface of a wooden platform, which was flush with the top of the keyswitch. Hand lengths and finger segment dimensions were then measured with a caliper.

Subjects tapped synchronously to a 0.75 Hz auditory signal for 1 min. Subjects were instructed to tap normally on a keyswitch (IBM Personal computer AT keyboard, International Business Machines Corp.; buckling-spring design with a 0.3-N activation), as they would on a computer keyboard, and to minimize contact time. After 20 s of tapping, 40 s of data were collected. Vertical keyswitch position was measured using an optical system (Jindrich et al., 2003), which tracked the position of an infra-red LED glued to one side of the keyswitch.

Horizontal and vertical fingertip forces were measured using a two-axis strain-gauge force transducer securely anchored to a table (Jindrich et al., 2003). The transducer had a resolution of 2.5 mN and a resonant frequency of 1000 Hz.

Three individual miniature goniometers (Shape Sensors, Measurand Inc.) measured joint flexion angles of the distal interphalangeal (DIP) joint, the proximal interphalangeal (PIP) joint, and the metacarpo-phalangeal joint (MCP; Fig. 1). The active element of the sensor (a 12 mm segment) was positioned between the two balsa wood platforms mounted on the dorsal side of the finger ensuring that rotation about only one joint caused local bending of the active region. Each goniometer was statically calibrated using flexion angles from 0° to 60°, at increments of 10°. Sensor data during calibrations at each angle were averaged over a period of 1 s. A digital image of the finger, hand, and keyswitch was acquired after practice taps and before data collection. The images provided estimates of the initial angle between the fingertip and the keyswitch, which in turn provided a reference for the joint angles measured by the goniometers in the coordinate frame of the force sensor. The dynamic response of the miniature goniometers and mounting system was validated by comparing goniometer output to joint angles measured using a high-speed video system (Motionscope, Redlake Imaging) during rapid finger movements.

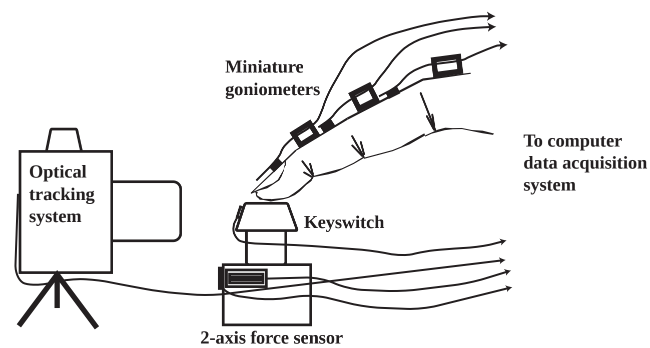

Fig. 1. The experimental apparatus consisted of a two-dimensional force transducer measuring fingertip forces at the keyswitch, and finger joint goniometers measuring joint angles during the contact period. A CCD camera tracked the vertical position of the keyswitch.

Voltage outputs from the sensors were amplified and acquired at 10 kHz using computer data-acquisition hardware and software (SCXI 1121 Isolated Sensor Input Module and LabVIEW, National Instruments, Austin, TX). Acquired voltage measurements were filtered at 500 Hz using a fourth-order Butterworth low-pass filter. To eliminate 60 Hz noise in the input signal, vertical keyswitch position data were filtered with a Butterworth bandstop filter with a 40 Hz low- and 80 Hz high-frequency cut-off.

Contact periods were identified as periods when the vertical force exceeded 0.02 N and the average vertical force exceeded 0.3 N over the entire period. Two types of keystrike phases were identified. The first set included the three phases of keyswitch compression: impact, pulp compression and release as defined by Rempel et al. (1994). We also identified a loading and unloading phase for the finger, which overlap these three characteristic keystrike phases. The loading phase, which overlaps the impact and the first part of the pulp compression phase, begins with the first contact with the keycap and ends at the second local force maximum during the pulp compression phase. The unloading phase begins at the second local maximum and ends at the release of the keyswitch.

Net joint torques were calculated from fingertip forces, segment velocities and accelerations using an iterative Newton–Euler algorithm (Craig, 1989). Uniform cylinders with the density of water represented the mass and moments of inertia of the finger segments. Velocity and acceleration of the keyswitch and the joints were calculated by differentiating position data using a fourth-order difference equation (Biewener and Full, 1992). To facilitate comparison with previous studies (Gerard et al., 1999; Rempel et al., 1994), force was not adjusted to account for keycap inertia.

We fit a lumped-parameter model to the mechanical behavior of each joint during tapping using the following equation:

$$T(t) = k\theta(t) + b\dot{\theta}(t), \quad (1)$$

where $T(t)$ is the net joint torque as described above, $\theta(t)$ and $\dot{\theta}(t)$ are joint angular position and angular velocity. The constants k and b were estimated using a least-squares method. We calculated a model estimate of the torque, $T_p(t)$, by evaluating Eq. (1) with the measured values $\theta(t)$, $\dot{\theta}(t)$ and the fitted parameters k and b. We estimated the variance accounted for by the model (VAF) the using the equation:

$$\mathrm{VAF} = 100\left[1 - \frac{\sum_{t=0}^{t=\tau}\left[T(t) - T_p(t)\right]^2}{\sum_{t=0}^{t=\tau} T(t)^2}\right] \quad (2)$$

To evaluate the relative contributions of position- and velocity-dependent components of the model to describing joint behavior, we calculated model estimates using only the angular position dependent components or the angular velocity-dependent components of Eq. (1) and estimated the VAF for each using Eq. (2).

Work of the finger joints during the loading phase (E_{load}) and unloading phase (E_{unoad}) was calculated by integrating joint torque with respect to joint angle. Energy input (E_{in}) and output (E_{out}) for the keyswitch was calculated by integrating vertical force with respect to position for negative and positive increments of keyswitch position, respectively.

We analyzed 332 taps from 15 subjects, on average 22 taps per subject. Calculated parameters were averaged for each subject, then compared using paired t-tests, using a statistics computer program (JMP 4.0.2, SAS Institute Inc., Cary, NC). Across-subject means were considered significantly different if $P < 0.05$.

3. Results

Similar to typing on a keyboard, vertical force production showed three phases: a period of keyswitch compression during the first $21 \pm 17\%$ (mean $\pm$ standard deviation) of the compression period, a local maximum at $23 \pm 18\%$ associated with the end of key travel and corresponding finger impact, and finally a second local maximum at $43 \pm 18\%$ of the contact period preceding force decline at the end of the tap (Rempel et al., 1994; Fig. 2).

Horizontal forces (average 0.05 ± 0.096 N) were an order of magnitude smaller, and were more variable than vertical forces (average 0.64 ± 0.28 N). The positive horizontal forces were directed proximally towards the hand, indicating that the fingers pulled the keyswitch during the contact period. Unlike vertical force, horizontal force did not show distinctive phases of the contact period, and were variable in magnitude and direction (Fig. 2).

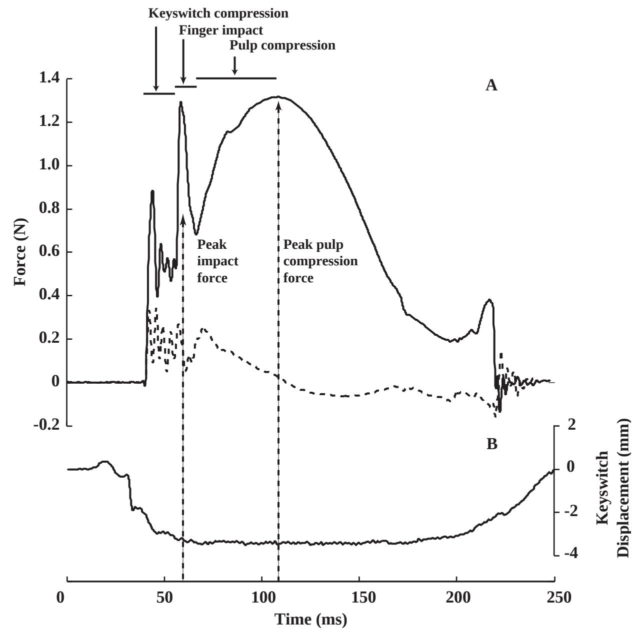

Fig. 2. Force and keyswitch displacement for a representative tap. Vertical (solid line) and horizontal (broken line) forces over time. Phases of the contact period identified by Rempel et al. (1994) are indicated above force traces, with arrows indicating local vertical force maxima.

Movement kinematics were different across the index finger joints during the contact period. The MCP joint flexed during the loading phase, reached a maximum at $59 \pm 28\%$, and extended during the unloading phase (Fig. 3(A); Table 1). The DIP joint showed the opposite pattern of movement, extending during loading, reaching a minimum at $56 \pm 20\%$, and flexing during unloading. For 12 of 15 subjects, movements of the PIP joint showed a similar pattern of extension then flexion, reaching a minimum at $61 \pm 31\%$, but PIP joint excursions were significantly smaller, and were more variable, than those observed for DIP joint.

The horizontal and vertical forces generated during tapping, coupled with the finger joint kinematics indicated that all joints generated net flexor torques during contact (Fig. 3(B)–(D); Table 1). Proximal joints generated significantly higher average and maximum net joint torques than more distal joints.

Work during the loading and unloading phase illustrated different patterns across the different joints (Table 1). During the loading phase of contact, the MCP joint showed positive (flexor) torques coupled with joint flexion, indicating that the MCP joint did positive work and produced energy (Fig. 4). In contrast, the PIP and DIP joints showed flexor torques coupled with joint extension (Fig. 4), indicating net energy absorption (Table 1). PIP and DIP joints did not show significant differences in E_{load} or E_{unload}.

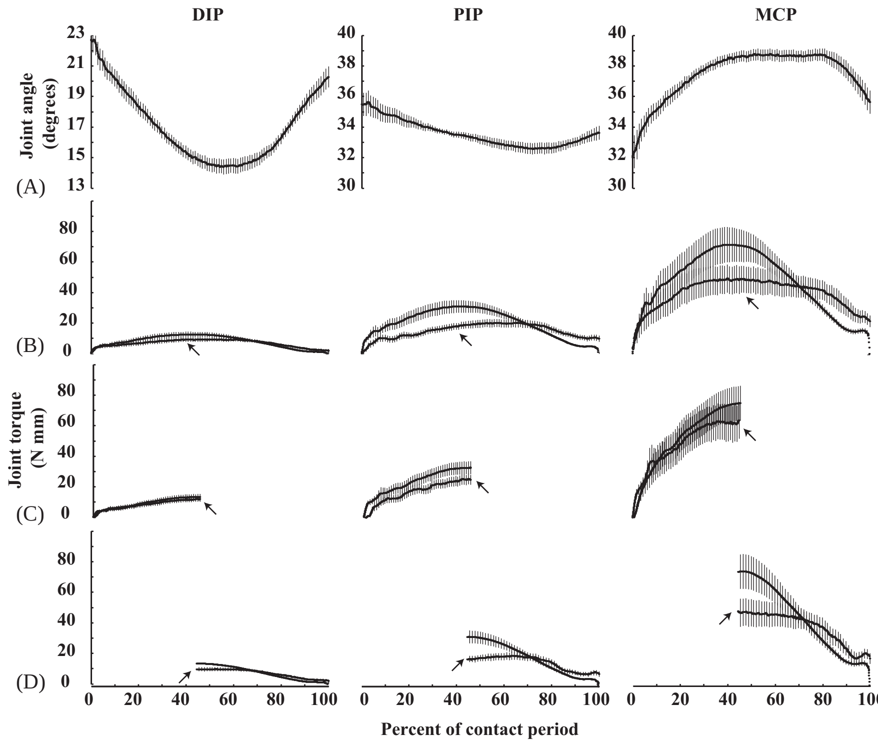

Fig. 3. Average joint excursions and joint torque production during the contact periods of taps. (A) Average joint excursions for index finger joints during the contact period of a tap on a computer keyswitch. For each subject, angle time series from the contact phase of each tap were scaled to percentage of the contact phase of the tap, then averaged. Since subjects exhibited joint excursions around different mean joint angles, joint angle data were normalized to mean joint angle for each subject. Subsequent average time series from all subjects were averaged. Vertical lines represent point-wise standard errors. (B) Measured joint torques and joint torques estimated by the linear spring-damper model (indicated by arrows) during the contact period of the tap. Data from individual taps were averaged within subject. Plotted value represents average across subjects. Vertical lines indicate point-wise standard errors of the mean values for comparison of mean curves. (C) Joint torques and joint torques estimated by the linear spring-damper model (indicated by arrows) during only the loading period of the tap. (D) Joint torques and joint torques estimated by the linear spring-damper model (indicated by arrows) during only the unloading period of the tap.

Table 1
Contact-period kinematics, torque, and energy exposure of index finger joints during tapping on a computer keyswitch

$N = 15$	MCP[a]	PIP	DIP
θ_I	33 ± 10	35 ± 19	21 ± 13
θ_{pc}	40 ± 10	33 ± 18	13 ± 10
θ_f	37 ± 12	33 ± 18	18 ± 11
T_{ave}(N mm)	46 ± 28	20 ± 10	8 ± 4
T_{max}(N mm)	91 ± 55	42 ± 20	18 ± 8
E_{load} (N mm)	5.74 ± 8.16	-0.55 ± 1.38	-1.26 ± 1.26
E_{unload} (N mm)	-1.19 ± 3.01	-0.38 ± 0.93	0.31 ± 0.60
E_{net} (N mm)	4.55 ± 5.57	-0.93 ± 1.70	-0.94 ± 0.79

[a] Values are means ± standard deviations.

A linear spring-damper model described over 89% of the variance in torque during the loading phase of contact and 83–88% of the variance during the unloading phase (VAF_{kb}; Table 2). Fitting the linear model to joint kinematics and net joint torque over the entire contact period resulted in parameters explaining 66–74% of the variance in torque production. These smaller VAF values are due to the observed temporal asymmetries in kinematics or torque production between the loading and unloading phases (Figs. 3 and 4). These asymmetries in kinematics and joint torques resulted in asymmetries in the force-displacement relationships observed during loading and unloading periods (Fig. 4).

4. Discussion

Measurements of horizontal forces and joint kinematics concurrently with vertical forces revealed that finger joints function differently during the contact period of tapping on a computer keyswitch. The MCP joint flexed and generated positive net work during the loading phase, whereas the PIP and DIP joints extended and absorbed energy. Moreover, the finger joints displayed different torque-angle displacement relationships for the loading phase and unloading phase. These asymmetries caused different linear spring and damping parameters for the loading and unloading phases.

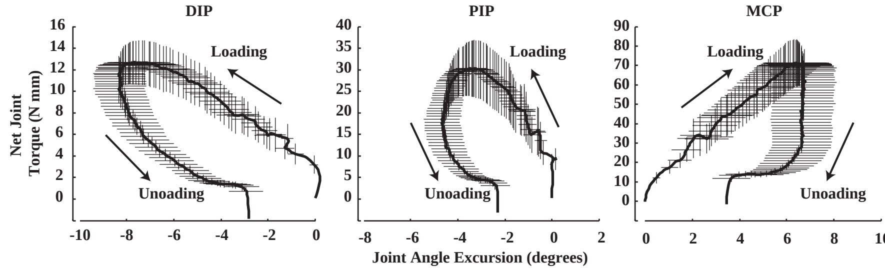

Fig. 4. Joint torque as a function of joint angle excursion during the contact period of tapping. Loading and unloading portions of the curves are indicated. Net joint torque and angle represent averages across subjects. For the PIP joint, curve represents average for subjects with negative joint stiffness, as observed for most subjects. Thin horizontal and vertical lines indicate point-wise standard errors of the mean values, as in Fig. 3.

Table 2
Lumped-parameter model parameters for finger joints during tapping on a computer keyswitch

$N = 15$	Entire contact period[a]	Loading period only	Unloading period only
MCP			
k (N mm rad^{-1})	540 ± 430	710 ± 540	450 ± 340
b (N mm s rad^{-1})	3.1 ± 5.0	1.7 ± 6.6	2.4 ± 11.0
VAF_{kb} (%)	74 ± 15	93 ± 5	86 ± 10
VAF_k (%)	71 ± 15	92 ± 5	83 ± 10
VAF_b (%)	4 ± 4	62 ± 13	41 ± 10
PIP			
k (N mm rad^{-1})	+270 ± 180 (4)	+240 ± 230 (4)	+266 ± 167 (4)
	−290 ± 270 (11)	−430 ± 400 (11)	−280 ± 270 (11)
b (N mm s rad^{-1})	+1.8 ± 0.9 (2)	+1.7 ± 2.0 (4)	+2.8 ± 1.2 (2)
	−3.3 ± 4.0 (13)	−2.3 ± 2.1 (11)	−5.4 ± 5.9 (13)
VAF_{kb} (%)	66 ± 18	89 ± 9	83 ± 9
VAF_k (%)	60 ± 17	87 ± 9	78 ± 9
VAF_b (%)	9 ± 13	63 ± 12	45 ± 16
DIP			
k (N mm rad^{-1})	−120 ± 130	−136 ± 155	−110 ± 120
b (N mm s rad^{-1})	−0.9 ± 0.8	−0.6 ± 0.5	−1.0 ± 1.2
VAF_{kb} (%)	73 ± 20	93 ± 8	88 ± 10
VAF_k (%)	71 ± 19	91 ± 8	84 ± 13
VAF_b (%)	7 ± 8	64 ± 9	40 ± 10

[a] Values are means ± standard deviations. For the PIP joint, parameters with both positive and negative values were observed, reflecting the variability in joint kinematics. To avoid this discontinuity in the stiffness measurements, means are grouped according to sign. Number of subjects showing positive and negative stiffness are indicated in parentheses.

Several limitations of this study place our conclusions into a specific context. First, the experimental apparatus and task differed from typing on a computer keyboard in several respects. We studied only tapping with the right index finger on an individual keyswitch removed from a keyboard. During typing, taps of the index finger alternate with key-depressions by other fingers, whereas our protocol consisted solely of a series of taps with the index finger. Second, the arm and wrist were fully supported at a horizontal angle. Although this posture may be employed when tapping on some types of keyboards, postural differences among workstations and tasks are very important considerations. The horizontal arm and wrist posture used were consistent with previous studies of computer workstation use (Serina et al., 1999). The average wrist extension angle was 15 ± 6°, 8° less than that measured by Serina et al. (1999) during typing at a computer workstation. However, Serina et al. (1999) employed a keyboard with 8° slope. Finally, the lumped-parameter model that we fit to the data is linear, and assumes that model parameters are time independent.

Forces during tapping on an isolated keyswitch were similar in pattern to forces during typing on a computer keyboard, but showed differences in tap duration. The mean peak vertical force during the impact period of 1.32 ± 0.71 N was 4.3 times the keyswitch make force, within the range of 1.8–7.9 times the keyswitch make forces observed during typing (Armstrong et al., 1994; Gerard et al., 1999; Martin et al., 1996; Sommerich et al., 1996). Tap duration was 226 ± 54 ms (mean ± standard deviation; $N = 15$), substantially higher than tap durations during typing (typically 100 ms; Rempel et al., 1994). This difference in tap duration may affect the specific parameters measured; however, we expect that the overall patterns of joint function are similar to those observed during typing.

The range of joint angles observed in subjects during the contact period of tapping were comparable to joint angles observed during typing. Subjects in the current study employed a slightly more flexed MCP posture, but similar PIP and DIP posture to those measured during typing. MCP angles ranged from 33° to 40°, compared to the mean values during typing of $28 \pm 13°$ measured by Sommerich et al. (1996) and 16–27° measured by Nelson et al. (2000), whereas the PIP angle range of 33–35° during tapping was only slightly below the range of PIP angles of 35–45° measured by Nelson et al. (2000), and 1° below the average PIP angle of $36 \pm 11°$ measured by Sommerich et al. (1996). The range of DIP angles of 13–21° observed during tapping was slightly below the 14–28° DIP angles measured during typing (Nelson et al., 2000).

Although the MCP, PIP, and DIP joints all generated net flexor torques during the contact period of tapping, concurrent measurements of joint kinematics show differences in function among joints during tapping. The MCP joint flexed producing energy and the PIP and DIP joints extended during the loading phase. Consequently, the hypothesis that finger joints function similarly during tapping is not supported.

Horizontal forces were approximately 10% of the vertical forces, and on average directed towards the hand. In situations where vertical forces at the endpoint could result in large net joint torques, horizontal force generation could result in decreases in net joint torque requirements. (Alexander, 1977; Full et al., 1991). For the finger posture employed by subjects in the current study, larger horizontal forces directed away from the hand could substantially decrease net torques around all of the IP joints (Fig. 5), although the required forces would be in opposite direction to the measured horizontal forces. However, smaller net joint torques are not always directly related to forces experienced by the muscles articulating a specific joint (Darling and Cole, 1990; Zajac et al., 2002).

A linear lumped-parameter model explained over 89% of the variance in finger joint torque during the loading phase of tapping. Finger joints acted primarily in a spring-like manner during tapping on computer keyswitches. The position-dependent, spring-like components of the lumped-parameter model could explain 87–92% of the variance in torque (VAF_k; Table 2), whereas the velocity-dependent damping component could only explain 62–64% of the variance during the loading phase of the contact period (VAF_b; Table 2), and only 4–9% of the variance when the entire contact period was considered.

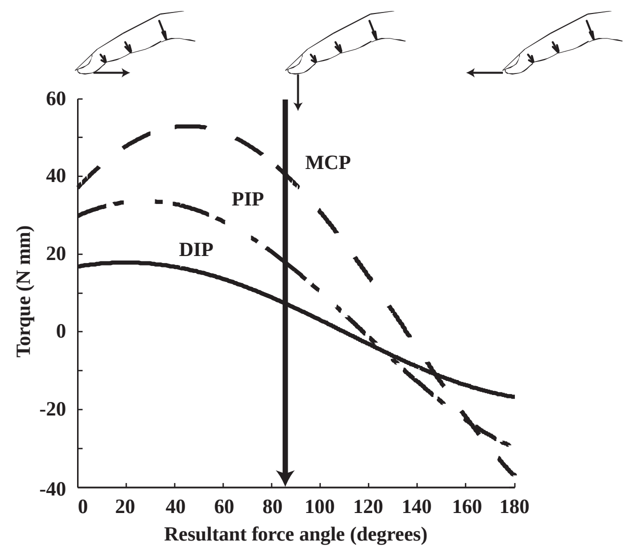

Fig. 5. Joint torques as a function of force direction for average posture employed by subjects. Thick vertical arrow indicates average force direction observed during tapping.

Asymmetries in kinematics and joint torques may account for the decrease in the VAF_k from 87–92% during loading to 60–71% during the entire contact period. During the unloading portion of the keystrike, the finger extensors are activated while the flexor tendons are still contracting, potentially changing the system dynamics (Dennerlein et al., 1998, 1999).

Joint stiffness dominated the dynamic response of fingers during tapping, as indicated by the similar values of VAF_k and VAF_{kb} for all finger joints (Table 2). Dynamic joint stiffness values measured during tapping were less than those measured during isometric loading (Becker and Mote, 1990; Hajian and Howe, 1997; Milner and Franklin, 1998). During the loading phase of tapping, the measured value of k for the MCP joint of 710 N mm rad^{-1} represents only 25% of the stiffness measured for fingers in a fully extended posture and generating 2 N endpoint force (stiffness calculated from Hajian and Howe (1997) assuming a finger length equal to the mean length measured in the present study of 8.2 cm). Endpoint force magnitude, finger posture, and loading regime are all likely to affect measured joint stiffness. Endpoint force magnitude is directly related to joint stiffness (Becker and Mote, 1990; Hajian and Howe, 1997; Milner and Franklin, 1998), and over short time-scales, this relationship is linear (Hajian and Howe, 1997). However, Hajian and Howe (1997) measured stiffness during forced extension of all three IP joints, whereas during tapping the MCP joint undergoes flexion. Considering that the mean and peak vertical force of 0.7 and 1.2 N are 35% and 60%, respectively, of the 2 N vertical forces used by Hajian and Howe (1997), we would expect the MCP joint stiffness in an extended posture to be 1010–1732 N mm rad^{-1} at the force levels observed during tapping. For the mean vertical force, the expected stiffness would be approximately 140% of the observed values. In extended postures, passive elements may substantially contribute to joint stiffness. A relaxed finger in an extended posture exhibited MCP joint stiffness of 130 N mm rad^{-1}, 20% of the stiffness observed during an intermediate level of muscle contraction (Becker and Mote, 1990). Furthermore, adopting a more flexed finger posture (i.e. increased flexion of the PIP and DIP joints) decreases MCP joint stiffness by 64% (Milner and Franklin, 1998). Taking passive forces and joint posture into account, we might expect finger stiffesses of approximately 563–1025 N mm rad^{-1} based on the measurements of Hajian and Howe (1997), Milner and Franklin (1998) and Becker and Mote (1990). Considering the lower force levels and flexed posture employed during tapping, the stiffness constant of 710 N mm rad^{-1} during loading is comparable to the values measured during isometric loading of the finger.

The metacarpalphalangeal and interphalangeal joints of the index finger did not function similarly in terms of energy production. The MCP joint exhibited net energy production during the loading phase and net energy absorption during the unloading phase, and the DIP joint exhibited the opposite pattern. The PIP joint was relatively stiff with much smaller joint excursions during the contact portion of the keystroke. Yet, on average the energy absorbed and produced by the joint was similar in magnitude as the DIP joint. Moreover, the amount of work done on the keyswitch during the loading phase of contact was 1.7 ± 0.7 N mm, only 30% of the energy generated by the MCP joint during the same period. Although calculating energy transfer requires consideration of the entire system (Zajac et al., 2002), only a portion of the energy produced by the MCP joint contributes to depressing the keyswitch. The other portion may be transferred to the IP joints and the fingertip pad (Jindrich et al., 2003). Additional characterization of the distribution of force and energy among upper-extremity tissues will allow better understanding of the causes of work-related musculoskeletal disorders (Gibson, 1961).

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