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Effects of keyswitch design and finger posture on finger joint kinematics and dynamics during tapping on computer keyswitches

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Abstract

Objective. To examine the effects of postural and keyswitch characteristics on musculoskeletal tissue loading during tapping on computer keyswitches.

Design. We hypothesized that joint torques, stiffness and work parameters differ across keyswitch designs and finger postures typical of those observed during computer keyboard typing. We experimentally measured joint kinematics and calculated joint torques while tapping on different keyswitches in different postures, and analyzed the data using mechanical impedance models.

Methods. Sixteen human subjects tapped with the index finger on computer keyswitches mounted on a sensor which measured vertical and horizontal forces. Miniature electro-optical goniometers mounted dorsally across each finger joint measured joint kinematics. Joint torques were calculated from endpoint forces and joint kinematics using an inverse dynamics algorithm. A linear spring-damper impedance model was fitted to joint torque, position, and velocity during the contact period of each tap. Subjects tapped in three postures approximating those employed during tapping on three rows of a computer keyboard, on four different keyswitches, resulting in 12 conditions.

Results. More extended finger posture was associated with greater joint torques, energies, and stiffnesses, despite minimal differences in endpoint forces across posture. Greater keyswitch make forces were associated with increased forces, joint torques and joint stiffnesses, however this relationship was not monotonic.

Conclusions. Joint torques and stiffness parameters differed across keyswitch designs and finger postures. Estimates of joint impedance and work provided a unique perspective into finger dynamics.

Relevance

Determining the causes of work-related musculoskeletal disorders is facilitated by characterizing workplace task biomechanics, which can be linked to specific injury mechanisms.

1. Introduction

Computer keyboard use has been associated with upper extremity musculoskeletal disorders (MSDs) (Gerr et al., 2002). Specifically, keyboard and keyswitch design can influence the pain and symptoms associated with a common MSD, carpal tunnel syndrome (Rempel

et al., 1999; Tittiranonda et al., 1999). However, the specific relationships between these keyboard designs and finger biomechanics are relatively unknown.

Force–displacement relationships of computer keyswitches affect fingertip force, muscle activity and fatigue while typing. The force–displacement curves for most keyswitches are not monotonic, but instead are characterized by rising to a peak force, known as the activation or make force, then declining in force as the switch is further depressed and finally increasing in force as the keyswitch travel ends (Armstrong et al., 1994). The magnitude of the activation or make force, the force at

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which the switch contacts are closed, has been shown to affect subject comfort, fingertip force and muscle activity (Feuerstein et al., 1997; Gerard et al., 1999; Rempel et al., 1997). However, Rempel et al. (1999) reported a decrease in carpal tunnel syndrome symptoms for a small cross-sectional cohort that typed on a keyboard with a higher make force but a different force–displacement relationship. Key travel also affects the endpoint forces associated with tapping (Radwin and Jeng, 1997; Radwin and Ruffalo, 1999).

Hand and arm posture has been shown to affect muscle forces and activity. During static force production, flexed finger posture can reduce finger stiffness (Milner and Franklin, 1998), which is associated with muscle force (Hajian and Howe, 1997). Theoretical studies have hypothesized that flexed finger posture leads to reductions in the muscle forces experienced by the finger (Harding et al., 1993). Typing is a dynamic finger task that requires the generation of fingertip forces to depress the keyswitches across different finger postures associated with different rows and columns of the keyboard.

We seek to characterize finger biomechanics during typing by using mechanical impedance models for the finger joints. Differences in finger joint stiffness, relating joint torque with joint excursions, may indicate different levels of internal exposure of the musculoskeletal system to mechanical forces during tapping, and provide a link between differences in endpoint forces and differences in tissue exposure (Becker and Mote, 1990; Hajian and Howe, 1997; Milner and Franklin, 1998). Therefore we tested the hypotheses that during single finger tapping, joint torques, stiffness and damping parameters differ across keyswitch designs and finger postures typical of those observed during computer keyboard typing. We conducted a series of single finger tapping experiments to test these hypotheses.

2. Methods

Sixteen subjects (8 male, 8 female), ages 20–35 (mean = 27, SD 5) participated in the study. Subjects were touch-typists, with average finger segment lengths of 25 SD 3 mm, 23 SD 4 mm, 34 SD 10 mm for the distal, middle, and proximal phalanges, respectively. 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 tapped in three postures on four different keyswitches (3×4 factor repeated-measures design). Subjects were seated and allowed to rest their right forearm on a smooth wooden surface level with the top of an isolated keyswitch attached to a two-directional force sensor (Fig. 1). Miniature goniometers (Shape
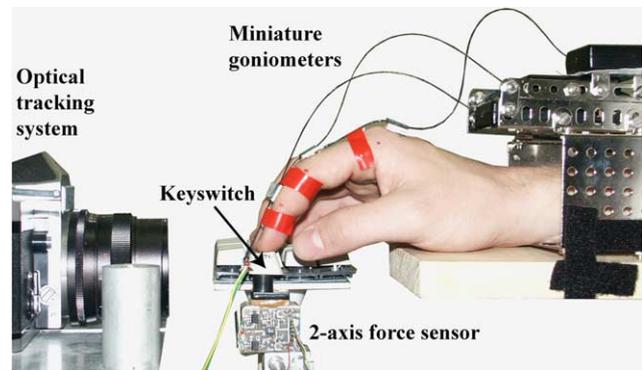

Fig. 1. Experimental apparatus.

Sensors, Measurand Inc.) were attached across the three index finger joints: the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints. Vertical keyswitch position was measured using an optical system (Jindrich et al., 2003), and digital images of the finger in the sagittal plane were collected with a digital still camera (Dimage 7, Minolta Corp.) to enable expression of finger segment orientations within the coordinate frame of the force sensor.

Subjects tapped on four different keyswitches representing two different keyswitch designs and each exhibiting different force–displacement relationships (Fig. 2; Table 1). Two of the keyswitches, A and B, utilized a buckling-spring design to create the breakaway force, while the other two, C and D, utilized a buckling rubber-dome to achieve the tactile experience. Keyswitch A was from a Supertouch Enhanced keyboard (SIIG, Inc., Fremont, CA, USA), and Keyswitch B was from an IBM Personal computer AT keyboard (International Business Machines Corp.; Fig. 2B). Keyswitches C and D were from separate Apple MacPro Plus keyboards (Keytronic, Inc.; Fig. 2A).

To facilitate posture selection, a keyboard guide containing three rows of computer keys was positioned with its middle row of keys adjacent to the keyswitch attached to the force sensor. For one posture (the 'Middle' posture) subjects were instructed to align their fingers along the middle row of the keyboard guide as if they were typing on the middle row of a computer keyboard. Tapping on the keyswitch in the Middle posture was meant to approximate tapping on a key in the middle row of a computer keyboard. For a second posture (the 'Upper' posture), subjects were instructed to align their fingers along the bottom row of the keyboard guide, then to tap on the keyswitch. Tapping on the keyswitch in the Upper posture was meant to approximate tapping on a key in the upper alphabetical row of a computer keyboard when the rest of the hand remained positioned at the home row. For the third posture (the 'Lower' posture), subjects were instructed
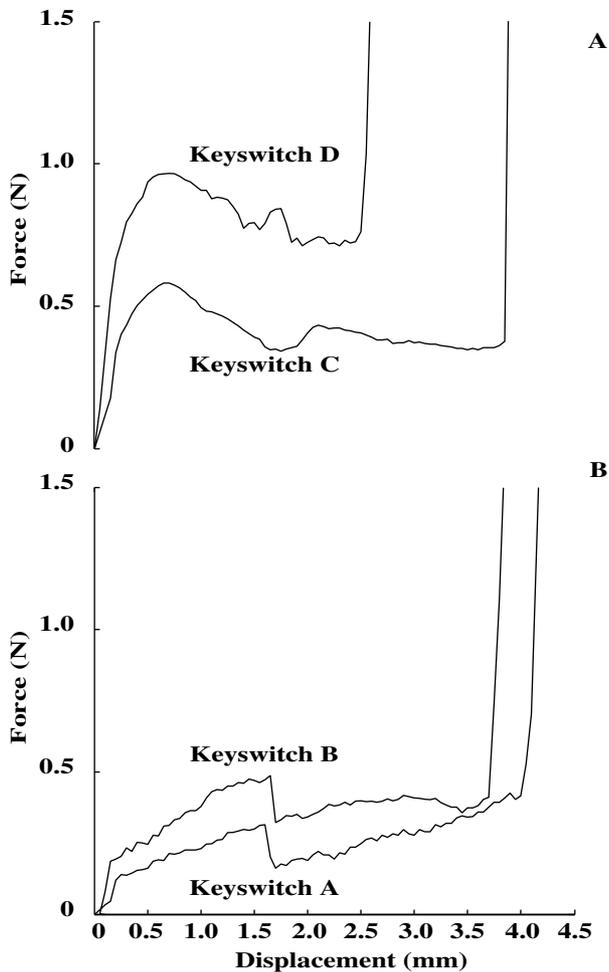
Fig. 2. Keyswitch quasi-static force–displacement relationships. (A) Rubber-dome keyswitches. (B) Buckling-spring keyswitches.

Table 1
Keyswitch parameters

Design	Keyswitch			
	A	B	C	D
	Spring	Spring	Dome	Dome
Activation force (N)	0.31	0.49	0.58	0.96
Total travel (mm)	4.1	3.8	3.9	2.6
Quasi-static E_{load} (mJ)	1.19	1.39	1.74	2.08

to align their fingers along the top row of the keyboard guide, then tap on the keyswitch. Tapping on the keyswitch in the Lower posture was meant to approximate tapping on a key in the lower row of a computer keyboard. The order of keyswitches and the order of postures within each keyswitch were randomized.

Before each keyswitch was used, the goniometers were calibrated using flexion angles from 0° to 60° in 10° increments. Subjects then tapped synchronously with a 0.75 Hz auditory signal for 1 min. After 20 s of tapping, 40 s of data were collected. Subjects were then allowed

to rest for at least 1 min. After the rest period, subjects were instructed to adopt the next posture and begin tapping when comfortable.

Data from the force sensor, keyswitch position sensor and goniometers were filtered, calibrated, and contact periods were identified (Jindrich et al., in press). Tap duration (τ_{tap}) and the duration of the loading phase (τ_{load}) were calculated as the duration of the contact period of the tap and the period from the beginning of the tap until the local maxima corresponding to pulp compression, where force begins to decrease (Rempel et al., 1994). 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). Net joint torques were calculated from fingertip forces, segment velocities and accelerations using an iterative Newton–Euler algorithm (Craig, 1989). Net work of the fingertip joints during the loading phase (E_{load}) was calculated by integrating joint torque with respect to joint angle from the beginning of contact until the force maxima during pulp compression. Net work for the keyswitch during the loading and unloading phases was calculated by integrating vertical force with respect to position.

We fit a lumped-parameter model of a linear spring and damper to the joint torque and angle excursion behavior during the loading phase of tapping using the following equation

$$T_{load}(t) = k_{load}\theta(t) + b_{load}\dot{\theta}(t) \qquad (1)$$

where $T_{load}(t)$ is the joint torque during the loading phase, $\theta(t)$ and $\dot{\theta}(t)$ are joint angular position and angular velocity, respectively. The loading phase was selected because stiffness parameters are different for the loading and unloading phases of the contact period, and are of higher magnitude during the loading phase (Jindrich et al., in press). The constants k_{load} and b_{load} were estimated using a least-squares method. We calculated a model estimate of the torque, $T_p(t)$, using Eq. (1) with the measured values $\theta(t)$, $\dot{\theta}(t)$ and the fitted parameters k_{load} and b_{load}. We estimated the variance accounted for by the model (VAF) the using the equation:

$$VAF_{load} = 100 \times \left[1 - \frac{\sum_{t=0}^{t=\tau}[T_{load}(t) - T_p(t)]^2}{\sum_{t=0}^{t=\tau} T_{load}(t)^2} \right] \qquad (2)$$

We analyzed 3900 taps from the 16 subjects, on average 20 taps per keyswitch and position condition for each subject. Calculated parameters were averaged for each condition within each subject. These means were then compared using a mixed-model, repeated-measures analysis of variance (proc mixed; SAS 8.2), with keyswitch design and finger posture as fixed effects and subject as a random effect. Least-squares means, which represent values for each category of independent variable when all other independent variables are set to their

mean values, were calculated for each condition. Standard errors are from ANOVA residuals. Differences between group means were tested using Turkey's test and considered significant when $P < 0.05$.

3. Results

Both finger position and keyswitch affected joint kinematics and torques (Fig. 3). More extended finger posture was associated with greater joint torques, energies, and stiffnesses, despite minimal differences in endpoint forces across posture. Greater keyswitch make forces were associated with increased forces, joint torques and joint stiffnesses, however this relationship was not monotonic.

During the loading phase of the contact period, the MCP joint flexed, resulting in a greater flexion angle at mid-tap (i.e. when joint torques are highest) than at the beginning of contact (Fig. 3). Subsequently, during the unloading phase of contact, the MCP joint extended, reaching a final angle at the end of the contact period more flexed than at the beginning of contact. The PIP and DIP joints, however, showed the opposite pattern of

movement, extending during the loading phase of contact and flexing during unloading.

The orientation of the resultant force at the fingertip, coupled with the finger kinematics, indicated that all IP joints generated primarily positive (flexor) torques (T_{ave}) across all keyswitches and positions (Fig. 3). Positive joint torques, coupled with the measured kinematics, indicated that the MCP joint exhibited positive net work during the loading phase and negative work during the unloading phase, whereas the DIP exhibited the opposite pattern of work production. The PIP joint acted similarly to the DIP joint for all keyswitches except for Keyswitch B and all positions except for the Lower position, for which the PIP exhibited positive net work during the loading phase. The linear spring-damper model was able to describe 88–94% of the variance in torque (Eq. (2)) across the measured keyswitches and positions.

Finger postures, torques, and energy parameters differed significantly across the three finger positions. Changes in PIP and DIP angles, and to a lesser extent MCP angles, during contact were associated with more extended finger joint postures as the position of the hand varied from the Lower to the Upper position (Fig. 4A).
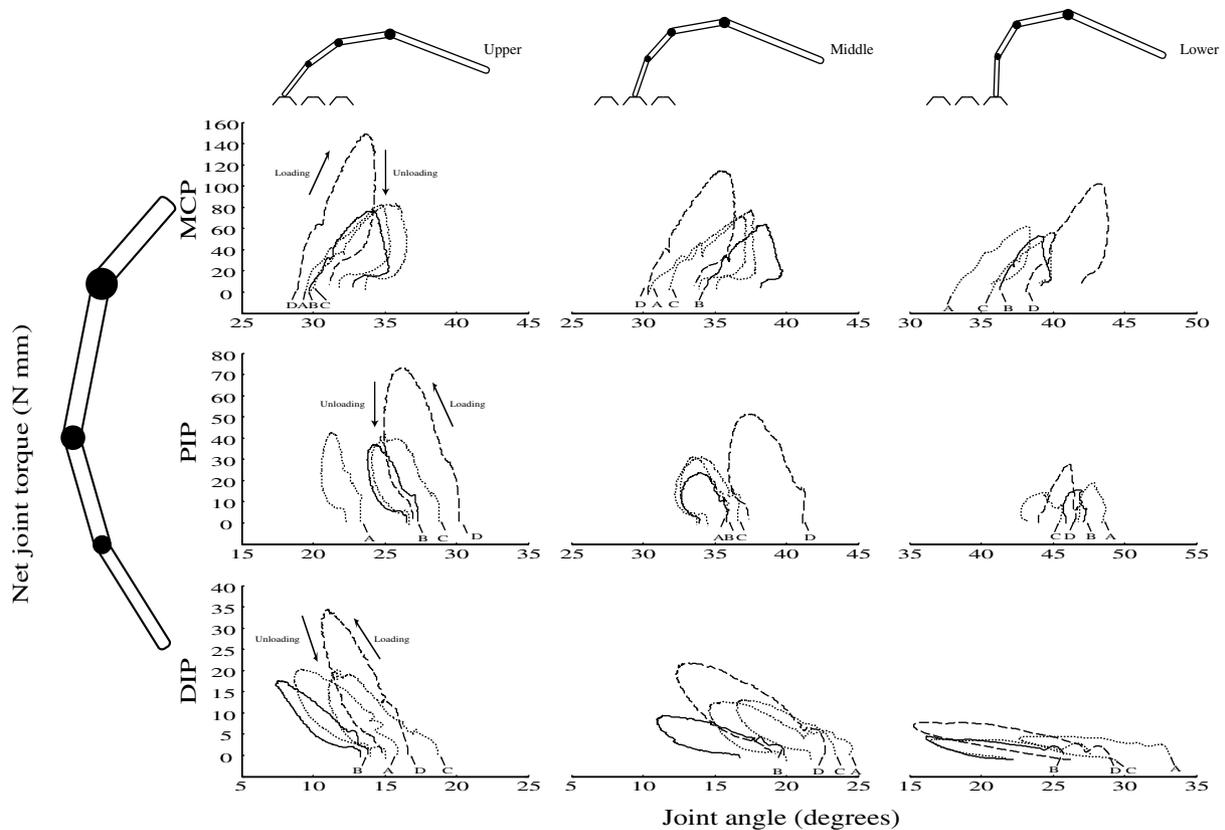

Fig. 3. Joint torque plotted versus joint angle during the contact period of tapping, for Upper, Middle and Lower postures. Letters (A, B, C and D) and arrows indicate joint torque and angle at the beginning of the contact period. Loading and unloading portions of the contact period are indicated for the Upper position. Net joint torque and angle represent averages across 16 subjects.
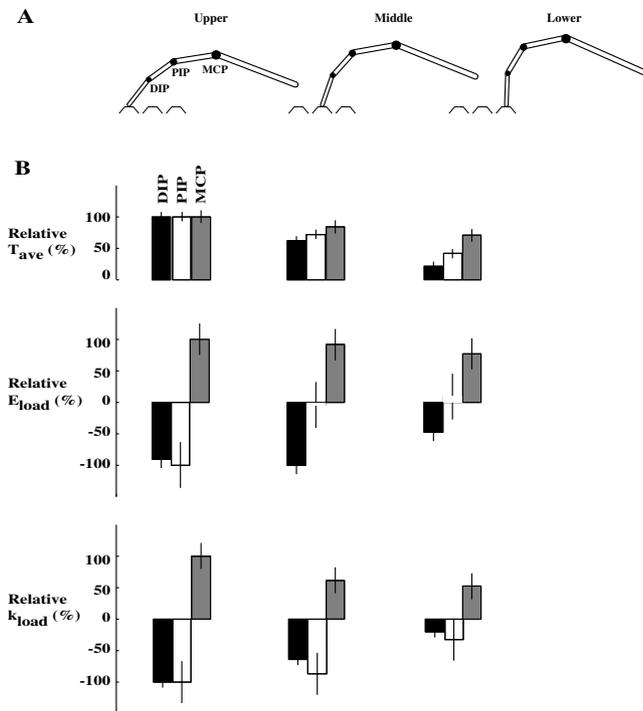
Fig. 4. Effects of posture on finger mechanics during tapping. (A) Finger postures at time of first contact (θ_i) when tapping as if typing on Lower, Middle, and Upper rows of a computer keyboard. (B) Average net joint torque (T_{ave}), net work during the loading phase (E_{load}), and joint stiffness (k_{load}) during the loading phase for Lower, Middle and Upper postures. Values are normalized to the maximum value for each joint across keyswitches. Values for MCP, PIP, and DIP joints are indicated by gray, white, and black bars, respectively. Lines in the middle of each bar indicate standard errors of the mean.

Initial, mid-point, and final MCP, PIP and DIP angles were significantly more flexed (greater) in the Lower posture than in the Upper and Middle postures, and PIP and DIP joints showed significantly more flexed angles in the Middle posture than in the Upper posture. Finger position had the greatest effect on PIP angle. The PIP joint in the Lower position was 20°–22° more flexed than in the Upper position, compared to 8°–13° for the DIP joint and 6°–7° for the MCP joint.

Tapping position did not significantly affect vertical fingertip force or work done on the keyswtiches (Table 2); however average F_h in the Lower position was significantly greater (i.e. pulling more towards the subject) than in the Middle or Upper positions. Hand position also affected endpoint velocities. Downward keycap velocity was significantly less in the Lower position than velocity in either the Upper or Middle positions.

As the finger postures became more extended in the Middle and Upper positions, the magnitudes of the average and maximum joint torques and energy produced by the joints increased significantly (Fig. 4B; Table 3). Average torques in the Upper position were 20–60% higher than T_{ave} in the Middle position across

joints, and T_{ave} in the Middle position were 20%— 2.8 times higher than T_{ave} in the Lower position.

As the fingers extended in the Upper posture, the joint stiffness values increased significantly (Fig. 4B; Table 3). In contrast, there were few differences in joint damping observed among postures. DIP damping constant, b_{load}, in the Middle position was significantly different from b_{load} in the Lower position, but no other comparisons of b_{load} showed significance for the DIP or other joints.

Keyswitch design did not show significant effects on finger postures as measured through the joint angles during the keystrike. However, tapping on different keyswitch designs affected both endpoint and finger joint mechanics.

Tap duration, fingertip impact and average forces, and work done on the keyswitch by the fingertip all increased with switch activation force, whereas average fingertip velocity during contact decreased with activation force (Table 2). Decreases in fingertip velocity during contact were not due to differences in initial fingertip velocity, which did not show significant differences among keyswitches. Net work done on the keyswitch (KS E_{load}) increased with activation force, with a 1.7-fold range among the four different switches (Table 2). Keyswitch D, (which has a higher activation force) absorbed significantly more energy than all other keyswitch designs. However Keyswitch A, with the lowest activation force, returned significantly more energy (KS E_{unload}) than Keyswitches B and C. Endpoint velocities during contact, as indicated by keycap velocity, showed the opposite pattern of magnitudes than endpoint forces.

Finger joint torques increased with increasing activation force, with Keyswitch D having significantly higher values than the other keyswitch designs (Table 3; Fig. 5). Finger joint stiffness values varied significantly with keyswitch design; however the relationship was not monotonic with key activation force. MCP k_{load} when tapping on Keyswitch D was significantly higher than k_{load} when tapping on any other keyswitch (Table 3). For the PIP and DIP joints, Keyswitch D was associated with significantly higher k_{load} than Keyswitches C and B, but not Keyswitch A. Damping coefficients (b_{load}) did not vary across keyswitches.

Few keyswitch–posture interactions were significant. Of the parameters measured, only initial MCP angle and PIP E_{net} showed significant keyswitch–posture interactions.

4. Discussion

Both keyswitch design and finger posture affected the endpoint forces, joint torques, and joint stiffnesses observed during tapping. Increased keyswitch activation force and extended postures were associated with

Table 2
Tap duration, fingertip kinematics, force and energy production across positions and keyswitch designs

	Position			P	Keyswitch				P
	Upper	Middle	Lower		A	B	C	D	
Tap duration (s)	0.230 (0.016)[L]	0.230 (0.016)[L]	0.242 (0.016)	0.022	0.216 (0.016)[B,D]	0.232 (0.016)[D]	0.235 (0.016)[D]	0.252 (0.016)	<0.0001
Initial fingertip velocity (mm s^{-1})	153 (39)	151 (39)	139 (39)	0.54	160 (39)	130 (39)	163 (39)	137 (39)	0.09
Average downward fingertip velocity (mm s^{-1})	106 (16)[L]	96 (16)[L]	72 (16)	0.0007	119 (16)[C,D]	104 (16)[D]	83 (17)	60 (16)	<0.0001
Average vertical force, F_v (N)	0.89 (0.08)	0.87 (0.08)	0.86 (0.08)	0.71	0.71 (0.08)[C,D]	0.70 (0.08)[C,D]	0.85 (0.08)[D]	1.25 (0.08)	<0.0001
Peak pulp compression force, PCF$_v$ (N)	1.56 (0.14)	1.55 (0.14)	1.59 (0.14)	0.85	1.21 (0.14)[C,D]	1.31 (0.14)[C,D]	1.57 (0.14)[D]	2.19 (0.14)	<0.0001
Average horizontal force, F_h (N)	0.05 (0.03)[L]	0.06 (0.03)[L]	0.13 (0.03)	<0.0001	0.1 (0.03)[B,C]	0.05 (0.03)[D]	0.06 (0.03)[D]	0.11 (0.03)	0.002
Work done on keyswitch, KS E_{load} (N mm)	−2.3 (0.1)	−2.3 (0.1)	−2.5 (0.1)	0.37	−1.9 (0.2)[D]	−2.2 (0.1)[D]	−2.2 (0.2)[D]	−3.2 (0.2)	<0.0001
Work done by keyswitch, KS E_{unload} (N mm)	0.9 (0.08)	1.0 (0.08)	0.9 (0.08)	0.96	1.2 (0.08)[B,C]	0.9 (0.08)[C]	0.7 (0.08)	1.0 (0.08)	<0.0001

Values reported are least-squared means (standard errors); $N = 16$. In cases where ANOVA model showed significant effects, letter superscripts indicate specific comparisons between positions (M = Middle, L = Lower) and Keyswitches (B, C, D) which Tukey tests determined were significantly different. For clarity, only comparisons with values in columns to the right of each value are indicated (for example, a 'L' superscript in the Upper column indicates that the Upper–Lower comparison showed significant difference, but the reciprocal Lower–Upper comparison is not shown in the Lower column).

increases in finger joint torque, energy exposure, and stiffness during tapping. However, impedance (i.e. stiffness) and work done by the individual joints did not strictly correlate with fingertip force across the various keyswitch designs, indicating that the internal load may be different than loads predicted solely on the basis of forces, and that mechanical task requirements may affect motor control.

Several limitations are inherent in our laboratory study of finger tapping mechanics. First, tapping on an isolated keyswitch instead of a keyboard causes changes in some the key strike parameters. For example, tap durations of 216–252 ms were greater than those measured during typing on a computer keyboard (typically less than 100 ms; Rempel et al., 1994). Second, finger and hand kinematics when tapping may be different than when typing on a computer keyboard. Subjects here assumed a resting posture on one row of keys, and tapped on the keyswitch as if it were one row above or below without moving their hand or arm. When typing on a computer keyboard, the arm and hand are free to move, potentially changing the postures employed when tapping on keys in different keyboard rows. Although flexion and extension about the wrist were possible, the position of the wrist relative to the keyswitch was not changed within each set of keyswitch–posture trials. Similarly, this study did not address differences in kinematics or force requirements associated with tapping on different keyboard columns, requiring finger abduction and/or adduction.

Finger kinematics, endpoint forces, net joint torques and energy production when tapping on four different keyswitches in three different postures showed similar patterns. During the contact period of tapping, the MCP joint showed flexion in the first half of the contact period, followed by extension in the second half of contact (Fig. 3). PIP and DIP joints showed the opposite pattern of movement: extension during loading and minimal movement or flexion during unloading for all keyswitches and postures. These joint kinematics, coupled with the net flexor torques generated by each joint during the contact period, resulted in net energy production (i.e. positive E_{net}) by the MCP joint and energy absorption by the DIP joint during the loading phase for all keyswitches and postures measured (Table 3). The PIP joint showed energy absorption during the loading phase for all but one keyswitch/posture condition. The work done on the keyswitch, DIP and the PIP joints was slightly below that of the work produced by the MCP joint.

Increasingly flexed finger postures were associated with significantly reduced T_{ave} and T_{max} for all IP joints (Table 3). Differences in joint torque were not due to differences in F_v or F_h among finger postures. Similar to typing on a keyboard (Armstrong et al., 1994), F_v was not significantly different when tapping in postures associated with typing on different keyboard rows (Table 2). F_h was significantly higher for the most flexed Lower posture. Increased F_h for the Lower posture would tend to increase joint torques, contrary to the pattern observed. Differences in joint torque were instead due to finger posture. When fingertip forces are near-vertical, increased joint flexion causes joint centers to be closer to the force line of action, resulting in decreases in net joint torque. For example, distances between the keyswitch and the MCP joint were 85, 74, 62

Table 3
Torque, energy exposure, and impedance model parameters of finger joints during tapping across positions and keyswitch designs

		Position			P	Keyswitch				P
		Upper	Middle	Lower		A	B	C	D	
Average	MCP	57.5 (6.6)[M,L]	47.2 (6.6)[L]	39.0 (6.6)	<0.0001	40.3 (7.0)[D]	36.7 (7.0)[D]	42.4 (6.7)[D]	72.2 (6.7)	<0.0001
Joint torque	PIP	30.0 (2.3)[M,L]	21.4 (2.3)[L]	12.2 (2.3)	<0.0001	18.9 (2.3)[D]	15.5 (2.4)[D]	18.1 (2.4)[D]	32.3 (2.4)	<0.0001
T_{ave} (N mm)	DIP	14.6 (1.0)[M,L]	9.0 (1.0)[L]	3.2 (1.0)	<0.0001	7.9 (1.0)[D]	6.5 (1.1)[D]	7.6 (1.2)[D]	13.7 (1.1)	<0.0001
Joint energy	MCP	6.4 (1.7)	5.9 (1.7)	5.0 (1.7)	0.068	4.9 (1.7)[D]	4.5 (1.7)[D]	6.0 (1.7)[D]	7.8 (1.7)	<0.0001
during loading	PIP	−1.1 (0.4)[L]	−0.5 (0.4)	0.0 (0.4)	<0.001	−0.2 (0.4)[D]	0.0 (0.4)[D]	−0.2 (0.4)[D]	−1.6 (0.4)	<0.0001
E_{load} (N mm)	DIP	−2.0 (0.3)[L]	−2.1 (0.3)[L]	−1.0 (0.3)	0.007	−1.3 (0.4)[D]	−1.3 (0.4)[D]	−1.6 (0.4)	−2.5 (0.4)	0.01
Net energy	MCP	5.5 (1.3)[M,L]	5.4 (1.3)	4.3 (1.3)	0.08	3.9 (1.3)[D]	4.0 (1.3)[D]	5.5 (1.3)	6.9 (1.3)	<0.0001
Production	PIP	−1.3 (0.4)[L]	−1.1 (0.4)[L]	−0.3 (0.4)	0.001	−0.5 (0.4)[D]	−0.2 (0.4)[D]	−0.4 (0.4)	−2.3 (0.4)	<0.001
E_{net} (N mm)	DIP	−1.4 (0.2)	−1.6 (0.2)	−1.0 (0.2)	0.07	−1.0 (0.3)[D]	−1.0 (0.3)[D]	−1.5 (0.3)	−1.9 (0.3)	0.01
k_{load} (N mm rad^{-1})	MCP	711 (134)[L]	433 (134)	393 (134)	0.02	472 (141)[D]	320 (142)[D]	356 (147)[D]	901 (141)	0.0004
	PIP	−199 (86)	−216 (86)	−70 (86)	0.12	−192 (90)	−64 (91)[D]	−88 (94)[D]	−300 (90)	0.04
	DIP	−174 (15)[M,L]	−110 (15)[L]	−34 (15)	<0.0001	−110 (16)	−82 (16)[D]	−87 (17)[D]	−147 (16)	0.002
b_{load} (N s mm rad^{-1})	MCP	2.26 (1.22)	1.30 (1.21)	2.70 (1.2)	0.6	0.7 (1.20)	1.9 (1.22)	3.11 (1.26)	2.64 (1.21)	0.51
	PIP	−0.9 (0.50)	−0.82 (0.49)	−1.10 (0.49)	0.8	−1.17 (0.53)	−0.07 (0.53)	−1.23 (0.56)	−1.28 (0.53)	0.16
	DIP	−0.65 (0.16)[M,L]	−0.77 (0.16)[L]	−0.40 (0.16)	0.02	−0.49 (0.17)	−0.6 (0.17)	−0.58 (0.18)	−0.78 (0.17)	0.22
VAF$_{load}$ (%)	MCP	82 (3)	79 (3)	74 (3)		79 (3)	75 (3)	77 (3)	82 (3)	
	PIP	72 (3)[L]	69 (3)	64 (3)		69 (3)	67 (3)	66 (3)	72 (2)	
	DIP	79 (2)	81 (2)	70 (2)		79 (3)	75 (3)	76 (3)	77 (3)	

Data reported are least-squared means (standard errors); $N = 16$. Superscripts as in Table 2.

mm for Upper, Middle, and Lower postures, respectively. Moreover, increased joint flexion may also lead to greater flexor tendon moment arms, which could further reduce the muscle forces required to depress the keyswitch (Harding et al., 1989, 1993).

Joint stiffness for the Lower posture was 44%, 64% and 80% less than stiffness for the Upper posture for the MCP, PIP, and DIP joints, respectively. The reduction of stiffness for the MCP joint was similar to the equivalent stiffness reduction of 54% observed in flexed postures by Milner and Franklin (1998). However, during tapping changes in finger posture resulted in greater stiffness reductions than during the isometric loading regime employed by Milner and Franklin (1998), which involved decreases in stiffness of 10% and 35% for the PIP and DIP joints, respectively (Milner and Franklin, 1998). The greater stiffness reductions observed during tapping relative to isometric loading are surprising considering that the differences between extended and flexed postures employed by Milner and Franklin (1998) were 53° and 35° for the PIP and DIP joints, respectively. These differences were substantially larger than the maximum differences of 22° and 13° employed by subjects in the current study. These differences could be due to the lower forces observed during tapping than the approximately 10 N forces employed by Milner and Franklin (1998). If muscle properties contribute substantially to joint stiffness, then as finger forces approach 100% MVC, the potential for changes in joint stiffness would be expected to decrease.

Keyswitch design affected the endpoint fingertip forces generated during tapping. Higher average and peak forces were associated with tapping on keyswitches with higher activation forces (Table 2). Increased vertical forces were not related to increases in finger kinetic energy. Average downward fingertip velocity during keyswitch compression decreased as activation force increased (Table 2).
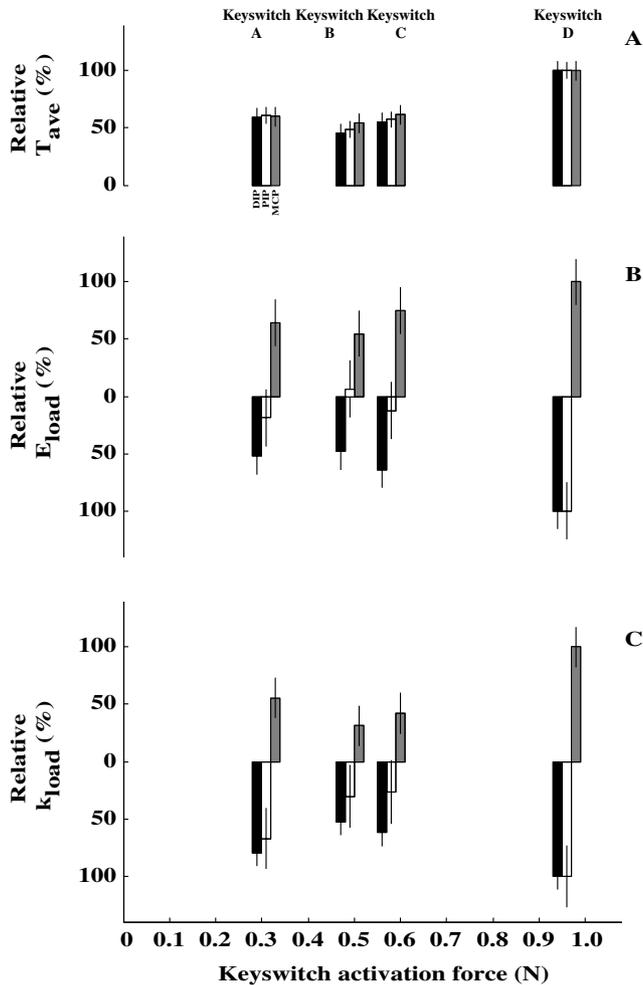
Fig. 5. Effect of keyswitch design on finger mechanics. Values are normalized to the maximum value for each joint across keyswitches. Values for MCP, PIP, and DIP joints are indicated by gray, white, and black bars, respectively. Lines in the middle of each bar indicate standard errors of the mean. (A) Average net joint torque (T_{ave}). (B) Net work during the loading phase (E_{load}). (C) Joint stiffness (k_{load}) during the loading phase.

Average fingertip forces were directly related to keyswitch activation force for all keyswitches with the exception of Keyswitch A. Activation forces for Keyswitches A, B and C were 32%, 51% and 60% of the Keyswitch D activation force, and the relative forces observed during keyswitch compression (KSF$_v$; Table 2) closely matched relative keyswitch activation forces (3% difference for Keyswitches B and C and 10% difference for A; Table 2).

Average F_v ranged from 130% of keyswitch make force for Keyswitch D, to 229% for Keyswitch A, and peak PCF$_v$ ranged from 236% of make force for Keyswitch D to 435% for Keyswitch A. These ratios follow the trend that the 'safety margin' (the ratio of applied force to make force) decreases as make force increases (Gerard et al., 1996; Martin et al., 1996; Radwin and Jeng, 1997; Rempel et al., 1997). However, the safety margins measured in the present study during tapping were less than those measured during typing. For example, in the present study, safety margins for peak F_v for Keyswitch C (0.57 N make force) and Keyswitch D (0.96 N make force) were 340% and 236%, respectively. In comparison, Rempel et al. (1999) measured safety margins of 545% for Keyboard 2 (0.47 N make force) and 339% for Keyboard 3 (1.02 N make force), and Gerard et al. (1999) measured safety margins of 536% for a 0.56 N make force keyswitch, and 458% for a 0.83 N make force keyswitch. The low safety margins for Keyswitch D were also surprising considering the short key travel for this keyswitch, since decreasing key travel is associated with increased peak forces (Radwin and Jeng, 1997). It is possible that when tapping on an isolated keyswitch in a controlled position, subjects were able to more precisely control endpoint force production to reduce their safety margins relative to typing on a computer keyboard. Consequently, our measurements may represent conservative estimates of the exposure of the musculoskeletal system to mechanical forces during tapping on computer keyswitches.

Keyswitch design had significant effects on joint torques, energies, and stiffness during tapping. Changes in T_{ave} paralleled changes in endpoint forces. On average, relative T_{ave} differed by only 7% (range of 1–13%) from relative changes in average F_v (Fig. 5).

Hajian and Howe (1997) found a nearly linear relationship between isometric fingertip force and finger stiffness. A close correspondence between changes in k_{load} and changes in average F_v was only observed for the DIP joint and Keyswitches B and C (changes in k_{load} relative to Keyswitch D were within 3–6% of relative changes in average F_v; Tables 2 and 3). For the MCP and PIP joints for Keyswitches B and C, relative k_{load} was 20–39% below relative F_v. However, values for relative k_{load} for Keyswitch A were 13–43% higher than those for Keyswitches B and C. This discrepancy may be explained by the differences in unloading characteristics of the keyswitches. Keyswitch A released 20–70% more energy (KS E_{unload}; Table 2) than the other keyswitches studied. The decrease in finger stiffness allowed by reduced activation force for Keyswitch A may have been offset by increased stiffness necessary to stabilize the finger during unloading.

5. Conclusions

Measurement of finger kinematics and two-dimensional endpoint forces has shown that both keyswitch design and finger posture affect finger joint characteristics during tapping. The nearly-vertical forces observed during tapping result in lower net joint torques and joint stiffness for more flexed postures as might be experienced when tapping on the lower row of keyboard keys.

This finding supports the hypotheses that flexed postures result in lower net joint torques (Harding et al., 1989, 1993), stiffness (Milner and Franklin, 1998), and consequently muscle and tendon forces during tapping. Average vertical forces were correlated with keyswitch activation forces; however, consideration of net joint stiffness supports the hypothesis that aspects of keyswitch design other than activation force (such as unloading characteristics) contribute to forces experienced by the musculoskeletal system during tapping.

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