Keyswitch Orientation Can Reduce Finger Joint Torques During Tapping on a Computer Keyswitch

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Objective: To examine the effects of keyswitch orientation on joint torques. **Background:** The fingertip produces primarily vertical forces during single-finger tapping on a computer keyswitch. However, horizontal force components within the sagittal plane of the finger could reduce net joint torques. **Method:** Eleven participants tapped on a keyswitch oriented in three directions: vertical, tilted 30° such that when pressed it moved away from the user (similar to a positive-tilt keyboard), and tilted 30° such that when pressed it moved toward the user (similar to a negative-tilt keyboard). Participants also tapped on a prototype cantilever keyswitch design in which the key cap moves along the arc of a bending beam gradually away from the user. Miniature electro-optical goniometers measured the finger posture, and a two-axis force sensor measured fingertip forces. **Results:** Tapping on a keyswitch oriented such that it moves away from the user when pressed reduced net joint torques by 47% relative to tapping on a vertically orientated keyswitch and by 56% relative to tapping on a keyswitch oriented toward the user, whereas the cantilever design resulted in 14% decreases in net joint torque relative to the vertical orientation. **Conclusion:** Reductions of torques resulted from decreasing the moment arm of the fingertip force about the joints. **Application:** Keyboard design should incorporate keyswitch mechanism angles along with other postural and geometric constraints to reduce exposure of the finger joints and muscles to force during typing.

INTRODUCTION

Computer keyboard use has been associated with upper extremity musculoskeletal disorders (Bureau of Labor Statistics, 2002; Faucett & Rempel, 1994; Gerr et al., 2002; Hales et al., 1994). Although the specific injury mechanisms for these disorders are unclear, musculoskeletal forces are considered to be a factor contributing to their development (Feuerstein, Armstrong, Hickey, & Lincoln, 1997; Pascarelli & Kella, 1993). Force-displacement relationships of computer keyswitches can affect fingertip force, muscle activity, and fatigue while typing (Gerard, Armstrong, Foulke, & Martin, 1996; Gerard, Armstrong, Franzblau, Martin, & Rempel, 1999; Martin et al., 1996; Radwin & Jeng, 1997). Keyboard designs can affect muscle activity and pain, implying that different keyboard designs incur varying degrees of physical risk with use (Gerard et al., 1999; Rempel, Tittiranonda, Burastero, Hudes, & So, 1999; Tittiranonda, Burastero, & Rempel, 1999).

Current keyswitch designs employ vertical key travel and result in the production of nearly vertical forces at the fingertip (Jindrich, Balakrishnan, & Dennerlein, 2004b), which is not along the axis of the finger during the key strike. This creates a high external torque around the finger joints. However, additional horizontal forces can actually reduce required joint torques and muscle forces during contact with a surface (Alexander, 1977). Jindrich et al. (2004b) argued that current keyswitch designs may not minimize joint torques and that a horizontal force component that causes the resultant keyswitch force angle to be oriented approximately 30° off vertical away from the user

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(clockwise in Figure 1a) in the sagittal plane of the finger would reduce net finger joint torque during tapping.

Therefore, we sought to characterize finger joint kinematics and torques during tapping on a keyswitch in three directions within the sagittal plane. We tested the hypothesis that joint torques during tapping differ across keyswitch orientations. We also developed a prototype keyswitch design that incorporates horizontal movement through a cantilever design. We hypothesized that this cantilever design reduces net joint torque during tapping relative to a conventional vertical keyswitch design. We conducted a series of single-finger tapping experiments to test these hypotheses.

METHODS AND MATERIALS

The 11 participants (6 men, 5 women), ages 21 to 36 years (mean = 25.4 ± 4.2 *SD*), gave informed consent prior to experiments. All experimental procedures and consent forms were approved by the Human Subjects Committee at the Harvard School of Public Health.

Participants sat beside the experimental apparatus, rested their right arm on a platform directly in front of the keyswitch, and adjusted their chair to a comfortable elbow and shoulder position with the elbow at approximately 90° of flexion and the shoulder relaxed. The participants 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.

We tested one key oriented in three different directions within the sagittal plane as well as a new keyswitch design, for a total of four conditions presented to each participant in a random order. The keyswitch used for three of the conditions was from an IBM personal computer AT keyboard (International Business Machines Corp.) with an activation force of 0.49 N and a total travel distance of 3.75 mm (Jindrich, Balakrishnan, & Dennerlein, 2004a). The three different orientations for the keyswitch were positive tilt, vertical orientation, and negative tilt (Figures 1a–1c). In the vertical orientation condition, the keyswitch was mounted such that keyswitch displacement was vertical. In the positive-tilt condition, the keyswitch was mounted such that when pressed it moved away from the user at an angle of 30° off vertical, similar in direction to that of a positively sloped keyboard. In the negative-tilt condition, the keyswitch was mounted such that when pressed it moved toward the user, similar in direction to that of a negatively sloped keyboard. In all cases, the movement required for keyswitch activation was along the normal of the keycap surface.

In addition to keyswitch orientation, we tested a keyswitch design developed to reduce net finger joint torques (Figure 1d). Similar in design to that of Radwin and Jeng (1997), the key curved down and out following the arc of a bending beam around a fulcrum. The design utilizes a thin (2 mm thick) flexure that bends around a cantilever base

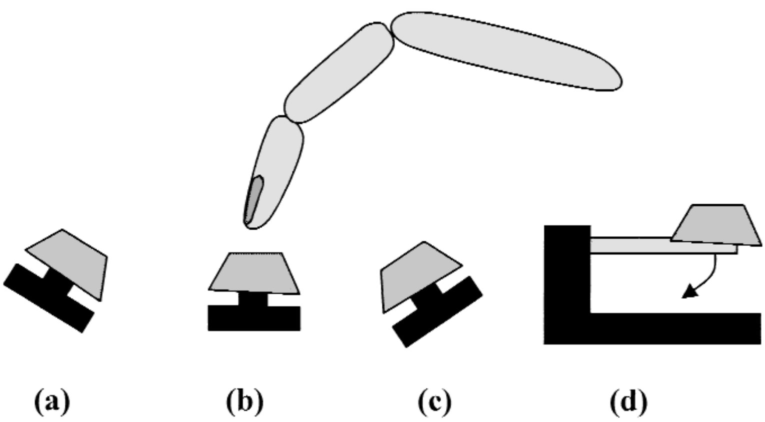

Figure 1. The four keyswitch conditions tested: (a) positive tilt, (b) vertical, (c) negative tilt, and (d) cantilever. The center of the key cap surface was located at the same place across all four conditions such that the finger posture at the point of contact would not vary across the conditions.

with a large moment arm. The result is that the key trajectory is at first fairly vertical and then becomes more horizontal as the key is pressed farther (Figure 2). The point of keyswitch activation was placed 1 mm below the resting position of the key cap, corresponding to a 0.54-N vertical force.

Horizontal and vertical force measurements were recorded using a strain-gauge force transducer securely anchored to a table (Jindrich et al., 2004b). The transducer had a resolution of 2.5 mN and a dynamic resonant frequency greater than 1000 Hz. Miniature goniometers (Shape Sensors, Measurand Inc., http://www.measurand.com/) attached across the three index finger joints – distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) – measured finger joint kinematics (Figure 3). Positive angles denote internal joint flexion away from full extension (i.e., parallel orientation of both segments constituting the joint). The goniometers had an angular resolution of 0.003° and a time resolution of 1000 Hz. Comparison of goniometer measurements with those derived from high-speed digital video of one trial yielded average errors of 1.5° ± 1.9°, 0.5° ± 3.2°, and 1.2° ± 3.9° for the MCP, PIP, and DIP joints, respectively. Digital images of the finger in the sagittal plane were collected (Dimage 7, Minolta Corp.) to enable expression of finger segment orientations within the coordinate frame of the force sensor.

Before and after testing of the four conditions, the goniometers were calibrated by instructing the participants to bend individual joints around metal rods to result in joint flexion angles of 0°, 20°, and 50°. Participants were then instructed to tap synchronously with a 0.75-Hz auditory signal for 3 min. After 20 s of tapping, 160 s of data were collected. Participants were then allowed to rest for at least 1 min. After the rest period the keyswitch condition was changed, and participants were instructed to begin tapping when comfortable.

Data from the force sensor and goniometers were calibrated and filtered using a fourth-order, low-pass Butterworth filter with a 500-Hz cutoff frequency. Contact was identified as periods when the force exceeded 0.02 N and was considered a successful key strike when the average vertical force exceeded 0.3 N over the entire contact period. The level of 0.02 N was selected as a level that exceeded the noise range of the sensor during the period before contact. For each trial, we identified loading and unloading phases of contact. The loading phase began when the fingertip first contacted the key cap and ended at the second local force maximum during the pulp compression phase. The unloading phase began at the second local maximum and ended at the release of the keyswitch.

Finger joint centers were identified by palpation and reference to surface landmarks, and segment

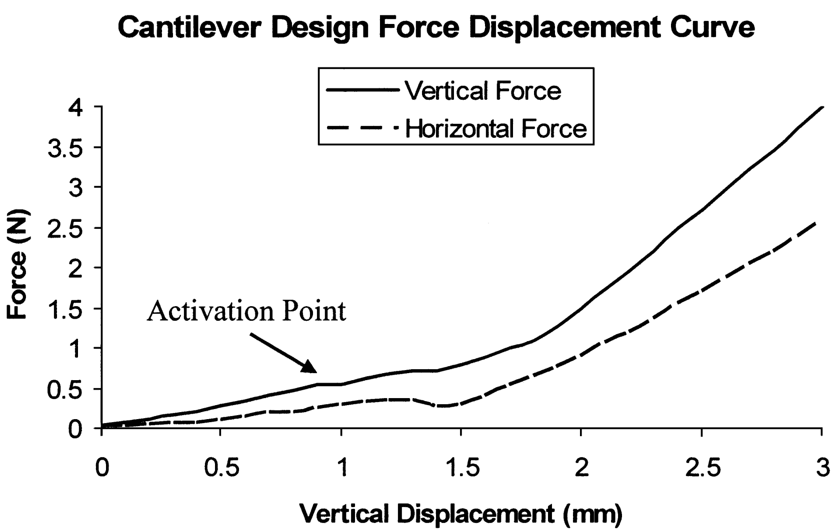

Figure 2. Cantilever force-displacement characteristics for both the vertical and horizontal force. Activation occurred at approximately 1.0 mm of travel and 0.54 N of vertical force.

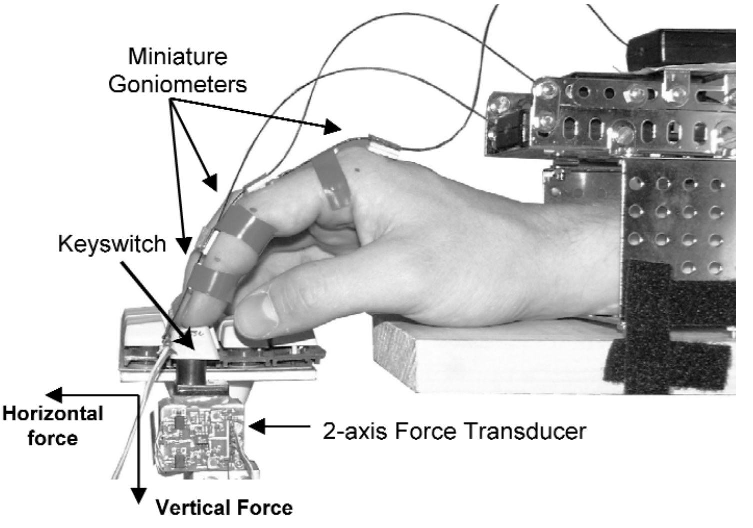

Figure 3. Experimental apparatus consisted of a keyswitch mounted on top of a two-axis force sensor and electro-optical miniature goniometers to measure finger joint kinematics.

lengths were measured with calipers. Finger segment diameter was measured as the caliper aperture at first depression of the midsegment ventral skin. The mass and moments of inertia of the finger segments for each participant were modeled as uniform cylinders with the density of water. Net joint torque was calculated from fingertip forces, segment lengths, segment velocities, and accelerations using a two-dimensional inverse-dynamic model of the finger (Craig, 1989). Velocity and acceleration of the keyswitch and the joints were calculated by differentiating position data using a fourth-order difference equation (Biewener & Full, 1992). Energy of the finger joints during the loading phase (E_{load}) and unloading phase (E_{unload}) was calculated by integrating joint torque with respect to joint angle.

We analyzed 1046 taps from 11 participants – on average, 24 taps per participant per condition. Limitations in the data collection program reduced the number of gathered taps. For example, the overhead necessary to store the data files resulted in intermittent periods when data were not collected, and data collection beginning or ending in the middle of a tap resulted in discarding the tap. Calculated parameters were averaged for each participant and then compared using repeated measures analysis of variance, using a statistics computer program (SAS, SAS Institute Inc., Cary, NC). Across-participant means were considered significantly different if $p < .05$.

RESULTS

Tapping on the keyswitch in the positive-tilt configuration was associated with lower joint torques and energies, whereas tapping in the negative-tilt configuration was associated with higher joint torques and energies. The proposed prototype design was associated with lower joint torques and energies with respect to the vertical and negative-tilt orientations.

The magnitude of the resultant fingertip force was not significantly different among the three keyswitch orientations tested; however, the directions as indicated by the average horizontal and vertical force components were significantly different (Table 1, Figure 4). Fingertip forces were aligned with the direction of key travel. Horizontal forces were 77% and 59% of vertical forces for the negative- and positive-tilt conditions, respectively, compared with 4% for the vertical orientation. For the cantilever design, horizontal forces were 20% of the vertical force, five times greater than those observed for the vertically oriented keyswitch. For the cantilever design, the direction of the average resultant force was between that of the vertical and positive-tilt conditions, approximately 10° to 20° degrees from vertical.

Although the tip of the keyswitch was in the same position for all four conditions, initial joint angles for all three finger joints differed significantly across the conditions (Table 1). Initial MCP

TABLE 1: Fingertip Kinematics and Average Forces Across the Four Conditions

	Keyswitch*				
	Positive Tilt	Vertical Orientation	Negative Tilt	Cantilever	*p*
Tap duration (s)	0.168 ± 0.009^{A}	0.147 ± 0.009^{B}	0.139 ± 0.009^{B}	0.143 ± 0.009^{B}	.004
Avg. vertical force, F_v (N)	0.70 ± 0.1^{A,B}	0.73 ± 0.1^{A,B}	0.62 ± 0.1^{B}	0.87 ± 0.1^{A}	0.05
Avg. horizontal force, F_h (N)	–0.41 ± 0.07^{C}	0.03 ± 0.07^{B}	0.48 ± 0.07^{A}	–0.17 ± 0.07^{B,C}	<.0001
Avg. resultant force, F_r (N)	0.89 ± 0.11	0.78 ± 0.11	0.85 ± 0.11	0.97 ± 0.11	0.3
Initial MCP angle, θ_i (°)	24.8 ± 3.8^{A,B}	18.92 ± 3.8^{C}	20.13 ± 3.8^{B,C}	26.7± 3.8^{A}	.002
Initial PIP angle, θ_i (°)	40.1 ± 4.3^{B}	48.7 ± 4.3^{A}	48.3 ± 4.3^{A}	40.9 ± 4.3^{B}	.002
Initial DIP angle, θ_i (°)	22.5 ± 4.5^{C}	32.1 ± 4.5^{A,B}	32.6 ± 4.5^{A}	25.1 ± 4.5^{B,C}	.001
Avg. relative angle of force, F_p (°)**	7.83 ± 3.0^{A}	2.37 ± 3.0^{A}	4.58 ± 3.0^{A}	–9.54 ± 3.0^{B}	.0004

*Values reported are least-squared means ± standard errors; N = 11. Positive horizontal resultant forces are away from the user. In cases where significant effects for keyswitch orientation were found, the same letter superscripts indicate groups with no statistical differences. Hence different superscripts indicate significant pair wise differences from the Tukey posthoc tests with the ranking of A>B>C.

**Average angle of the force relative to the direction of the keyswitch orientation. Positive angles are counterclockwise in Figure 1.

angles were slightly more flexed in the positive-tilt and cantilever design conditions (24.8° and 26.7°, respectively) than in the vertical orientation and negative-tilt conditions (18.92° and 20.13°, respectively). In contrast, the PIP and DIP joints were slightly more extended for the positive-tilt (40.1° and 22.5°, respectively) and cantilever design conditions (40.9° and 25.1°, respectively) than for the vertical orientation (48.7° and 32.1°, respectively) and negative-tilt conditions (48.3° and 32.6°, respectively).

Force angles at peak compression differed significantly across all four conditions, with the force vectors aligning with the various keyswitch orientations (Table 1). The orientation of the force vector at peak compression relative to the individual keyswitch orientations were 8°, 3°, and 5° more toward the user (counterclockwise in Figure 1) for the positive-tilt, vertical orientation, and negative-tilt conditions, respectively. The orientation of the force for the cantilever design was –9°, hence slightly away from the user.

Interphalangeal joint torques differed significantly across the three orientations, with the largest values for negative tilt and the smallest with positive tilt (Table 2). Finger joint torques increased from the positive-tilt to the negative-tilt conditions for all of the finger joints, but differences were not significant for the MCP joint (p = .07). Negative tilt had significantly higher values than did positive tilt for both the PIP and DIP joints ($p < .0001$). The effective moment arms of the average resultant fingertip force about all of the joints also significantly differed across the four conditions, with the effective moment being the lowest for the positive-tilt condition (Table 2).

Positive joint torques, coupled with the measured kinematics, indicated that the MCP joint exhibited energy production during the loading phase of all conditions, whereas the DIP exhibited energy absorption during the loading phase (Table 2). The PIP joint acted similar to the DIP joint for the positive-tilt and vertical orientation conditions and similar to the MCP joint for both the negative-tilt and the cantilever key conditions.

DISCUSSION

Measurement of forces and joint kinematics during tapping on different keyswitch orientations revealed two major findings: (a) Fingertip resultant

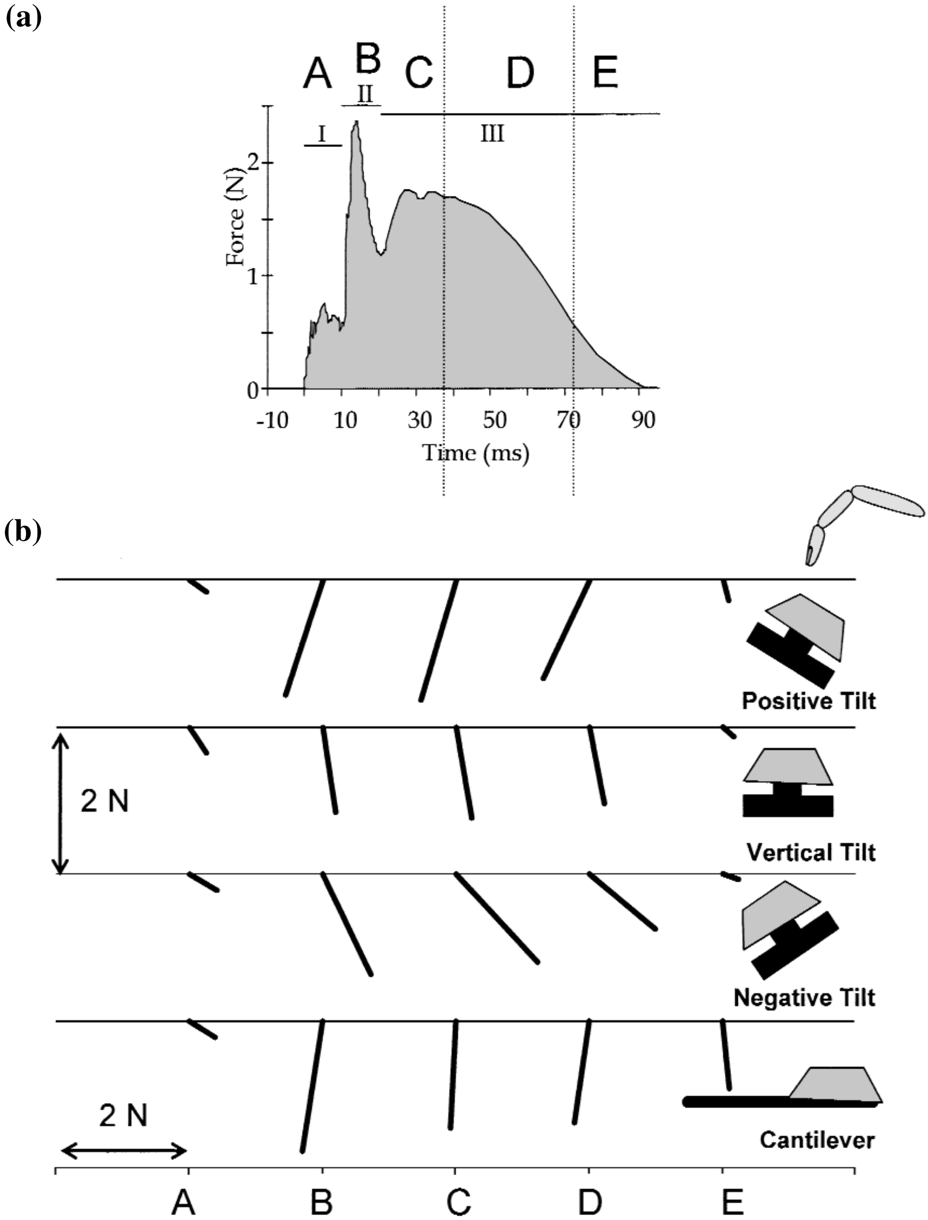

Figure 4. The typical temporal segments of the key strike's vertical fingertip force including the regions identified by Rempel et al. (1994) (a) and (b) the typical fingertip force vectors illustrating the direction of the resultant fingertip force for the four conditions tested over the time course of the keystroke (b). The resultant force vectors align with the direction of the keyswitch motion. Data here are for single key strikes from one participant, and the different phases were identified by inspection.

forces during a key strike align with the orientation of the motion of the keyswitch design, and (b) finger joint torques are reduced when the movement of the keyswitch is directed away from the user in a positive-tilt configuration, which is a result of minimizing the moment arm of the fingertip force around the finger joints. A prototype design with a curved path can also incorporate horizontal forces to reduce the net joint torques, as compared with the net joint torques associated with conventional keyswitch designs.

Several aspects of the study design place the

TABLE 2: Net Torque, Moment Arm, and Energy Exposure of Finger Joints During Tapping Across Four Conditions

		Keyswitch				
		Positive Tilt	Vertical Orientation	Negative Tilt	Cantilever	p
Average net joint torque, T_{ave} (N · mm)	MCP	29.9 ± 6.4	45.2 ± 6.4	45.7 ± 6.4	44.3 ± 6.4	.07
	PIP	8.5 ± 3.1^{C}	22.8 ± 3.1^{A,B}	31.8 ± 3.1^{A}	17.3 ± 3.1^{B}	<.0001
	DIP	2.8 ± 1.5^{C}	9.9 ± 1.5^{B}	15.7 ± 1.5^{A}	6.8 ± 1.5^{B,C}	<.0001
Average moment arm, M_{ave} (mm)	MCP	38.8 ± 4.5	51.7 ± 4.5	47.2 ± 4.5	39.8 ± 4.5	.08
	PIP	15.7 ± 2.4^{C}	28.4 ± 2.4^{A,B}	34.2 ± 2.4^{A}	20.5 ± 2.4^{B,C}	<.0001
	DIP	7.1 ± 1.6^{C}	13.1 ± 1.6^{A,B}	17.4 ± 1.6^{A}	9.5 ± 1.6^{B,C}	<.0001
Joint energy during loading, E_{load} (N · mm)	MCP	3.0 ± 1.1	5.2 ± 1.1	5.0 ± 1.1	5.3 ± 1.1	.2
	PIP	–0.7 ± 0.3^{B}	–0.5 ± 0.3^{B}	0.5 ± 0.3^{A}	0.09 ± 0.3^{A}	.003
	DIP	–1.1 ± 0.5	–1.6 ± 0.5	–1.1 ± 0.5	–1.5 ± 0.5	.7

Note. Data reported are least-squared means ± standard errors; N = 11. See note to Table 1 regarding superscripts A, B, and C.

results in a specific context. First, to examine simple movements with fine detail, we measured synchronous single-finger tapping, not the typical asynchronous finger motion associated with multiple-finger typing. Second, the forearm and proximal part of the palm were completely supported during these experiments, whereas during typing the arm and wrist dynamics play an important role (Serina, Tal, & Rempel, 1999). Third, we neglected inertial components of the key strike. However, this was a repeated measures experiment, so any effects of neglecting these components were removed. Additionally, along with Rempel, Dennerlein, Mote, and Armstrong (1994) and Harding, Brandt, and Hilberry (1989), we found the inertial forces of the finger are quite small compared with the fingertip forces during the key strike. The effects of these limitations can be explored in future studies of typing on full prototype keyboards.

The forces aligning with the movement of the keyswitch most likely constitute a fundamental component of motor control for the tapping task. Most examination of fingertip force production has been isometric (Valero-Cuevas, Zajac, & Burgar, 1998). A key strike is more complex, involving both movement and force production of the fingertip. Tapping on a keyswitch requires moving the key with enough force to overcome the resistance of the keyswitch design. Any force not aligned with the movement of the key cap does not contribute to the task and therefore may be avoided by the users. Because pressing the key requires a certain direction of fingertip movement and associated accelerations, it follows that the direction of the force would be aligned with the movement.

The fundamental factor for reducing the torque about the joints is the reduction of the effective moment arm of the resultant fingertip force about the finger joints (Table 2). As the resultant force becomes directed more toward the user, the vector aligns closer to the joints, reducing the mechanical advantage of the tip force. The force capabilities of the finger, however, also change as the force vector rotates in direction about the fingertip. On average, horizontal forces found in the vertical orientation condition were 4% of the vertical forces and were directed toward the hand. This finding is consistent with force measurements found by Jindrich et al. (2004a, 2004b). In the positive- and negative-tilt orientations, the magnitudes of the average horizontal forces were 0.41 N (59% of the vertical forces) and 0.48 N (77% of the vertical forces), respectively, but were in the opposite direction of each other. The resultant fingertip force vectors are well within the feasible force polyhedron as defined by Valero-Cuevas (2000) and, in fact, the maximum strength for the finger is pushing away slightly from the user, as would be the case for the positive-tilt configuration.

Previous studies have associated flexed finger postures with reduced joint torques, which also reduces the effective moment arm of the external force (Harding et al., 1989; Harding, Brandt, & Hilberry, 1993; Jindrich et al., 2004a). We found a similar result, in that joint torques were reduced when there was MCP flexion coupled with increased alignment of the force with the finger joints. Appropriate design of a keyboard should take into consideration the interaction between joint postures and the direction of the force vector.

Finger movements were different across the conditions and, as a result, sharing of the joint torques across the muscles may also vary. For positive tilt, while the key is pressed the MCP joint flexes, thereby producing energy, whereas the interphalangeal joints extend, absorbing energy. This pattern of energy production and absorption was also found for vertically oriented keyswitches by Jindrich et al. (2004a, 2004b). This reciprocal motion (Landsmeer & Long, 1965) involves more activity of the intrinsic muscles of the hand and may increase their exposure to force. For the negative-tilt condition, the PIP also flexes, producing energy along with the MCP joint. Pure flexion movement involves primarily extrinsic flexor force activity (Landsmeer & Long, 1965) and hence may increase their loading. Furthermore, as the force aligns more with the distal phalanx of the finger, joint stability (i.e., avoidance of the buckling of the kinematic chain) may become an issue, and muscle cocontraction may exist to increase joint stability. Electromyographic studies are needed to understand differences in muscle activity across the four test conditions.

Incorporating positive tilt into keyboard designs poses a significant challenge. The positive-slope keyswitch is contrary to most recommendations for keyboard slopes on adjustable surfaces. Positive-slope keyboards often lead to wrist extension by increasing the pressures within the carpal tunnel (Weis, Gordon, Bloom, So, & Rempel, 1995) as well as the loads on the wrist extensors (Keir & Wells, 2002; Marklin, Simoneau, & Monroe, 1999). Therefore, keyboard layouts that promote neutral and slightly flexed wrists are often recommended for users. These neutral and flexed postures may be leading to higher torques across the finger joints and also across the wrist joints during typing. To incorporate a positive-slope keyswitch movement into a keyboard requires a combination of promoting less extended wrist postures while incorporating keyswitch movements that allow for horizontal forces to minimize finger joint torques. The cantilever design could minimize this problem because its initial movement is vertical and does not require a positively sloped keyboard. Other designs can be developed to solve this dilemma.

The cantilever keyswitch used a mechanical design similar to that of Radwin and Jeng (1997) to achieve a different purpose: the addition of horizontal forces to the keyswitch force-displacement relationship. The cantilevered keyswitch was designed to integrate well into current keyboard layouts and to maintain a similar task requirement of near-vertical motion up to the point of switch activation, followed by the introduction of horizontal forces to reduce joint torques during overtravel. Previous studies have shown that a majority of force impulse and joint energy production occurs after keyswitch activation and, indeed, after the keyswitch has reached the end of key travel (Rempel et al., 1994). The cantilever keyswitch design not only introduces horizontal forces to reduce net joint torques and stiffness but also allows for a longer key travel and a less abrupt end to key travel (Radwin & Jeng, 1997). The cantilever design resulted in joint torques and effective moment arm values between those of the vertical and positive-tilt conditions. The alternative design produced a force vector that was oriented slightly away from the user relative to the keyswitch surface (Table 1). Future studies should address whether reduced joint torques result in reduced muscle and tissue loading during tapping.

In conclusion, our study of keyswitch orientation showed that changing the direction of key travel relative to finger can affect net joint torque during tapping. Directing key travel away from the user resulted in joint torques smaller than those found when the travel was directed toward the user, despite the finding that resultant force magnitudes were unchanged. Overall, the results show that geometric orientation of the keyswitch relative to the keyboard, finger, and hand should also be incorporated into keyswitch design specifications.

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