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Computer keyswitch force–displacement characteristics affect muscle activity patterns during index finger tapping

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Abstract

This study examined the effect of computer keyboard keyswitch design on muscle activity patterns during finger tapping. In a repeated-measures laboratory experiment, six participants tapped with their index fingers on five isolated keyswitch designs with varying force–displacement characteristics that provided pairwise comparisons for the design factors of (1) activation force (0.31 N vs. 0.59 N; 0.55 N vs. 0.93 N), (2) key travel (2.5 mm vs. 3.5 mm), and (3) shape of the force–displacement curve as realized through buckling-spring vs. rubber-dome switch designs. A load cell underneath the keyswitch measured vertical fingertip forces, and intramuscular fine wire EMG electrodes measured muscle activity patterns of two intrinsic (first lumbricalis, first dorsal interossei) and three extrinsic (flexor digitorum superficialis, flexor digitorum profundus, and extensor digitorum communis) index finger muscles. The amplitude of muscle activity for the first dorsal interossei increased 25.9% with larger activation forces, but not for the extrinsic muscles. The amplitude of muscle activity for the first lumbricalis and the duration of muscle activities for the first dorsal interossei and both extrinsic flexor muscles decreased up to 40.4% with longer key travel. The amplitude of muscle activity in the first dorsal interossei increased 36.6% and the duration of muscle activity for all muscles, except flexor digitorum profundus, decreased up to 49.1% with the buckling-spring design relative to the rubber-dome design. These findings suggest that simply changing the force–displacement characteristics of a keyswitch changes the dynamic loading of the muscles, especially in the intrinsic muscles, during keyboard work.

Keywords: Finger; Keyswitch; Force–displacement characteristics; Design; Keyboard; Computer; Electromyography; Force; Motor control

1. Introduction

The computer keyboard is a standard input device for personal computing. However, computer keyboard use has been associated with upper extremity musculoskeletal disorders (Gerr et al., 2002) and pain specific to the hand and forearm (Kryger et al., 2003; Lassen et al., 2004). While the specific underlying injury mechanisms are still unknown, keyboard keyswitch force–displacement characteristics seem to play a fundamental role in the development of upper extremity musculoskeletal symptoms and disorders (Marcus et al., 2002) and reduction in hand pain (Rempel et al., 1999).

There are three important design factors of keyswitch force–displacement characteristics: (1) activation force, (2) key travel, and (3) shape of the force–displacement curve (Fig. 1). Previous experimental studies have found that typing on keyboards with higher activation forces (or make force) were associated with larger typing forces (Armstrong et al., 1994; Gerard et al., 1999; Rempel et al., 1997), hand and forearm muscle activities (Gerard et al., 1999; Rempel et al., 1997), muscle fatigue (Gerard et al., 1996; Radwin and Ruffalo, 1999), and a greater risk of hand/arm musculoskeletal symptoms and disorders for keyboards with key activation forces greater than 0.47 N (Marcus et al.,

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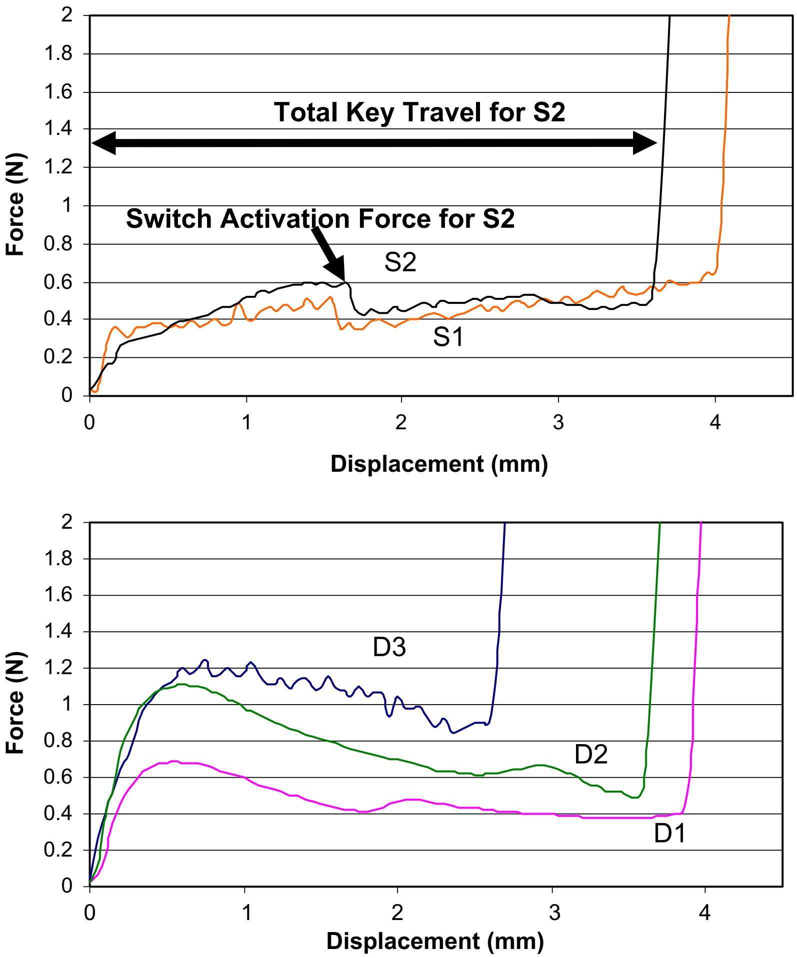

Fig. 1. Static force–displacement characteristics for the five keyswitches (S1, S2, D1, D2, and D3). The top figure represents keyswitches S1 and S2, which both utilize a buckling-spring switch design, whereas the bottom figure represents keyswitches D1, D2, and D3, which all utilize a rubber-dome switch design. The switch activation force and key travel design factors are indicated in the top figure.

2002). Key travel (or displacement) also affects applied fingertip force in that longer key travel designs are associated with smaller applied key forces (Radwin and Jeng, 1997; Radwin and Ruffalo, 1999).

The shape of the force–displacement curve, which is associated with the mechanical design inside the keyswitch, is also an important factor (Gerard et al., 1999; Rempel et al., 1999). Rempel et al. (1999) compared two similar keyboards each utilizing a different keyswitch design that primarily differed in the shape of the force–displacement curve, specifically with (1) the travel distance to the activation point and (2) the stiffness at the end of the key travel. The keyboard utilizing keyswitches with the longer key travel to the activation force point and a gradual increase in stiffness at the end of key travel were associated with a decrease in hand pain symptoms (Rempel et al., 1999). The shape of the force–displacement curve (e.g., buckling-spring versus rubber-dome designs) also affects typing force and muscle activities during keyboard work (Gerard et al., 1999). Gerard et al. (1999) found that typing on buckling-spring keyboards resulted in smaller typing forces and decreased finger muscle activities of the extrinsic finger flexors and extensors, compared to rubber-dome keyboards of similar key travel.

Most of these studies, however, have been limited to general amplitude parameters of surface electromyography (EMG) on extrinsic finger muscles while typing on full keyboards, and have not identified intrinsic muscle activity or explained their specific patterns of muscle activity. Two previous experimental studies have examined the kinematics and muscle activity patterns of the index finger during tapping on isolated keyswitches, however, were either limited to measuring fingertip force and kinematics without directly measuring muscle activity (Jindrich et al., 2004) or measuring muscle activity patterns with only one keyswitch design (Kuo et al., 2006). Hence, the role of the intrinsic and extrinsic hand muscle activation patterns underlying the relationship between muscle force and specific keyswitch design factors still remain unclear.

Therefore, the purpose of this study was to compare the applied fingertip forces and intramuscular muscle activity patterns of two intrinsic and three extrinsic muscles that articulate the index finger during tapping on five different isolated keyboard keyswitch designs with varying

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force–displacement characteristics. Through pairwise comparisons, this study tested the hypothesis that differences in the keyswitch design factors of (1) activation force, (2) key travel, and (3) shape of force–displacement curve (i.e., buckling-spring vs. rubber-dome) would affect fingertip force and muscle activity amplitude and timing.

2. Methods and materials

2.1. Subjects

Six participants (3 female, 3 male) were recruited for the experimental study. The mean age of the participants was 25.8 ± 2.5 years. All participants were experienced computer users with mean self-estimated computer usage times of 2.7 ± 1.9 h per weekday, and 5.3 ± 3.4 h per weekend. All participants reported no history of upper extremity musculoskeletal disorders. Informed consent was gained from all participants, and all experimental procedures were approved by the Harvard School of Public Health Human Subjects Committee.

2.2. Experimental design

In a repeated-measures laboratory experiment, fingertip force and intramuscular muscle activity were simultaneously measured as participants tapped with their right index finger on five different isolated keyswitches. Extracted from computer keyboards, the keyswitches were specifically chosen to provide pairwise comparisons between the three keyswitch design factors of (1) activation force, (2) key travel, and (3) shape of the force–displacement curve (Tables 1 and 2). Keyswitches S1 and S2 provided a means for comparing the effect of activation force on fingertip force and muscle activity for buckling-spring keyswitch designs. Keyswitches D1 and D2 provided a means for comparing activation forces of rubber-dome keyswitches. Keyswitches D2 and D3 provided a means for comparing key travel given their similar activation forces. Keyswitches S2 and D1 provided a means for comparing the shape of the force–displacement curve (buckling-spring vs. rubber-dome) since both designs have similar activation forces and key travel.

Table 1
Keyswitch characteristics for all keyswitches used in the study, and their pairing for the specific pairwise comparisons for the different design factors below

Design factor	Keyswitch				
	S1	D1	S2	D2	D3
Activation force (N)	0.31	0.55	0.59	0.93	0.99
Key travel (mm)	4.0	3.8	3.5	3.5	2.5
Shape of the force–displacement curve	Spring	Dome	Spring	Dome	Dome
Pairwise comparisons					
Activation force (spring)	X		X		
Activation force (dome)		X		X	
Key travel				X	X
Shape of the force–displacement curve		X	X		

Keyswitches are presented in order of increasing activation forces. Keyswitch nomenclature was designated as a combination of design (i.e., S for spring; D for dome) and increasing activation forces (i.e., S1 < S2; D1 < D2 < D3 in activation force). The X's in each row denote the keyswitches used for the pairwise comparisons of each design factor.

2.3. Experimental setup

Participants were instructed to tap at a rate of 0.8 taps per second paced by a metronome for 10 s. To ensure that participants minimized contact time, participants practiced tapping while monitored by an oscilloscope until their contact times were below 150 ms, similar to the duration of keystrokes observed during touch-typing (Rempel et al., 1994). The index fingers of the participants were positioned in a posture that simulated a typing posture on the middle (home) row of a keyboard, guided by a keypad placed next to the keyswitch (Kuo et al., 2006). The remaining fingers and the wrist were rested on a fixed platform to control the posture and influence of the other fingers and wrist (Kuo et al., 2006).

2.4. Fingertip force

Vertical fingertip forces were measured using a strain-gauge force transducer mounted underneath the keyswitch. The force transducer was calibrated as described by Jindrich et al. (2004) and Kuo et al. (2006). Data from the force transducer were acquired at 10 kHz using a computer data-acquisition hardware and program (SCXI 1121 Isolated Sensor Input Module and LabVIEW, National Instruments, Austin, TX). To minimize noise amplification during data analysis, the force signals were digitally filtered (filtfilt function in Matlab, Mathworks, Natick, MA) based on a fourth-order Butterworth low-pass filter (20 Hz) with zero-phase shift.

2.5. Muscle activity

Muscle activity was measured using five pairs of bipolar intramuscular (finewire) EMG electrodes (50 μm stainless steel wires with nylon insulation) on two intrinsic and three extrinsic hand muscles that articulate the index finger. The EMG electrodes were inserted into the intrinsic hand muscles of the first lumbricalis (LUM) and first dorsal interosseus (FDI), and the extrinsic muscles of the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and extensor digitorum communis (EDC) muscles using 29-gauge needles (Burgar et al., 1997). The signals from the electrodes were amplified though a custom-made EMG system and then recorded at 10 kHz simultaneously with force (Kuo et al., 2006). The recorded EMG signals were digitally band-pass filtered at 30–700 Hz. Background 60 Hz and 60 Hz harmonic noise in the EMG data were removed using a fourth-order Butterworth notch filter with zero-phase shift (filtfilt function in Matlab, Mathworks, Natick, MA). The EMG data were rectified and normalized to the highest activity level over the entire experimental session for each muscle (Kuo et al., 2006).

From the force data, individual taps were identified, defining the reference times for fingertip force contact periods and bursts of EMG activity for each muscle (Kuo et al., 2006). A contact period was defined when the vertical force exceeded 0.02 N; the beginning of contact period was defined as the reference (or zero) time, with following time as positive and the time preceding contact as negative (Kuo et al., 2006). For each burst of EMG activity, the onset and offset were identified, and the duration was

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Table 2
ANOVA model and post-hoc pairwise comparison *p*-values for the fingertip force and muscle activity parameters

			ANOVA	Pairwise comparisons (design factor)			
				S1, S2 (activation force (spring))	D1, D2 (activation force (dome))	D2, D3 (key travel)	S2, D1 (shape of F–D Curve)
Fingertip force	Tap duration		**0.0104**	0.1143	0.9978	0.9850	**0.0092**
	Average vertical force		**<0.0001**	0.9376	0.7155	**<0.0001**	0.8147
	Peak impact force		0.0919				
Muscle activity amplitude	LUM		**0.0025**	0.0525	0.9768	**0.0428**	0.1042
	FDI		**<0.0001**	**0.0067**	0.9845	0.0824	**<0.0001**
	FDS		0.1331				
	FDP		0.7727				
	EDC		**<0.0001**	0.4469	0.1544	0.1432	0.1845
Muscle activity timing	LUM	Onset	**<0.0001**	0.4616	**0.0046**	**0.0018**	**0.0058**
		Offset	**0.0004**	0.9667	0.3266	0.9622	0.2498
		Duration	**<0.0001**	0.9998	1.0000	0.8152	**0.0113**
	FDI	Onset	**<0.0001**	0.1321	0.7422	**<0.0001**	0.9222
		Offset	**<0.0001**	**0.0153**	**0.0343**	0.6422	**0.0055**
		Duration	**<0.0001**	0.5373	0.3493	**<0.0001**	**0.0074**
	FDS	Onset	**<0.0001**	0.6320	0.8142	**0.0003**	0.1527
		Offset	**<0.0001**	0.6446	0.9824	**0.0030**	**<0.0001**
		Duration	**<0.0001**	0.4727	0.9257	**<0.0001**	**<0.0001**
	FDP	Onset	**0.012**	0.9903	0.8208	0.9806	0.8827
		Offset	**<0.0001**	0.9675	0.1361	**<0.0001**	0.9990
		Duration	**<0.0001**	0.9169	0.0522	**<0.0001**	0.9990
	EDC	Onset	0.6696				
		Offset	**<0.0001**	**<0.0001**	**0.0081**	**0.0171**	**0.0074**
		Duration	**<0.0001**	**<0.0001**	**0.0150**	0.0550	**0.0112**
Integrated EMG	LUM		**<0.0001**	0.2787	1.0000	0.1868	0.6988
	FDI		**<0.0001**	1.0000	0.8319	**<0.0001**	0.9670
	FDS		**<0.0001**	0.9938	0.9996	0.6180	**0.0010**
	FDP		**<0.0001**	0.9929	0.4139	**0.0085**	0.9978
	EDC		**0.0001**	0.9476	0.0802	0.9735	0.9836

The five muscles are first lumbricalis (LUM), first dorsal interossei (FDI), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and extensor digitorum communis (EDC). Pairwise comparisons across design factors of activation force (spring, dome), key travel, and shape of the force–displacement curve are provided when ANOVA values are significant; bolded *p*-values denote statistical significance at $p < 0.05$.

calculated. A threshold of 0.2 for normalized muscle activity was chosen to represent the onset and offset of EMG activity such that onset was defined when the rectified EMG value exceeded the threshold and offset defined when the signal fell below the threshold; onset and offset of muscle activity were verified iteratively for each burst (Kuo et al., 2006). Amplitude of muscle activity was calculated by a root-mean-square (RMS) calculated over the duration of each burst of EMG activity for each tap. Integrated EMG was calculated by the taking the product of the amplitude and duration of muscle activity for each burst of EMG activity.

2.6. Data analysis

Pairwise comparisons of the fingertip force and EMG amplitude and timing (onset, offset, and duration) parameters across keyswitch design factors were obtained from the post-hoc multiple comparison results of repeated-measures ANOVA analyses (Proc Mixed) in SAS 9.1 (SAS Institute Inc., Cary, NC, USA). The dependent variables of the ANOVA models were tap duration, vertical fingertip force (average vertical force, peak impact force), and the EMG muscle activity measures (amplitude, duration, onset, offset, integrated EMG). The independent variable (i.e., main effects used in the models) was keyswitch (keyswitches S1, D1, S2, D2, D3). Subject was included in the models as a random effect. Each dependent variable was tested in a separate statistical model. Least square means were computed in the mixed models, and multiple comparison adjustments for the *p*-values and confidence limits for the differences of least squares means were completed using the Tukey–Kramer adjustment. Significance was noted for probability of a false positive being less than 5% (i.e., $\alpha = 0.05$).

3. Results

There were changes in the fingertip force parameters (Fig. 2) for tap duration and average vertical force across keyswitch design ($p < 0.0104$; Table 2). Increasing activation force for buckling-spring designs had a non-significant tendency to increase average vertical force by 3.6% ($p = 0.1143$). Increasing key travel decreased average vertical force by 30.4% ($p < 0.0001$). The buckling-spring design

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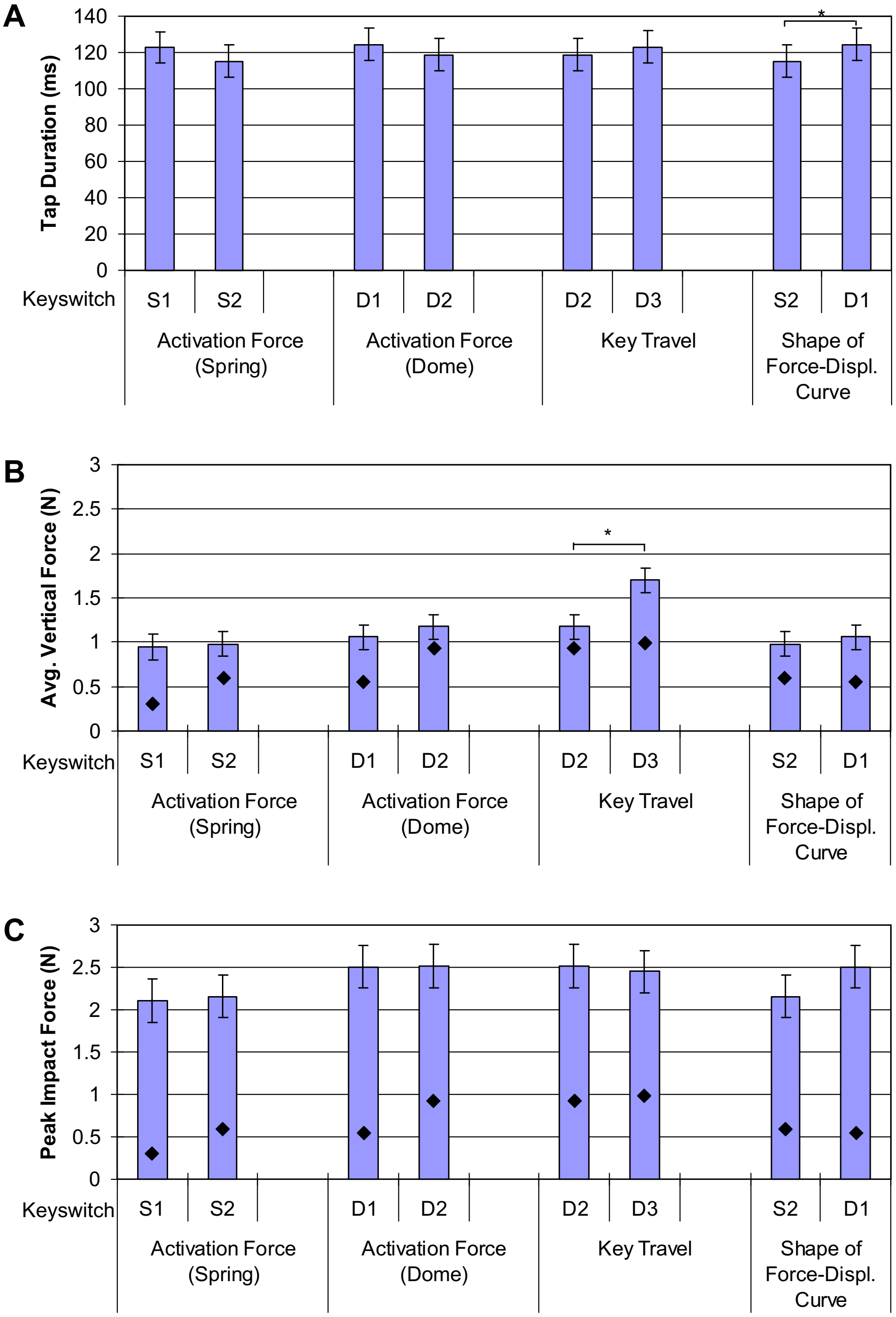

Fig. 2. The mean (and standard error) values of the tap duration (A), average applied vertical fingertip force (B), and peak applied impact force (C) across the pairwise comparisons of the keyswitch design factors (activation force (spring), activation force (dome), key travel, and shape of the force–displacement curve (spring vs. dome)). S2, D1, and D2 keyswitches are repeated since those keyswitches are being compared in multiple design factors. Keyswitch activation forces are indicated in (B) and (C) by the diamonds. The '*' denotes statistical significance for the pairwise comparison at $p < 0.05$; p-values are provided in Table 2.

had significantly shorter (7.3%) tap durations relative to rubber-dome design ($p = 0.0092$).

The amplitude of the intrinsic muscle activity (i.e., EMG bursts) varied across keyswitch design (Fig. 3A and B; $p < 0.0025$), whereas the amplitude of extrinsic flexor muscle activity did not significantly vary across keyswitch design (Fig. 3C and D; $p > 0.1331$). Increasing activation force for the buckling-spring design increased the amplitude of muscle activity by 25.9% for the first dorsal interossei ($p < 0.0001$) and to a lesser extent (4.4%) for the first lumbricalis ($p = 0.053$). Longer key travel decreased the amplitude of the first lumbricalis by 5.9% ($p = 0.0428$); a non-significant tendency of decreased amplitude (17.7%) with longer key travel was also found for the first dorsal

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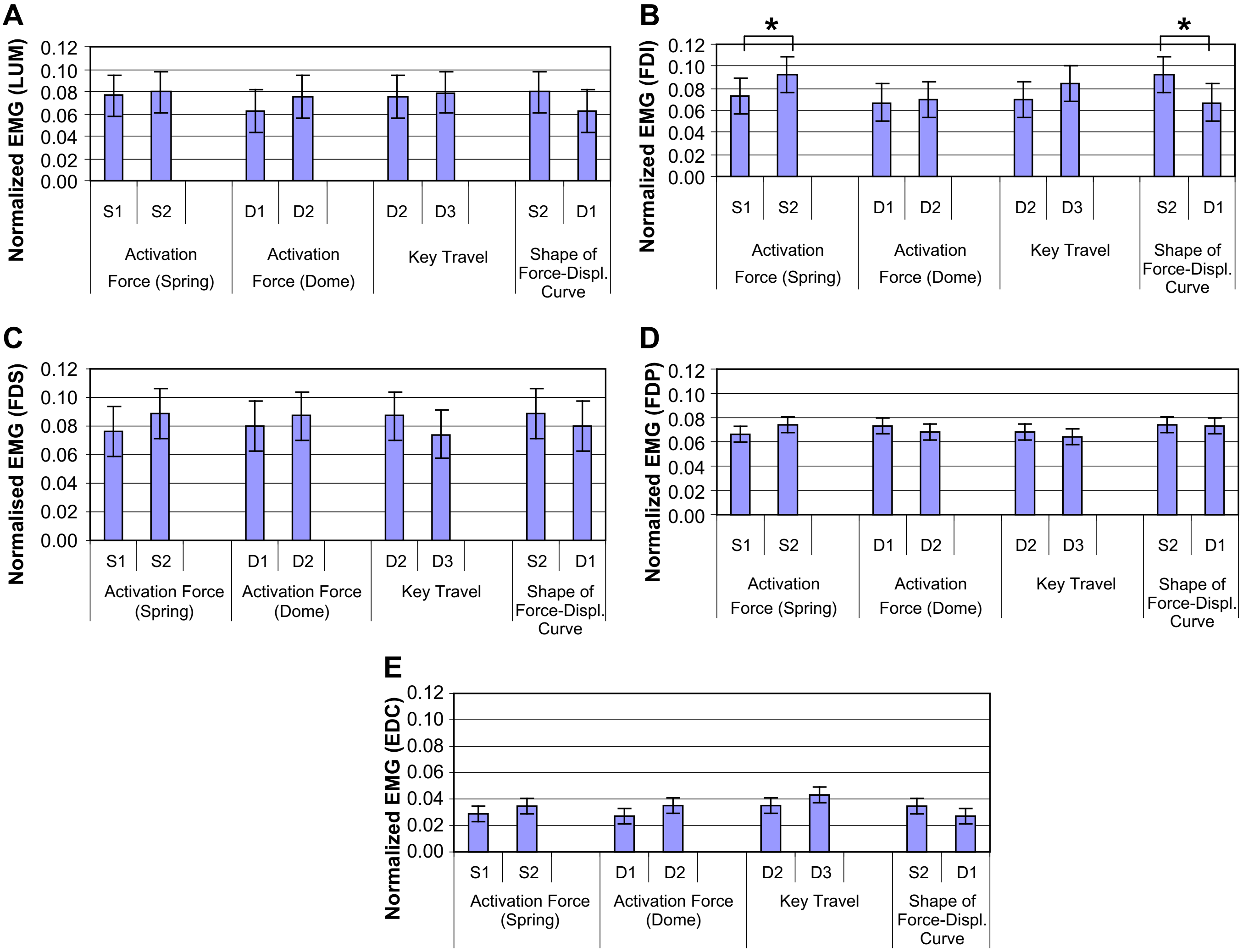

Fig. 3. Mean (and standard error) EMG amplitude of the five muscles (first lumbricalis (LUM) (A), first dorsal interossei (FDI) (B), flexor digitorum superficialis (FDS) (C), flexor digitorum profundus (FDP) (D), and extensor digitorum communis (EDC) (E)) across the pairwise comparisons of keyswitch design factors (activation force (spring), activation force (dome), key travel, and shape of the force–displacement curve (spring vs. dome)). S2, D1, and D2 keyswitches are repeated since those keyswitches are being compared in multiple design factors. The '*' denotes statistical significance for the pairwise comparison at $p < 0.05$; p-values are provided in Table 2.

interossei ($p = 0.0824$). The buckling-spring design resulted in 36.6% of increased muscle activity amplitude in the first dorsal interossei ($p < 0.0001$) relative to the rubber-dome design; a non-significant tendency of an increase in amplitude (26.5%) for buckling-spring designs relative to rubber-dome design was found for the first lumbricalis ($p = 0.1042$).

The timing (onset, offset, and duration) of the intrinsic muscle activities (Fig. 4A and B) differed across keyswitch design ($p < 0.0004$). Increased activation force for the buckling-spring design resulted in a 29.9 ms earlier offset of muscle activity for the first dorsal interossei ($p = 0.0153$). Increased activation force for rubber-dome designs was found with a 31.7 ms later onset of muscle activity for the first lumbricalis ($p = 0.0046$) and a 25.4 ms later offset of muscle activity for the first dorsal interossei ($p = 0.0343$). Longer key travel resulted in up to 38.6 ms later onset of both intrinsic muscle activities ($p < 0.0018$), leading to a 27.3% decreased duration of muscle activity for the first dorsal interossei ($p < 0.0001$). The buckling-spring design resulted in up to 27.8% shorter duration of muscle activities for both intrinsic muscles relative to the rubber-dome design ($p < 0.0113$), due to a 31.6 ms later onset of muscle activity for the first lumbricalis and a 30.9 ms earlier offset of muscle activity for the first dorsal interossei ($p < 0.0058$).

The timing of the extrinsic flexor muscles varied less across the three design factors than the timing of the intrinsic muscles (Fig. 4C–E). Changing the activation force did not affect the timing of the extrinsic flexors of the flexor digitorum superficialis and flexor digitorum profundus, except for a non-significant tendency ($p = 0.0522$) of longer durations with higher activation forces in rubber-dome designs for the flexor digitorum profundus. However,

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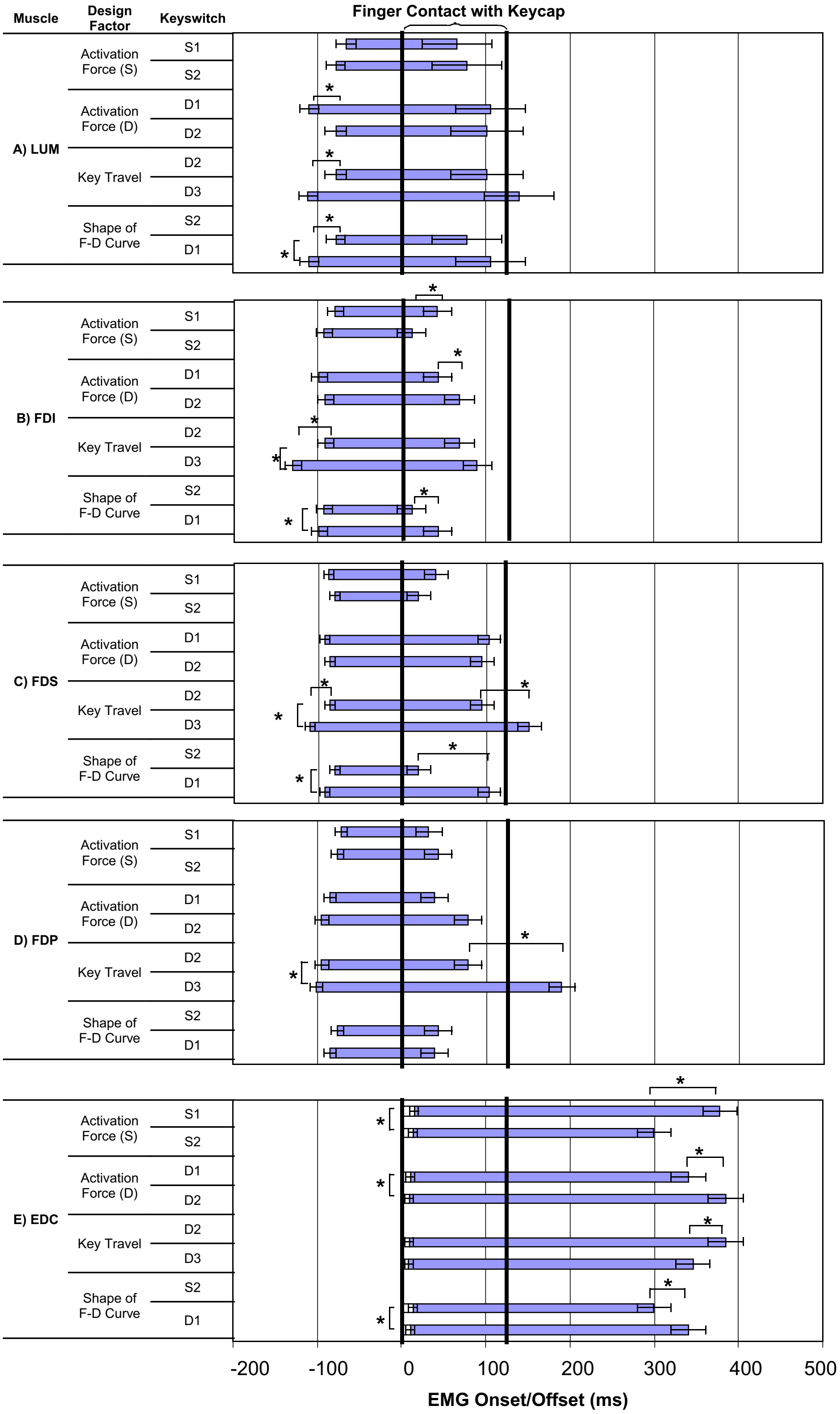

Fig. 4. Mean (and standard error) EMG timing (onset and offset) of the five muscles (first lumbricalis (LUM) (A), first dorsal interossei (FDI) (B), flexor digitorum superficialis (FDS) (C), flexor digitorum profundus (FDP) (D), and extensor digitorum communis (EDC) (E)) across the pairwise comparisons of keyswitch design factors (activation force (spring), activation force (dome), key travel, and shape of the force–displacement curve (spring vs. dome)). S2, D1, and D2 keyswitches are repeated since those keyswitches are being compared in multiple design factors. Zero time indicates initial fingertip contact with keycap; time when fingertip is released off keycap is indicated at 120.9 ms, averaged across all taps. Significance for EMG onset and offset are indicated by the horizontal bars. EMG duration is the time between the EMG onset and offset; significance for EMG duration is indicated by the vertical bars. The ‘*’ denotes statistical significance for the pairwise comparison at $p < 0.05$; p-values are provided in Table 2.

similar to the intrinsic muscles, longer key travel decreased the duration of muscle activity (up to 40.4%) for both of the extrinsic flexors ($p < 0.0001$) mostly due to earlier offsets of muscle activity (up to 111.4 ms) in both extrinsic flexors ($p < 0.0030$) and a 23.2 ms later onset of muscle activity for the flexor digitorum superficialis ($p = 0.0003$). Buckling-spring design resulted in a 49.1% shorter duration of muscle activity relative to the rubber-dome design for the flexor digitorum superficialis due to a 83.8 ms earlier offset of muscle activity ($p < 0.0001$). Differences in muscle activity timing for the extensor digitorum communis across all three design factors were found in the offset of muscle activity ($p < 0.0171$), and hence the duration of muscle activity for both buckling-spring and rubber-dome activation force designs and shape of the force–displacement curve design ($p < 0.0150$).

4. Discussion

This study examined how the design of the keyboard keyswitch affected index fingertip forces and finger muscle activity patterns. Through pairwise comparisons between keyswitch designs, this study specifically examined the effect of each design factor (i.e., activation force, key travel, and shape of the force–displacement curve) on fingertip force and muscle activity. The findings revealed that simply changing the force–displacement characteristics of a keyswitch changes the dynamic loading of the muscles, especially in the intrinsic hand muscles, during keyboard work.

The intrinsic muscles were more responsive to the force–displacement changes than the extrinsic muscles. In particular, the muscle activity pattern of the first dorsal interossei varied across all three design factors whereas the flexor digitorum profundus varied the least. This may be attributed to the fact that the small changes in keyswitch design factors were large enough to affect the smaller intrinsic hand muscles, which are considered to control the fine motor movements and force directions at the fingertip (Milner and Dhaliwal, 2002). Larger differences in the design factors may result in more significant changes in the motor control patterns of the flexor digitorum profundus, since the flexor digitorum profundus has the largest physiological cross-sectional area and average muscle volume (Holzbaur et al., 2007) among the measured muscles in this study.

Previous studies on keyswitch (Jindrich et al., 2004) and keyboard (Armstrong et al., 1994; Gerard et al., 1999; Rempel et al., 1997) design have shown that increasing activation force increased fingertip force and amplitude of muscle activities. Only the amplitude of intrinsic muscle activity for buckling-spring design increased with increasing activation force. The lack of significance for the other muscles and for the rubber-dome design could be due to either the relatively small increases between the keyswitch designs of S1 and S2, and D1 and D2, with differences of 0.28 N and 0.38 N, respectively, or a lack of statistical power due to the limited sample size. Nevertheless, this finding supports the hypothesis by Jindrich et al. (2004) in that tapping on keyswitches with lower activation forces requires lower muscle forces in the muscles that articulate the index finger.

The key travel findings in this study corresponded well with those of Radwin and Jeng (1997) and Radwin and Ruffalo (1999). Longer key travel was associated with decreased average vertical force. The decrease in fingertip force could be partially attributed to the smaller amplitude of intrinsic muscle activity in the first lumbricalis and shorter durations of both intrinsic and extrinsic flexor muscle activities in the first dorsal interossei, flexor digitorum superficialis, and flexor digitorum profundus. Later offsets of muscle activity were found with shorter key travel for the extrinsic flexors of the flexor digitorum superficialis and flexor digitorum profundus, suggesting that users may have reached the end of key travel and yet continued to produce muscle force. Since longer key travel was associated with lower average fingertip forces and smaller amplitudes and durations of muscle activity as described above, these findings support the idea that a longer overtravel (the distance between activation force and end of key travel) may reduce force exertions and therefore muscle overexertion during keyboarding work (Radwin and Jeng, 1997).

The shape of the force–displacement curve affected the fingertip forces and muscle activities through varying patterns of force and muscle activity relationships consistent with findings from Gerard et al. (1996) and Rempel et al. (1999). Buckling-spring designs were found to have significantly shorter tap durations, higher amplitude of first dorsal interossei muscle activity, and shorter durations of muscle activity across four of the five muscles relative to the rubber-dome design. This suggests that participants tapped on the buckling-spring design with shorter tap durations, yet maintained similar fingertip forces by utilizing a motor control strategy of higher amplitude, yet shorter duration, of muscle activity in the index finger muscles relative to the rubber-dome design. Since the shape of the force–displacement curves differ primarily in the travel distance to the activation point and the stiffness at the end of key travel (Rempel et al., 1999), it is unclear if one or both differences play a different or synergistic role in the changes in the motor control strategies between the designs. Nevertheless, the internal mechanical switch design located within the keyswitch appears to play a role in the varying motor control patterns during tapping across different keyswitch designs.

Although differences in intrinsic and extrinsic flexor muscle activity patterns were found across each of the design factors, the overall general coordination of fingertip mechanics and temporal muscle activity patterns were consistent with previous studies on finger tapping on isolated keyswitches (Dennerlein et al., 1998; Kuo et al., 2006). Coupled muscle activities between the intrinsic (first lumbricalis, first dorsal interossei) and extrinsic finger flexors (flexor digitorum superficialis, flexor digitorum profundus) across all keyswitch designs were found during the downswing period of the finger prior to finger contact. The bursts of intrinsic and extrinsic flexor muscle activity prior to keyswitch contact were always followed by a burst of extrinsic extensor muscle activity prior to the release of the finger off of the keyswitch, suggesting that the role of the extrinsic finger extensor (extensor digitorum communis) was to lift the finger off the keyswitch and help prepare the finger for the next tap.

The differences found in both the amplitude and timing of muscle activity measures could not be fully captured with integrated EMG (Table 3). Although this study found that increasing key travel resulted in smaller integrated EMG muscle activity patterns of the first dorsal interossei and flexor digitorum profundus, and smaller integrated EMG for the flexor digitorum superficialis with buckling-spring design relative to the rubber-dome design, the other differences in the muscle activity patterns across design factors, especially in the intrinsic muscles, were not found with the integrated EMG measure. This indicates that examining the muscle activity patterns in terms of amplitude and timing provide a more detailed representation, and thus improved interpretation, of the muscle activity patterns during a keystroke, especially given the small changes across the three keyswitch design factors.

The mechanisms investigated in this study were intensity and duration of muscle loading during a keystroke. Although small changes were found in muscle loading across different design factors, these changes may be larger and be more clinically meaningful with greater number of repetitions and longer exposures to each keyswitch design. Furthermore, the combination of changes in force and repetition as measured through the changes in duration may magnify the small changes in muscle loading (Viikari-Juntura and Silverstein, 1999), which might explain some of the clinical findings in previous field studies, such as reductions in hand pain with different force–displacement keyboards (Rempel et al., 1999).

There exist many design challenges for keyboard design that incorporate functional and aesthetic appeal with fundamental ergonomic and biomechanical principles. For example, the increasing popularity of slim and low-profile desktop keyboards and notebook designs make the design of keyboards that incorporate keyswitches with longer key travel more difficult. Current standard guidelines for the force–displacement characteristics of keyboard keyswitch design limit the range of keyswitch activation forces from 0.25 N to 1.5 N, and keyswitch displacement (or key travel) from 1.5 mm to 6 mm (Human Factors and Ergonomics Society (BSR/HFES100), 2002; International Organization of Standards (ISO9241-4), 1998). However, this study found that even small changes to the force–displacement characteristics are enough to change the finger muscle activity patterns, particularly in the intrinsic muscles. The reduction in muscle loading for both the intrinsic and extrinsic muscles with smaller applied keyswitch forces may reduce the risk of muscle and tendon injury (Armstrong et al., 1994) and hand/arm musculoskeletal symptoms and disorders (Marcus et al., 2002); however, further epidemiological and experimental studies would be needed with larger differences in activation forces. In addition, given the various keyboard designs available, from alternative (i.e., split-keyboard design) to notebook (i.e., laptop) keyboards, further research is warranted in assessing the motor control strategies, as well as postural effects, in reducing index finger muscle activity and fingertip forces during keyboard work on these designs.

There were limitations in the study design that place the findings in a specific context. First, the limited sample size may have reduced the ability to detect significant differences in muscle activity and fingertip force across the different keyswitch designs. Second, although this study attempted to select keyswitches that would provide direct pairwise comparisons of the design factors, there was expected measurement error due to the values not being identical (e.g., the activation forces between keyswitches D1 and S2 were very close but not exactly the same). Third, the EMG data was normalized to the highest EMG signal across all conditions, which allowed EMG comparisons across participants, but may have limited generalizability to related research studies. Although normalizing to a

Table 3
Mean (and standard error) integrated EMG in units of normalized-EMG ms of the five muscles (first lumbricalis (LUM), first dorsal interossei (FDI), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and extensor digitorum communis (EDC)) across the pairwise comparisons of keyswitch design factors (activation force (spring), activation force (dome), key travel, and shape of the force–displacement curve (spring vs. dome))

Keyswitch/muscle	Activation force (spring)		Activation force (dome)		Key travel		Shape of force–displacement curve	
	S1	S2	D1	D2	D2	D3	S2	D1
LUM	8.51 (4.12)	10.58 (4.00)	12.79 (4.03)	14.83 (4.30)	14.83 (4.30)	19.70 (4.02)	10.58 (4.00)	12.79 (4.03)
FDI	9.43 (2.97)	9.48 (2.97)	10.03 (2.98)	10.48 (3.01)	**10.48 (3.01)**	**19.68 (2.97)**	9.48 (2.97)	10.03 (2.98)
FDS	9.50 (3.78)	8.71 (3.78)	16.30 (3.78)	16.35 (3.80)	16.35 (3.80)	19.31 (3.78)	**8.71 (3.78)**	**16.30 (3.78)**
FDP	7.62 (1.49)	8.34 (1.49)	8.88 (1.49)	11.80 (1.52)	**11.80 (1.52)**	**17.63 (1.49)**	8.34 (1.49)	8.88 (1.49)
EDC	9.71 (1.57)	8.68 (1.56)	9.68 (1.59)	13.58 (1.64)	13.58 (1.64)	13.82 (1.57)	8.68 (1.56)	9.68 (1.59)

S2, D1, and D2 keyswitches are repeated since those keyswitches are being compared in multiple design factors. Bolded values denote statistical significance of the post-hoc pairwise comparisons at $p < 0.05$; p-values are provided in Table 2.

maximum voluntary contraction would make the results more comparable across studies, it was determined that the discomfort associated with the intramuscular EMG prevented the participants from exerting their true maximum voluntary contractions.

Another limitation is that this study examined single finger tapping, and not typing. However, the finger and wrist postures were controlled, and it was ensured that the tap durations and fingertip velocities were similar to typing (Kuo et al., 2006). Furthermore, the applied fingertip forces in this study were within the range of previous keyboarding studies. The ratio of average (and peak) fingertip force to keyswitch activation force in this study ranged between 1.3 and 3.1 (2.5 and 6.8), which is within the range of the ratios (between 1 and 3.1 (2.5 and 9.3)) of previous keyboarding studies that examined the effect of keyboard design on typing force (Armstrong et al., 1994; Gerard et al., 1996; Gerard et al., 1999; Martin et al., 1996; Rempel et al., 1997).

Lastly, this study tested the keyswitch activations in a single (home row) finger posture on two common keyswitch designs. Keyboard work involves the coordinated effort of all finger digits in multiple flexed and extended finger postures, as well as in various degrees of abduction and adduction, associated with activating the individual keyswitches on and between the various rows and columns of the keyboard. Therefore, further experimental research with finger postures emulating typing on the top (QWERTY) and bottom rows, in horizontal movements in abduction/adduction, and on other switch designs (i.e., scissor-switch, mechanical-switch) are warranted.

In conclusion, the findings of this study showed that subtle changes to the keyswitch design factors of activation force, key travel, and shape of the force–displacement curve all uniquely affect the finger muscle activity patterns, particularly in the intrinsic hand muscles, in activating the keyboard keyswitches. The findings provide further insight into the relationship between fingertip forces and muscle activity in the context of keyboard designs. Understanding how changes in keyswitch design factors affect motor control of the upper extremity can help provide further insight into the design of future keyswitch and potentially keyboard designs, as well as help gain further understanding into reducing the exposure to risk factors that may lead to upper extremity musculoskeletal injuries associated with computer keyboard work.

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References

Armstrong TJ, Foulke JA, Martin BJ, et al. Investigation of applied forces in alphanumeric keyboard work. Am Ind Hyg Assoc J 1994;55(1):30–5.

Burgar CG, Valero-Cuevas FJ, Hentz VR. Fine-wire electromyographic recording during force generation. Application to index finger kinesiologic studies. Am J Phys Med Rehabil 1997;76(6):494–501.

Dennerlein JT, Mote Jr CD, Rempel DM. Control strategies for finger movement during touch-typing. The role of the extrinsic muscles during a keystroke. Exp Brain Res 1998;121(1):1–6.

Gerard MJ, Armstrong TJ, Foulke JA, et al. Effects of key stiffness on force and the development of fatigue while typing. Am Ind Hyg Assoc J 1996;57(9):849–54.

Gerard MJ, Armstrong TJ, Franzblau A, et al. The effects of keyswitch stiffness on typing force, finger electromyography, and subjective discomfort. Am Ind Hyg Assoc J 1999;60(6):762–9.

Gerr F, Marcus M, Ensor C, et al. A prospective study of computer users: I. Study design and incidence of musculoskeletal symptoms and disorders. Am J Ind Med 2002;41(4):221–35.

Holzbaur KR, Murray WM, Gold GE, et al. Upper limb muscle volumes in adult subjects. J Biomech 2007;40(4):742–9.

Human Factors and Ergonomics Society (BSR/HFES100). Human factors engineering of computer workstations. Santa Monica: CA Human Factors and Ergonomics Society; 2002.

International Organization of Standards (ISO9241-4). Ergonomic requirements for office work with visual display terminals (VDTs) – Part 4: keyboard requirements. International Organization of Standards; 1998.

Jindrich DL, Balakrishnan AD, Dennerlein JT. Effects of keyswitch design and finger posture on finger joint kinematics and dynamics during tapping on computer keyswitches. Clin Biomech (Bristol, Avon) 2004;19(6):600–8.

Kryger AI, Andersen JH, Lassen CF, et al. Does computer use pose an occupational hazard for forearm pain; from the NUDATA study. Occup Environ Med 2003;60(11):e14.

Kuo PL, Lee DL, Jindrich DL, et al. Finger joint coordination during tapping. J Biomech 2006;39(16):2934–42.

Lassen CF, Mikkelsen S, Kryger AI, et al. Elbow and wrist/hand symptoms among 6943 computer operators: a 1-year follow-up study (the NUDATA study). Am J Ind Med 2004;46(5):521–33.

Marcus M, Gerr F, Monteilh C, et al. A prospective study of computer users: II. Postural risk factors for musculoskeletal symptoms and disorders. Am J Ind Med 2002;41(4):236–49.

Martin BJ, Armstrong TJ, Foulke JA, et al. Keyboard reaction force and finger flexor electromyograms during computer keyboard work. Hum Factors 1996;38(4):654–64.

Milner TE, Dhaliwal SS. Activation of intrinsic and extrinsic finger muscles in relation to the fingertip force vector. Exp Brain Res 2002;146(2):197–204.

Radwin RG, Jeng OJ. Activation force and travel effects on overexertion in repetitive key tapping. Hum Factors 1997;39(1):130–40.

Radwin RG, Ruffalo BA. Computer key switch force–displacement characteristics and short-term effects on localized fatigue. Ergonomics 1999;42(1):160–70.

Rempel D, Dennerlein J, Mote Jr CD, et al. A method of measur -ing fingertip loading during keyboard use. J Biomech 1994;27(8):1101–4.

Rempel D, Serina E, Klinenberg E, et al. The effect of keyboard keyswitch make force on applied force and finger flexor muscle activity. Ergonomics 1997;40(8):800–8.

Rempel D, Tittiranonda P, Burastero S, et al. Effect of keyboard keyswitch design on hand pain. J Occup Environ Med 1999;41(2):111–9.

Viikari-Juntura E, Silverstein B. Role of physical load factors in carpal tunnel syndrome. Scand J Work Environ Health 1999;25(3):163–85.

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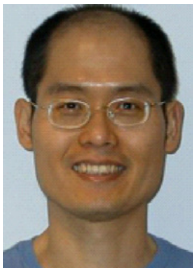

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