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The effect of keyboard keyswitch make force on applied force and finger flexor muscle activity

DAVID REMPEL†, ELAINE SERINA and EDWARD KLINENBERG
Ergonomics Laboratory, University of California, San Francisco, California, USA

BERNARD J. MARTIN, THOMAS J. ARMSTRONG, JAMES A. FOULKE and SIVAKUMARAN NATARAJAN
The University of Michigan, Ann Arbor, Michigan, USA

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The design of the force-displacement characteristics or 'feel' of keyboard keyswitches has been guided by preference and performance data; there has been very little information on how switch 'feel' alters muscle activity or applied force. This is a laboratory-based repeated measures design experiment to evaluate the effect of computer keyboard keyswitch design on applied finger force and muscle activity during a typing task. Ten experienced typists typed on three keyboards which differed in keyswitch make force (0·34, 0·47 and 1·02 N) while applied fingertip force and finger flexor electromyograms were recorded. The keyboard testing order was randomized and subjects typed on each keyboard for three trials, while data was collected for a minimum of 80 keystrokes per trial. No differences in applied fingertip force or finger flexor EMG were observed during typing on keyboards with switch make force of 0·34 or 0·47 N. However, applied fingertip force increased by approximately 40% ($p<0{\cdot}05$) and EMG activity increased by approximately 20% ($p<0{\cdot}05$) when the keyswitch make force was increased from 0·47 to 1·02 N. These results suggest that, in order to minimize the biomechanical loads to forearm tendons and muscles of keyboard users, keyswitches with a make force of 0·47 N or less should be considered over switches with a make force of 1·02 N.

1. Introduction

Based on epidemiologic studies in the industrial workplace, fingertip force has been identified as a risk factor for chronic musculoskeletal disorders of the upper extremities (Stock 1991, Armstrong *et al.* 1987). It has been postulated that this risk extends to typists where finger forces are lower but finger activity is more repetitive than in the industrial setting.

Up to now, keyboard designers and standards setting organizations have relied on psychophysical and performance data to specify keyswitch design. The American National Standards Institute/Human Factors Standard (ANSI/HFS 1988) states that the make force, or the minimum force required to electrically activate the switch 'shall range between 0·25 N and 1·5 N', but 'the preferred key force is between 0·5 N and 0·6 N'. The standard also recommends a range for key displacement and tactile

†Correspondence to: David Rempel, University of California Ergonomics Program, 1301 South 46th Street, Building 112, Richmond, CA 94804, USA

feedback. The studies referenced to justify the selection of keyswitch make force evaluated the effect of keyswitch characteristics on typing speed, error rate and short-term subjective preference (Kinkead and Gonzalez 1969, Klemmer 1971). While most contemporary keyboards appear to meet the ANSI guidelines, they still vary considerably in make force and other keyswitch characteristics that effect switch 'feel'.

Recently, keyswitch design was shown to effect the fingertip forces that users applied to the keyboard during keying; however, in that study several keyswitch characteristics (e.g. make force, tactile feedback, key displacement) changed simultaneously between keyboards (Armstrong *et al.* 1994). Therefore, the effects of specific force-displacement characteristics (e.g. make force) of the switch design on modifying fingertip force remain uncertain. Although other authors have measured finger flexor surface electromyograms (EMG) during keying (Lundervold 1958, Colombini *et al.* 1989), EMGs have not been collected previously during a systematic study of the effect of keyswitch characteristics.

The purpose of this study was to determine how keyswitch make force influences finger flexor EMGs and the actual fingertip force applied by keyboard operators. The keyswitches tested fall within the range of recommended ANSI standards (ANSI/HFS 1988) and are typical of keyboards in use throughout the world.

2. Method

This is a repeated measures experiment with a single factor, keyboard, and repeated observations. The equipment consisted of three keyboards, Kb1, Kb2 and Kb3, that differed only in the keyswitch make force. During a keying task, keyboard reaction forces were recorded from force transducers mounted under the keyboard while surface EMGs were recorded over the extrinsic finger flexor muscles.

2.1. *Subjects*

Ten healthy, right-handed subjects (five male and five female) were recruited for the study from university staff. Subjects were experienced touch typists. Ages ranged from 24 to 45 years, with a mean of 34·5 years. Typing speed was recorded during the study and varied between subjects from 38 to 92 words/minute.

2.2. *Keyboards*

The keyboards were Key Tronic MacPro Plus. Under the keycap of every keyswitch was a replaceable rubber dome; the characteristics of the rubber dome determined the stiffness of the keyswitch. The rubber domes under each keycap of each keyboard were replaced so that all the keys of Kb1, Kb2, and Kb3 contained rubber domes with make forces of 0·27, 0·56 and 0·83 N (manufacturer specification), respectively. Figure 1 indicates typical static key force versus displacement relationship for the 'f' key for each keyboard as measured using previously described techniques (Armstrong *et al.* 1994). The following reference points were extracted from each force displacement curve for 10 keys (l, p, h, j, m, v, d, f, q, s) for each keyboard (table 1).

(1) *Make force*: the peak force preceding the 'breakaway', which is near the electrical make point. The make force point is usually within the first half of the total travel and is the minimum force required to actuate the key.
(2) *Total travel*: The distance the keycap moves when the applied force is increased from zero to 1·5 N.

The mean keyswitch make forces, averaged over the 10 keys, were 0·34, 0·47 and 1·02 N, respectively, for the three keyboards, Kb1, Kb2 and Kb3. The measured values, which did not correspond to manufacturer's specifications, are used in this manuscript. There was no difference in total key travel between the three keyboards. The average total key travel was 3·7 mm (table 1).

2.3. *Data acquisition and calibration*

Applied fingertip force was measured using load cells placed under the computer keyboard (Armstrong *et al.* 1994). The plastic case was removed from the keyboard, which was clamped on a specially designed rigid frame bolted onto the load cells to minimize mechanical vibration. All three keyboards were mounted to the same load cell platform and the keyboards were interchanged with the platform using clamps. Output from the load cells was summed. The load cells were calibrated with a series of weights (10 to 5000 g) placed at four sites on the keyboard. The resulting calibration curve was linear, with a strong correlation between measured and actual force ($r^2 = 0{\cdot}99$).

Muscle activity of the right-hand finger flexors was recorded using two surface electrodes spaced 2 cm apart and embedded in a preamplifier. The ground electrode was placed on the subject's olecranon. Electrodes were placed to maximize their sensitivity to exertion of the fingers against a key. Final electrode location was usually near the proximal end of the ulna on the palmar surface of the forearm. The EMG signal was amplified and the RMS value was computed. The force and EMG signals were sampled at 250 Hz and recorded over 200 ms windows centred about a trigger signal generated by the activation of the key, detected by software.

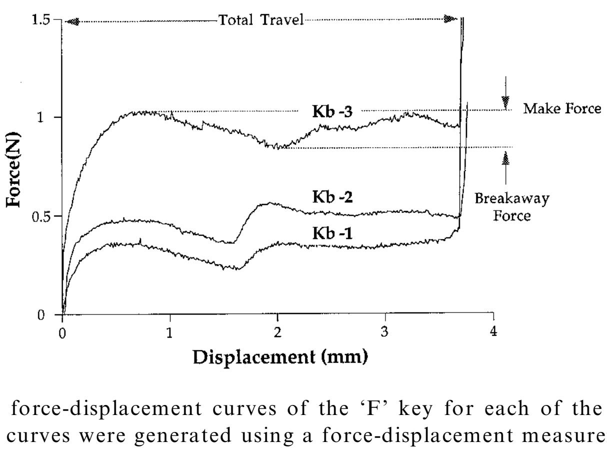

Figure 1. Static force-displacement curves of the 'F' key for each of the three keyboards studied. The curves were generated using a force-displacement measurement machine as described by Armstrong *et al.* (1994).

Table 1. Keyswitch characteristics for the three keyboards. Mean make force and total travel distance are based on sampling 10 keys (l, p, h, j, m, v, d, f, q, s). Between-key standard deviations are in parentheses.

	Keyboard 1	Keyboard 2	Keyboard 3
Make force (N)	0·34 (0·04)	0·47 (0·04)	1·02 (0·12)
Total travel (mm)	3·72 (0·03)	3·74 (0·05)	3·76 (0·04)

Prior to performing the keying task, subjects performed two trials of a graded quasi-static flexion exertion in the typing position on the keyboard, from 0 to 100% of maximum strength in 5 s, with each finger. Linear EMG-force relationship, forced through the origin, was calculated from the graded exertion collected during the calibration phase and used to express EMG measurements in force units.

2.4. *Typing tests*

Seat and keyboard height were adjusted so that the upper arms were near vertical and the forearm was approximately parallel to the floor. The typing text was on $8{\cdot}5 \times 11$ in. size paper, double spaced, New York font (14 point), placed on a document holder adjusted by the typist. The text comprised independent sentences and each sentence contained every letter of the alphabet.

Subjects were told that their 'typing style and performance' was being monitored. They were not told that keystroke force was being measured. Subjects were instructed to type at a comfortable rate and not to rest the wrists or fingertips on the keyboards during keying.

Keyboard order was randomly assigned based on a Latin-square design. Three typing trials were conducted on each keyboard. Each trial was 3 – 5 min in duration with a 1-min rest period between trials; data was collected for a minimum of 80 keystrokes per trial. Therefore, data from a minimum of 240 keystrokes was collected for each of the three keyboards for each subject. Subjects typed for 1 – 2 min before data collection began. Subjects did not know when data was collected.

2.5. *Data analysis*

Right-hand and left-hand data collected during the typing task were segregated. Mean force, peak force, mean EMG, peak EMG, and base-peak EMG were calculated for each keystroke. The force summary measures for each keystroke were calculated within a 120 ms window starting 40 ms after the beginning of each key record (Martin *et al.* 1996). Summary measures for EMG were computed within a 160 ms window starting 20 ms after the beginning of the record. Using the static EMG-force curves for each finger, EMG data was expressed also in force units. Force data was calculated in both Newtons and as a percentage of maximal voluntary contraction (% MVC). These outcome measures were averaged over the 240 keystrokes for each subject and keyboard.

The effect of keyboard on outcome measures was evaluated statistically using a single factor, repeated measures ANOVA (JMP, SAS Institute). If the effect of keyboard was found to be statistically significant, follow-up tests were conducted using the Tukey's Studentized Range Test at a procedure-wise error rate of 0·05. The percentage of variability of the outcome measures predicted by keyboard was assessed by calculating w^2 (Hayes 1988), a term analogous to r^2.

3. Results

3.1. *Applied force*

The effect of keyswitch make force on applied mean fingertip force is presented in figure 2. Each line represents data from a different subject and each point is a summary of the three keying trials for a subject and keyboard. In almost all subjects there is little difference between keyboards 1 and 2, but the applied mean force rises for keyboard 3. As summarized in table 2, the average applied force ranged from 0·85 to 1·20 N, for keyboards 1 and 3, respectively. The force applied to keyboard 3 was significantly higher than for the other keyboards ($p<0{\cdot}05$; Tukey Studentized Range Test). Approximately 40% of the variability (w^2) of applied mean force was explained by keyboard.

The same trend was noted for applied peak force as shown in table 2. The average peak forces ranged from 2·6 to 3·5 N. The peak force exertions correspond to 10 to 14% MVC. Therefore, doubling the switch make force from 0·47 N (keyboard 2) to 1·02 N (keyboard 3) led to a 35% increase in applied force. There was no change in applied force when the make force increased from 0·34 N (keyboard 1) to 0·47 N (keyboard 2). Approximately 23% of the variability (w^2) of applied peak force was explained by keyboard.

3.2. *EMG muscle activity*

Similar trends were also observed for the finger flexor EMG (RMS) values as presented in table 2. The average muscle activity throughout the keystroke is represented by the mean EMG value. The increase in muscle activity required for the keystroke is represented by the base-peak EMG value. The average of the mean EMG values range from 24% MVC (keyboard 1) to 28% MVC (keyboard 3). The average of the base-peak EMG values range from 19% MVC (keyboard 2) to 23% MVC (keyboard 3). There were no significant differences observed between keyboard 1 and keyboard 2 for EMG summary measures. However, all EMG measures were significantly greater for keyboard 3 when compared to keyboard 2 or keyboard 1. EMG summary measures increased by approximately 20% when the keyswitch make force was doubled from 0·47 to 1·02 N. The higher value of mean EMG compared to the base-peak EMG indicates that there is a relatively high tonic or background EMG activity throughout the typing task. Although changes in EMG measures with keyswitch make force closely parallel the changes in applied force, there was a much stronger relationship between applied force and keyswitch make force than between EMG measures and keyswitch make force. Only 2% of the variability of the EMG measures was explained by keyboard.

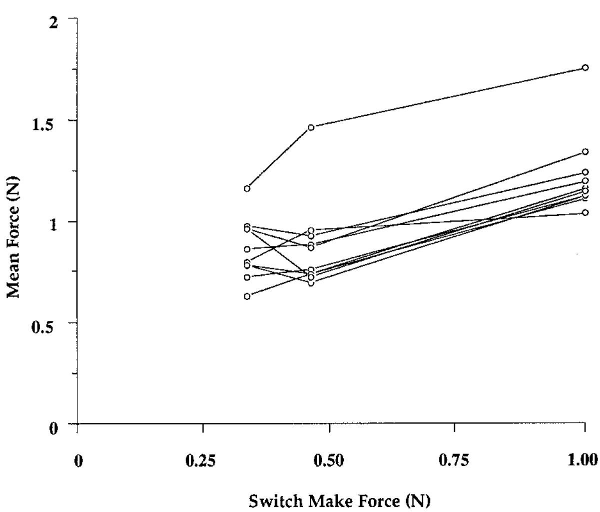

Figure 2. Mean force applied by subjects to the three keyboards. Each line is the data from one subject. Each point on the line is a force value averaged over 280 keystrokes.

Table 2. Measures of keystroke fingertip force and EMG by keyboard averaged across 10 subjects and 240 keystrokes per subject. Applied force, EMG, and force calculated from EMG are presented in Newtons (N) or % MVC. Between-subject standard deviations are in parentheses.

	Keyboard 1	Keyboard 2	Keyboard 3	$w^{2\dagger}$
Applied force				
Mean (N)	$0{\cdot}85^{a}$ (0·15)	$0{\cdot}86^{a}$ (0·22)	$1{\cdot}20^{b}$ (0·20)	0·40
Mean (% MVC)	$3{\cdot}4^{a}$ (1·4)	$3{\cdot}4^{a}$ (1·4)	$4{\cdot}8^{b}$ (2·0)	0·14
Peak (N)	$2{\cdot}70^{a}$ (0·66)	$2{\cdot}56^{a}$ (0·74)	$3{\cdot}46^{b}$ (0·66)	0·23
Peak (% MVC)	$10{\cdot}8^{a}$ (5·0)	$10{\cdot}3^{a}$ (5·3)	$14{\cdot}1^{b}$ (6·6)	0·08
EMG (RMS)				
Mean (% MVC)	$23{\cdot}8^{a}$ (12·5)	$24{\cdot}0^{a}$ (13·4)	$28{\cdot}2^{b}$ (15·2)	0·02
Base-peak (% MVC)	$18{\cdot}8^{a}$ (13·7)	$18{\cdot}7^{a}$ (15·0)	$23{\cdot}1^{b}$ (15·9)	0·02
Peak (% MVC)	$33{\cdot}9^{a}$ (18·9)	$33{\cdot}9^{a}$ (20·3)	$40{\cdot}6^{b}$ (22·6)	0·02
Force calculated from EMG				
Base-peak (N)	$4{\cdot}90^{a}$ (3·16)	$4{\cdot}76^{a}$ (3·31)	$5{\cdot}89^{b}$ (3·46)	0·02

^{a,b}Within a row, groups sharing a common superscript (^{a,b}) are *not* significantly different from each other using Tukey's Studentized Range Test at a procedure-wise error rate of 0·05.
$^{\dagger}w^2$ is analogous to r^2 and is a measure of the variability of the outcome measure explained by keyboard.

3.3. *Force estimated from EMG*

The force values calculated from the EMG measures are presented in table 2. The force calculated from the base-peak EMG ranged from 4·9 (keyboard 1) to 5·9 N (keyboard 3) and represents the dynamic muscle activity during the keystroke. The force estimated by the base-peak EMG was approximately 75% higher than the actual applied peak force.

4. Discussion

4.1. *Applied force*

No significant differences were observed in this study in fingertip force applied or finger flexor EMG during typing on keyboards with keyswitch make force of 0·34 or 0·47 N. However, compared to 0·47 N, a switch make force of 1·02 N led typists to apply greater fingertip forces with greater finger flexor EMG activity. It appears that subjects apply a minimum fingertip force during keying, regardless of keyswitch make force, and apply increasing force with keyswitch make forces greater than 0·47 N.

In a previous study by our group, fingertip reaction forces were measured while subjects typed on three different commerical keyboards (Armstrong *et al.* 1994). The keyboards differed in keyswitch force-displacement characteristics. In that study, unlike the present study, a number of keyswitch force-displacement characteristics varied simultaneously between the keyboards, For example, in the earlier study, keyswitch make forces for the three keyboards were: 0·47, 0·53 and 0·89 N, the corresponding key total travel distances were 4·3, 3·3 and 4·0 mm, and the breakaway forces (tactile feedback) were 0·14, 0·04 and 0·24 N, respectively. The corresponding peak fingertip reaction forces applied by subjects were 1·8, 1·9 and 2·2 N. Therefore, although the fingertip force exerted by keyboard operators was influenced by the keyswitch design, no definitive conclusions could be drawn about the role of specific keyswitch characteristics in modifying applied fingertip force. In the present study, the travel distance and breakaway forces were relatively constant while the make force varied between the keyboards.

4.2. *Muscle activity*

Two other studies have addressed the role of keyswitch design on flexor digitorum muscle activity. Colombini *et al.* (1989) studied 11 subjects who typed on three keyboards: a manual typewriter, an electric typewriter and a computer keyboard. All were adjusted to maintain comparable, low keyboard heights. The peak surface EMG values (equivalent to peak EMG as % MVC) for the keyboards were 23, 20 and 14% MVC for the right digitorum muscle group and 17, 12 and 8% MVC for the left, respectively. The corresponding median surface EMG values were 4, 3 and 3% MVC for the right and 4, 3 and 3% MVC for the left. The higher muscle activity applied during manual typewriter use were most likely due to differences in keyswitch characteristics. However, the specific force-displacement characteristics of the three keyboards were not described.

Guggenbühl and Krueger (1990) measured fingertip motion and flexor digitorum surface EMG in 12 subjects who used four different 10-key keypads. The four keypads differed in switch design: (1) membrane switch with no pressure point, (2) membrane switch with a 2·5 N pressure point, (3) a switch with conventional key travel, and (4) a piezo switch. Only the third keypad had significant key travel. Peak muscle activity almost doubled, from 23% MVC to 42% MVC, when subjects keyed on the membrane switch without a pressure point compared to one with a 2·5 N pressure point. This study confirmed an effect of switch make force on muscle activity, although a make force of 2·5 N is very high and not typical for keyboards. The average peak EMG was lowest, approximately 14% MVC, during keying on the keypad with conventional key travel. The authors of that study suggested that because the membrane switch sometimes did not react when it should have, typists were forced to re-enter missed keys and, therefore, modified their motor command to apply a greater isometric load. The lack of keyswitch force-displacement information from these studies limits conclusions that can be drawn about the role of switch characteristics on finger force control.

In the present study larger peak and mean EMG values were observed in subjects using a computer keyboard than was the case in either the Colombini *et al.* (1989) or the Guggenbühl and Krueger (1990) studies. The differences are probably due to differences in calculating EMG values. The present authors measured EMG values for each keystroke by windowing around single keystrokes and therefore excluded the lower muscle activity for a finger when it was 'idle'. By using the windowing process, the EMG results are more sensitive to variations in muscle activity associated with a keystroke.

What also is apparent from this study is that subjects rapidly adapt to changes in keyforce. Increasing keyswitch make force leads to an increase in applied finger force and decreasing make force leads to a reduction in applied force. This adaptation occurs within minutes of exposure. Such adaptation may be surprising at first as finger force exerted on the 'soft' keyboard (keyboard 1) is already 2·7 times higher than the force required to activate (make force) the 'stiffest' keyboard (keyboard 3). However, for the stiffest keyboard, the actual applied peak force is 3·4 times the keyboard make force. Thus, it may be assumed that the large applied-force/make-force ratio (R) contains a 'built-in or intrinsic' safety margin, probably to guarantee switch activation for each keystroke. Such a safety margin parallels what is described by Johansson and Westling (Johansson and Westling 1984, Westling and Johansson 1984), who observed grip force to be greater by a small amount than the minimal force required to lift objects using a pinch grip.

When comparing applied peak force to the force required to activate the key, subjects are applying 3·4 to 7·9 times the required force. As the make force increases, the ratio R decreases and probably converges on 1 as the make force approaches finger MVC. Thus the safety margin will decrease with increasing make force. Furthermore, as R is high for low make forces, the present data suggest that there is a make force below which there is no accompanying reduction in applied force. Based on this study, that operating point is somewhere between 0·47 and 1·02 N activation force. The implications for finger force control are that the switch activation force is part of the feedback since an adaptation was observed. However, the applied force is not tightly controlled since it seems to contain more than just a safety margin; that is, R is very high for the light touch keyboards.

The results of this study suggest that in order to minimize finger contact force and reduce the biomechanical loads to forearm tendons and muscles, keyboard keyswitches with a make force of 0·47 N or less should be used over switches with make force of 1·02 N or greater. Based on the brief exposures described in this study there appears to be no biomechanical advantage to reducing the keyswitch make force to 0·34 N. However, longer exposures to light touch keyboards or additional training might lead to further reductions of applied force and muscle activity. In addition, task-specific factors may influence muscle loading. For example, with tasks requiring infrequent keystrokes, a stiffer key may reduce muscle loading by allowing the fingertips to rest on the keycaps between keystrokes.

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