

Activation Force and Travel Effects on Overexertion in Repetitive Key Tapping

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Key switch design parameters, including make force, make travel, and over travel, were investigated for minimizing operator-exerted force while maximizing key-tapping speed. A mechanical apparatus was designed, constructed, and used for independently controlling key switch parameters and for directly measuring finger exertions during repetitive key tapping using strain gauge load cells. The task for the 25 participants involved using the index finger of the dominant hand to repeatedly depress a single key as rapidly as possible. Participants received visual and auditory feedback upon a successful keystroke. Peak force exerted decreased 24% and key-tapping rate increased 2% when over travel was distended from 0.0 to 3.0 mm. Although peak force exerted was not significantly affected by make point travel, key-tapping rate increased 2% when make point travel was reduced from 4.0 to 1.0 mm. These results indicate that key switch mechanisms that provide adequate over travel might enable operators to exert less force during repetitive key tapping without inhibiting performance.

INTRODUCTION

This research is motivated by reports of upper extremity maladies among intensive keyboard users (Bernard, Sauter, Fine, Petersen, & Hales, 1994; McPhee, 1982; NIOSH, 1990; Rose, 1991). Force is one factor often cited as increasing the risk for localized fatigue and musculoskeletal disorders. Studies have shown that the force exerted by keyboard operators during keying markedly exceeds the force necessary to activate the keys (Armstrong, Foulke, Martin, Gerson, & Rempel, 1994; Feuerstein, Armstrong, & Hickey, 1994). The actual force that a typist exerts can be af-

ected by numerous circumstances, including keyboard, workstation, and psychosocial factors, and individual factors, such as typing experience and proficiency. The current study is concerned with the effects of physical characteristics of key design on finger exertions in repetitive key tapping.

The physical characteristics of key switches are often described by their *make* and *break points*, which are measured from associated force and travel parameters. *Key force* is the force applied against the key cap. Because key force is usually opposed by a linear or nonlinear spring, when key force is applied, the key is depressed a corresponding displacement, defined as *key travel*. *Make* occurs when the switch makes electrical contact and the circuit is activated. *Break* occurs when the switch breaks electrical contact and the circuit is deactivated.

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Because there is often hysteresis in switch mechanisms, the break point is not necessarily equivalent to the make point. *Make point force* is therefore the key force that must be applied in order to activate the key, and *break point force* is the key force that must be released in order to deactivate the key. Correspondingly, *make point travel* is the key travel necessary to activate the key. *Over travel* is defined as the maximum travel a key can be depressed beyond the make point travel until the key hits bottom. The actual key force and travel characteristics depend on both the mechanical and electrical designs of the particular key switch.

The *American National Standard for Human Factors Engineering of Visual Display Terminal Workstations* (HFES, 1988) contains requirements for the force necessary for activating keys and associated key displacement. The standard specifies key activation force ranges between 0.25 and 1.5 N with a key displacement between 1.5 and 6.0 mm and a preferred displacement between 2.0 and 4.0 mm. The force required for activating keys, however, does not necessarily reflect the actual exertions operators make when using a keyboard. Peak force during keying has been measured to be as much as 2.5 to 4.6 times the required activation force (Armstrong et al., 1994; Feuerstein et al., 1994; Martin et al., 1994).

Previous studies have shown that applied finger force increases with keyboards that have greater make forces (Armstrong et al., 1994; Rempel, Klinenberg, et al., 1994). Armstrong et al. (1994) compared three keyboards with similar layouts but different make force and key travel characteristics. Although different applied forces were observed among the keyboards, each one had specific key switch parameters, so these effects are confounded.

Rempel, Klinenberg, et al. (1994) performed a similar study and also found that applied key force was affected by make force, whereas other key switch characteristics (i.e., total travel and tactile feedback) were held constant. Neither of these investigations could account for the combined effects of keyboard force and travel characteristics on applied finger force.

The purpose of this study was to systematically investigate keyboard design factors that affect operator exertion. Key switch design parameters were investigated that maximize key-tapping speed while minimizing peak key force exerted. The make point force, make point travel, and over travel for the key switch covered a wide range of parameters currently recommended for keyboards.

METHODS

Apparatus

An experimental apparatus was designed and constructed for manipulating key force and travel characteristics while measuring the actual force exerted during key tapping. The apparatus, illustrated in Figure 1, contained a leaf spring mechanism for simulating the basic linearized force-displacement characteristics of a single key. The spring element was made from a spring steel strip that was rigidly attached as a cantilever beam at one end; force was applied against a plastic key top mounted on the other end. Different-height mechanical stops were used to control total key travel distance.

The spring force-displacement parameters were controlled using different-size spring steel strips (Blake, 1985). The linear force-displacement relationship for a simple deflected beam can be described by the following equation:

$$D = FK = F \frac{L^3}{3EI}$$

where the beam deflection (mm) is D , the applied load (g) is F , and the constant K is a function of the strip length L (in millimeters), Young's modulus of elasticity for steel, E (200 000 N/mm²), and the moment of inertia, I (mm⁴). The moment of inertia was determined using the following equation:

$$I = \frac{WH^3}{12}$$

where W is the strip width (in millimeters) and H is the strip thickness (in millimeters).

Consequently, the force-displacement parameters

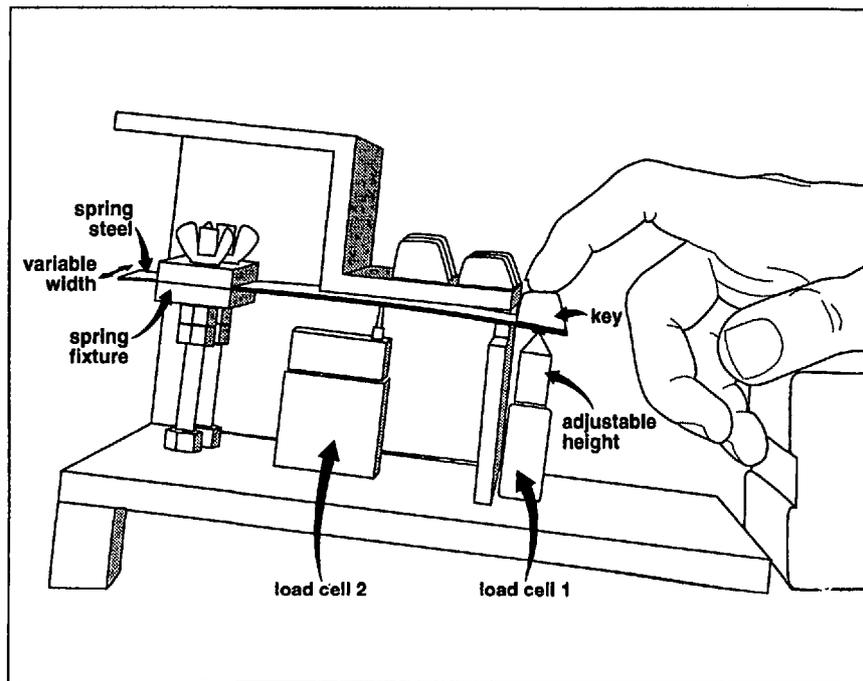


Figure 1. Experimental apparatus used for independently controlling key make force, make travel, and over travel. Key force-displacement characteristics were determined by the length, width, and thickness of the deflected spring steel strip. Load Cell 1 measured finger force after the key hit bottom. Load Cell 2 measured finger force exerted before the linear key spring static deflection limit was exceeded. Make force was controlled through software.

could be controlled simply by changing the spring steel strip thickness and width. These equations were used for estimating the spring steel strip sizes needed. Each strip width was cut slightly wider than estimated and calibrated. Calibration was accomplished by directly measuring the deflection using a digital micrometer and associated force against the strain gauge load cell and trimming each strip as necessary. Every strip had a fixed length (55 mm). Dimensions for make point force and make point travel characteristics used in this experiment are included in Table 1.

Finger force is registered through two strain gauge load cells (see Figure 1). Load Cell 1 is an 11.12 N Transducer Techniques™ (Temecula, CA) Model MDB-2.5, and Load Cell 2 is 0.5 N Transducer Techniques™ Model GS-500. When the key is depressed, finger force is initially transmitted to Load Cell 2 as the leaf spring bends.

When the force is large enough to displace the leaf spring to the static limit of the mechanical stop, Load Cell 1 registers the additional force. The force exerted at the key is a weighted sum of the force measured by the two load cells. This

TABLE 1

Spring Steel Beam Dimensions and Corresponding Make Point Force and Travel Parameters

Make Point Force (N)	Make Point Travel (mm)	Thickness (mm)	Width (mm)
0.31	1.0	0.64	7.3
0.31	2.5	0.38	13.6
0.31	4.0	0.38	8.5
0.51	1.0	0.64	12.2
0.51	2.5	0.38	22.6
0.51	4.0	0.38	14.2
0.71	1.0	0.64	17.1
0.71	2.5	0.64	6.8
0.71	4.0	0.38	19.8

force measurement was calibrated against known weights using linear regression.

Daytronic™ Model 9878A strain gauge conditioning amplifiers provided excitation, amplification and filtering of the load cell signals. A MetraByte™ Model DASH-16 12-bit data acquisition board sampled the analog data from each load cell at a 200-Hz sample rate using an IBM-PC microcomputer.

A plastic keyboard cap was mounted on the spring containing the letter *M*. A cosmetic enclosure for the experimental apparatus obscured visual cues (see Figure 1). Dummy keys were mounted in proximity to the active key relative to a conventional QWERTY keyboard. The simulated keyboard was inclined toward the operator 6.2° with respect to the horizontal.

The participant sat in front of a display screen in a posture similar to that when working at a computer workstation. The simulated keyboard was located 73.5 cm from the floor. The palm rested on a rubber pad with the fingers extended, similar to a typing posture. The height and location of the palm rest was adjustable so that every participant addressed the key in the same manner using the end of the distal finger pad.

Key activation was controlled through software. A successful keystroke occurred when exerted force exceeded a specific make force. Key travel and associated force were dependent on the particular spring constant used. Successive keystrokes could not occur until the key was released below a specific break force. Break force in this study was fixed at 80% of the make force.

Participants were provided discrete visual and auditory feedback on achieving the make force. The screen displayed a letter *M* every time a successful key strike occurred, similar to keying in a word-processing program. An auditory click was simultaneously presented through headphones. White noise and headphones were used for masking apparatus noise and external distractions during the experimental trials.

Procedure

The experimental task involved using the index finger of the dominant hand to repeatedly de-

press the key. Participants were instructed to type the letter *M* with the index finger as fast as possible. Only one key was repeatedly pressed, so participants were instructed to fully release the key so that the index finger was horizontal each time the key was struck in order to better simulate keying.

After becoming familiar with the task, participants practiced the key-tapping task until they said they were comfortable with the instructions and felt ready to begin the experiment. Three practice trials were then provided, using three different combinations of make force, make travel, and over travel.

Every trial lasted 13 s. The key-tapping rate was displayed to participants in terms of words per minute (five characters per word) after each trial. Participants were provided a 1½-min break between experimental conditions. Every trial contained a new experimental condition. Participants were permitted to practice as long as they desired before each new experimental condition. After participants practiced each condition, each one initiated a new trial with his or her first keystroke. An experimental session typically lasted 1 h.

Participants

The 25 participants were recruited through advertisements posted on campus bulletin boards and through electronic mail broadcasts to undergraduate engineering students. All applicants completed a demographics questionnaire. Eligible applicants verified that they were free of hand conditions, disorders, or injuries that might affect typing performance, and all used computer keyboards on a regular basis.

The 15 men and 10 women selected ranged in age from 18 to 41 years (mean = 25 years, *SD* = 6 years) and were paid a nominal fee for their services. Of the 25 participants, 22 were right handed and three were left handed.

Experimental Design

The experiment consisted of a 3 × 3 × 3 repeated-measures full-factorial design. The keyboard design factors of interest included key make force, make travel, and over travel. Make

point force conditions included 0.31 N (30 g), 0.51 N (50 g), and 0.71 N (70 g). Make point travel distances were 1.0, 2.5, and 4.0 mm. Over travel conditions were 0.0, 1.5, and 3.0 mm. A summary of the experimental conditions, including associated key force-displacement characteristics, is illustrated in Figure 2.

All 27 experimental conditions were counter-balanced within and between subjects. Data for the first 3 s (warm-up) of each 13-s trial were discarded, and data recorded for the next 10 s were retained for analysis.

Performance was measured as the actual force exerted and the rate that keystrokes were produced. Dependent variables in this experiment included peak key force and key-tapping rate. Peak force was the mean of the maximum force exerted for every keystroke during 10 s. Key-tapping rate was measured as the average number of keystrokes produced per second during the 10-s time window.

The static limit of deflection for a spring bounds its linear force-displacement characteristics, where applied force beyond that limit produces no corresponding displacement. This discontinuity is observed in a key switch when the key is depressed with sufficient force to displace it to its travel limit and the key contacts the bottom of the switch mechanism. Because the leaf spring has a linear force-displacement characteristic, the *bottoming rate*—the frequency that the key hits bottom—was estimated from the peak force mean and standard deviation as the probability that the key force exerted was sufficient to displace the key to its travel limit.

Repeated-measures analysis of variance was used for studying the significance of the independent variables and their interactions on keying performance. Significant contrasts were tested using the Tukey multiple contrast test.

RESULTS

Peak Exertion Force

The minimum average peak force was 1.04 N ($SD = 0.61$ N) and occurred when make force was 0.31 N, make travel was 4 mm, and over travel

was 3 mm. The maximum average peak force was 1.79 N ($SD = 0.60$ N), which occurred when make force was 0.71 N, make travel was 1 mm, and over travel was 0 mm.

The relationship between average peak force exerted and key make point force is plotted in Figure 3a. Average peak force significantly decreased 0.22 N (15%), $F(2, 48) = 26.46$, $p < .01$, when the make point force was reduced from 0.71 N to 0.31 N. Multiple contrasts indicated that the average peak force exerted for pairwise differences among all three make force levels differed for a significance level of $p < .01$.

No significant peak exertion force effect was observed when key make point travel increased from 1.0 to 4.0 mm, $F(2, 48) = 2.77$, $p > .05$. Average peak force exerted for each make point travel distance is plotted in Figure 3b.

Peak force exerted was significantly affected by key over travel, $F(2, 48) = 75.21$, $p < .01$, as illustrated graphically in Figure 3c. As over travel was augmented from 0 to 3 mm, average peak force exerted decreased by as much as 0.38 N (24%). Multiple contrasts among all combinations of the three over travel conditions were significant for $p < .01$.

Although the Make Point Travel \times Over Travel interaction was statistically significant, $F(4, 96) = 3.49$, $p < .05$, the effect accounted for only 0.91% of the total variance. Multiple contrasts indicated no significant ($p < .01$) peak force differences across make point travel distances for any given over travel condition. Alternatively, peak force exerted was significantly different ($p < .01$) among all over travel conditions across all make point travel conditions, except when make point travel was 1.0 mm and over travel distance was 1.5 mm or 3.0 mm.

Bottoming Rate

The frequency that the experimental apparatus was depressed with sufficient force to hit bottom was estimated as the probability that peak force exceeded the level needed to hit bottom using the average and standard deviation of the peak force measured, which was normally distributed. These probabilities are plotted respectively in

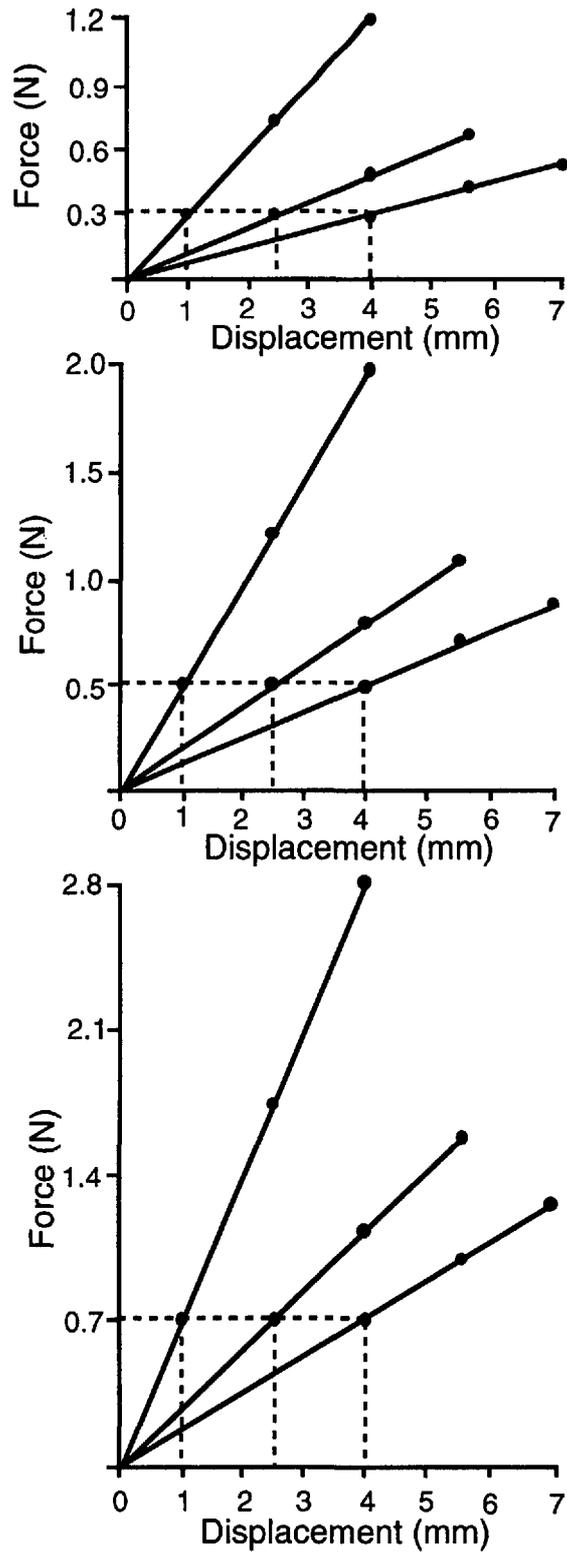


Figure 2. Key force-displacement, key travel, and over travel parameters for all 27 experimental conditions. Make point force and travel are indicated by the intersection of horizontal and vertical dotted lines, and over travel limits are indicated by dots. All graphs are plotted on the same scale.

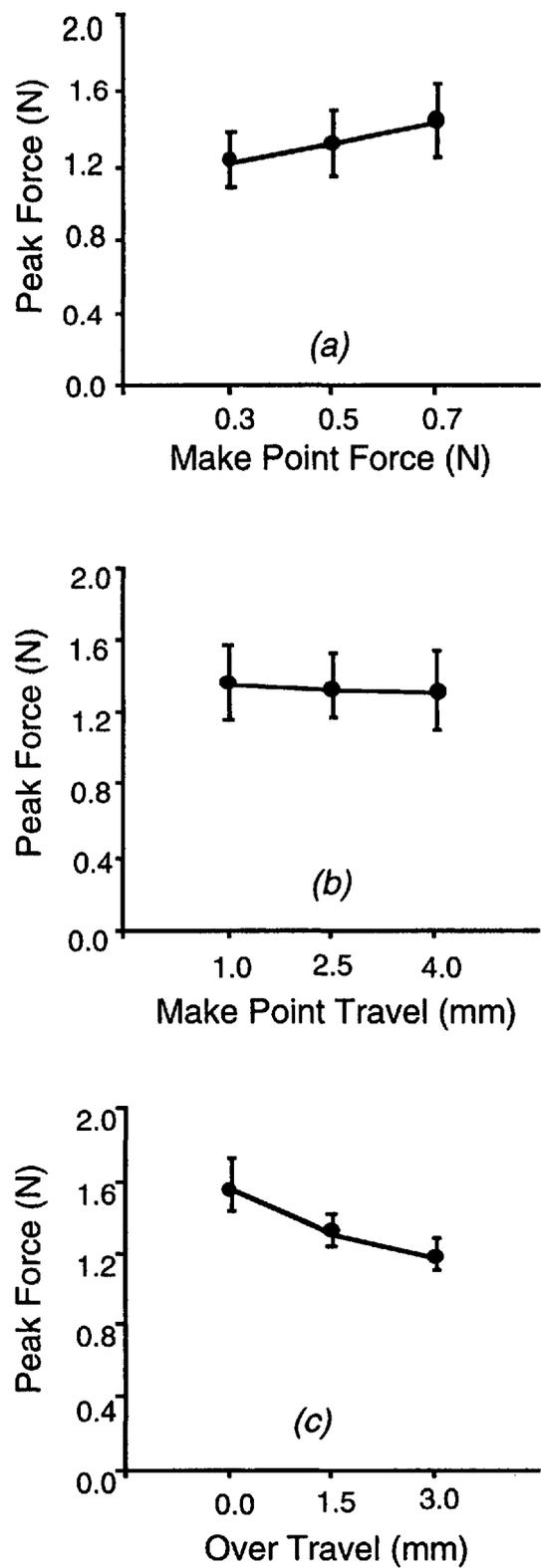


Figure 3. Average peak force exerted versus (a) make point force, (b) make point travel, and (c) over travel (25 participants).

Figures 4a, 4b, and 4c against the make point force, make point travel, and over travel conditions. The smallest average bottoming rate among all experimental conditions was 0%, which occurred when make point force was 0.51 or 0.71 N, make travel was 1 mm, and over travel was 3.0 mm.

Little correlation was observed between bottoming rate and peak exertion force. Correlation between average bottoming rate and average peak exertion force was only .36. The condition in which make point force was 0.31 N, make point travel was 4.0 mm, and over travel was 3.0 mm resulted in the least exertion force, although the bottoming rate for this condition was 88%.

Key-Tapping Rate

Key-tapping rate significantly increased 0.2 keys/s (4%), $F(2, 48) = 22.30, p < .01$, when the key make point force decreased from 0.71 to 0.31 N. Average key-tapping rate is plotted against make point force in Figure 5a. Multiple contrasts revealed that average key-tapping rate was significantly different among all pairwise combinations of the three make point force levels for a $p < .05$ significance level, but only contrasts between the 0.31 N and the other make point force levels were significantly different for $p < .01$.

Make point travel had a significant effect on key-tapping rate, $F(2, 48) = 9.67, p < .01$. Average key-tapping rate increased 0.13 keys/s (2%) as make point travel was reduced from 4.0 to 1.0 mm, as shown in Figure 5b. Pairwise contrasts between average key-tapping rate for a 4.0-mm make point travel distance and the other two make point travel conditions were significant for $p < .01$ using the Tukey test.

Key-tapping rate significantly increased 0.13 keys/s (2%) as over travel distance increased from 0.0 to 3.0 mm, $F(2, 48) = 76.54, p < .01$. Average key-tapping rate is plotted against over travel in Figure 5c. Multiple pairwise contrasts between average key-tapping rate for 0.0 mm and the other two over travel conditions were significant for $p < .01$.

DISCUSSION

This study provided a test paradigm for investigating operator keying behavior in terms of both keying speed and overshoot force under different key activation characteristics, including required force and key displacement, without being limited by a specific keyboard. Minimum peak exertion force and maximum key-tapping performance occurred when make force was 0.31 N and over travel was 3.0 mm. Although there was no significant make point travel effect for peak exertion force, bottoming rate and key-tapping rate were significantly greater when make point travel was 1.0 mm.

An explanation for reduced exertions when over travel is increased may come from the small increment in force from the over travel while the finger decelerates against the resistance of a spring. When a finger strikes a key, it collides with the key top in order to rapidly produce sufficient force to displace the key and to activate the switch. After the key is depressed and make force is achieved, the finger has to decelerate to reduce its velocity and reverse direction in order to release the key. The added over travel may enable the finger to decelerate and reverse direction against the incremental opposing force of the spring without colliding against the key bottom while finger velocity is high.

Greater levels of peak key force, however, were not dependent only on hitting bottom, considering that there was no correlation between bottoming rate and peak force. The least peak force was exerted when make force was small and over travel was high, although the bottoming rate was substantial. Consequently, key bottoming alone was not the only factor in overshoot force production. We have speculated that when over travel was sufficient, the finger was able to decelerate and thus collide with the bottom with less velocity. This should be investigated in future studies.

Rempel, Dennerlein, Mote, and Armstrong (1994) observed ballistic finger motion during typing and recorded peak fingertip velocities during the keystroke phase between 0.3 and 0.7 m/s.

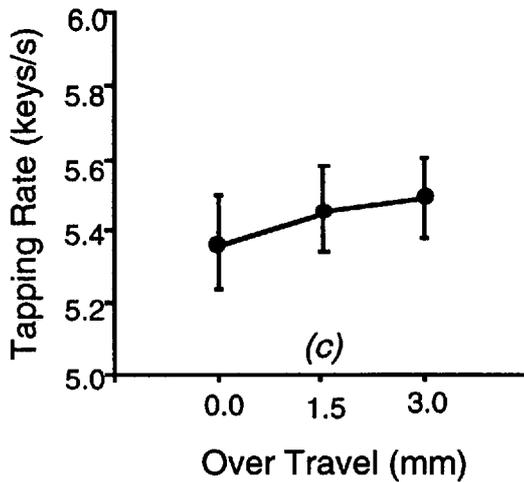
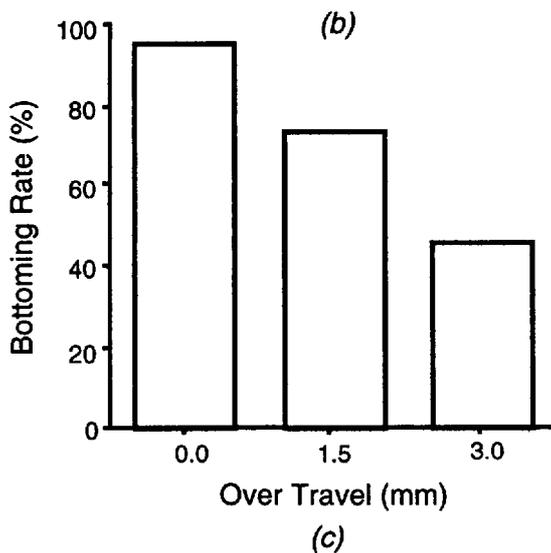
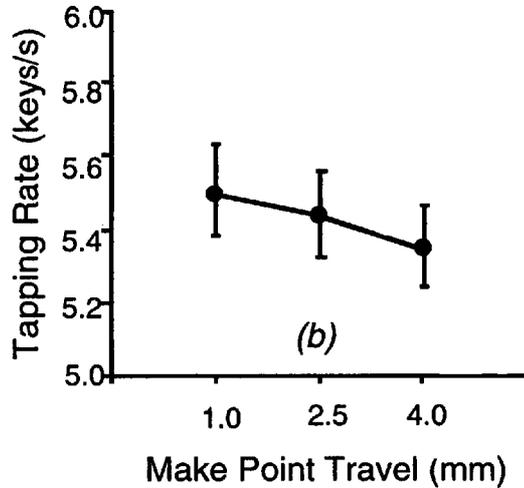
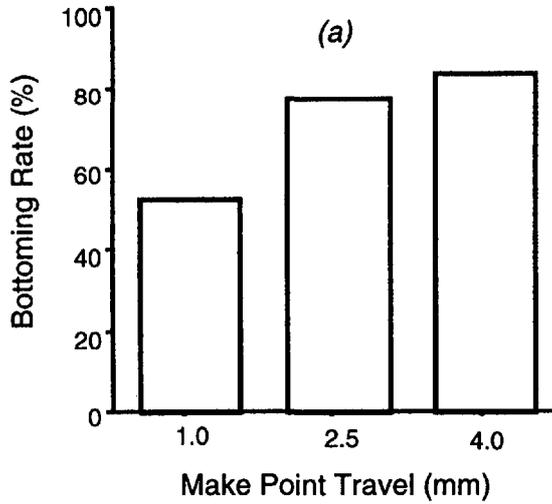
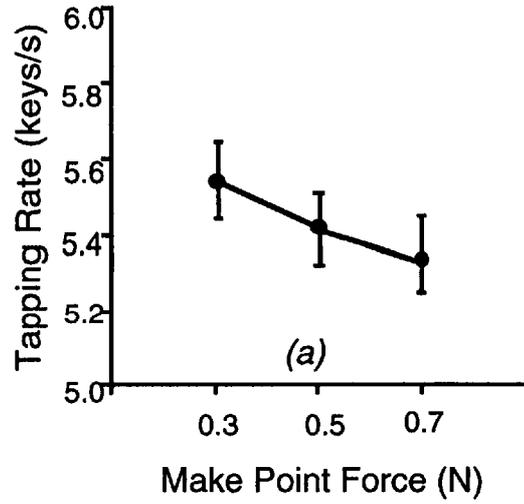
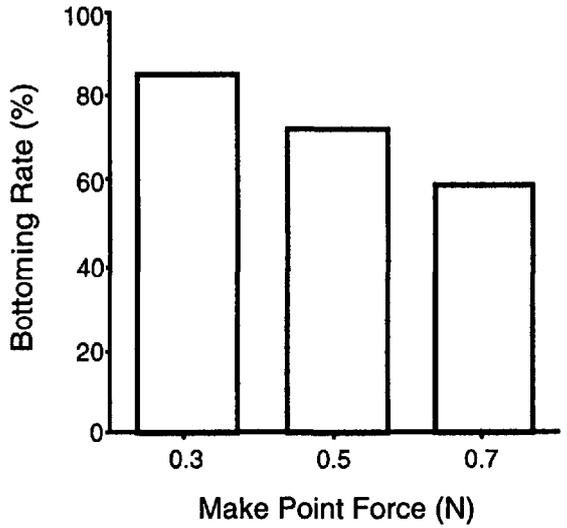


Figure 4. The probability that peak exerted force exceeds the key static limit of deflection for conditions of (a) make point force, (b) make point travel, and (c) over travel (25 participants).

Figure 5. Average key tapping rate versus (a) make point force, (b) make point travel, and (c) over travel (25 participants).

They observed that velocity was relatively constant during initial key strike and through the make point. Key-tapping rate increased in the current study when over travel increased, but it decreased when make point travel increased (see Figure 5). This may be because increased over travel may provide additional proprioceptive feedback.

Proprioception should be enhanced with increased over travel because it increases finger articular motion when striking the key. Greater finger joint displacement and tendon travel might enrich stimulation of joint capsule receptors and muscle spindles. Consequently, finger force may be better controlled when sufficient over travel is provided because force feedback is coupled with key displacement, which is proportional to the key force applied. When a key strikes bottom, the key force can increase without additional key travel and provide less force feedback.

Although increased over travel enables the finger to decelerate before colliding with the key bottom, increasing make point travel requires the finger to displace a greater distance at a constant velocity before achieving the necessary make point travel, resulting in a smaller tapping rate. In any regard, the magnitude in key-tapping rate changes observed when make point travel was increased was only 0.1 keys/s, which would be equivalent to 1.2 words/min (assuming five characters per word). The effect on actual typing performance, however, should be investigated in the future.

The results of the current study agree with the findings of previous investigations (Armstrong et al., 1994; Rempel, Klinenberg, et al., 1994). Rempel, Klinenberg, et al. (1994) observed no difference in applied finger force when typing on keyboards with 0.28 and 0.56 N make point forces. Mean applied finger force was 0.85 and 0.86 N, respectively. A notable increase in applied finger force (1.2 N) was observed, however, when a keyboard with a 0.83 N make point force was used. The better control and isolation of key switch parameters in the current study may have provided more resolution with regard to the make point force effect, based on the significant difference in

peak force observed between 0.31 and 0.51 N make point force.

All make point forces included in this study conformed with the ANSI/HFS 100-1988 standard (HFES, 1988), although they included only the lower half of the recommended range. The smallest peak force exertions in the current study occurred when total travel was 7 mm, which exceeds the ANSI recommendations for overall key travel. It may be possible to reduce the overall travel by designing a nonlinear spring that has a greater spring constant for 1 mm make travel and then decreases stiffness after make force is achieved in order to decrease resistance while increasing over travel. This will be the subject of a future study.

Similar to the findings in the current study, Loricchio (1992) reported that input speed was faster when keyboard activation force was 0.58 N than when activation force was 0.74 N for keys having the same key travel. Typists preferred the lower-force keyboard. Although the average key rate was 4.538 keys/s for a 0.58 N keyboard and 4.192 keys/s for a 0.74 N keyboard, the average numbers of words mistyped were not different. Although no difference in typing speed was observed between low-force (0.36 and 0.43 N) and high-force (0.71 N) keyboards, Akagi (1992) found that the two low-force keyboards produced 23% more errors than did the high-resistance keyboards. Maximum keying rates have also been reported when both key activation force and key displacement are small (Rose, 1991).

The results of the current study provide important information about force and displacement parameters for designing keyboards that minimize exertions. We anticipate that reducing overshoot force can ultimately lead to reduced stress from repetitive keyboard use. Stronger exertions may be associated with upper limb disorder symptoms (Feuerstein et al., 1994).

Jeng, Radwin, and Rodriguez (1994) observed a similar outcome for repetitive pinching in carpal tunnel syndrome. When rapidly pinching a strain gauge dynamometer, participants exerted an average of 0.52 N more than the required force, which was set between 5% and 50% of the

participant's maximum strength. Participants diagnosed with carpal tunnel syndrome exerted 82% more overshoot force during rapid pinch and release than did control participants free of carpal tunnel syndrome. Because carpal tunnel syndrome often impairs sensory nerves, these results provide evidence supporting the role of sensory feedback in force control. It is not yet known, however, whether increased key force exerted is a symptom or a causation factor.

Although investigators agree that peak applied force is reduced when make force is reduced, there are additional constraints on this design objective. The minimum force necessary to activate a key is limited by the force necessary to prevent accidental activation. In order to prevent the fingers from accidentally activating keys, operators would encounter increased forearm extensor static muscle contraction if the activation force were set too light. Rose (1991) measured participants' effective finger force when resting against a keyboard and concluded that in order to avoid accidental key activation (which may result in static postures in which the fingers are withdrawn from the keys and extensor muscle contraction is increased), at least 0.5 N of key activation force is needed. Increasing key over travel provides an alternative to reducing make force.

Although the key apparatus in this study was designed to have characteristics corresponding to keyboards, the linear spring mechanism was a convenient approximation; most keyboards today contain nonlinear elastomer collapsible dome spring elements. Brunner and Richardson (1984) reported fewer errors and faster typing for both skilled and occasional typists on keyboards equipped with elastomer key mechanisms. Akagi (1992), however, found little difference in typing performance and preference among touch typists using linear spring keys without tactile feedback and keys that provided snap-action tactile feedback. Domes develop a rapid breakaway after a critical force (and corresponding displacement) is exceeded, causing them to collapse and produce their characteristic click.

In addition to providing kinesthetic feedback from depressing the key, the apparatus used in

the current investigation provided visual and auditory feedback but no tactile snap. An investigation similar to the current study is needed to replicate these findings using a key mechanism that provides tactile feedback.

This study, however, does reveal that key switch parameters can have a remarkable effect on key-tapping performance and exertions. Because the current study used only a single key to investigate some design factors, it may not truly represent typing, considering that the biomechanics of the fingers are different when working in isolation compared with when they work in concert with the other fingers. A full-scale keyboard with the design features in the current study could be developed for follow-up in order to study actual keying behavior. Furthermore, the long-term effects of typing with keys containing different characteristics should be considered.

CONCLUSIONS

This study demonstrated that applied force during repetitive key tapping can be controlled by reducing make point force or increasing over travel. This finding is significant because it offers an alternative design objective to reduce make point force. Make point force reduction could be undesirable if it results in increased accidental key activation, and it could require additional muscular effort from antagonists in order to prevent unintentional key activation when resting the fingers. Alternatively, excessive over travel may not be practical for compact keyboards, such as laptop computers. Hence a suitable trade-off between these two design factors should be considered.

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