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Computer key switch force-displacement characteristics and short-term effects on localized fatigue

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This study investigates the effects of key switch design parameters on short-term localized muscle fatigue in the forearm and hand. An experimental apparatus was utilized for simulating and controlling key switch make force and travel using leaf spring mechanisms, and provided direct measurement of applied key strike force using strain gauge load cells. Repetitive key tapping was performed as fast as possible using the dominant index finger for 500 s per condition (8.3 min) and a work-rest schedule consisting of 15 s of key tapping alternating with 10 s of rest. One combination of two make force levels (0.31 and 0.71 N) and two over travel distances (0.5 and 4.5 mm) was presented randomly on four different days. Nine subjects participated. Localized muscle fatigue in the hand and forearm was assessed subjectively using a 10 cm visual analogue scale, and objectively using surface electromyography (EMG). Average peak key strike force exerted was 0.35 N less for the smaller make force and 0.59 N less for the longer over travel distance. Fatigue occurred in all cases but no significant differences were observed between key switch parameters based on RMS EMG. Subjective reports of localized fatigue after 500 s were less when the key switch make force was less; however, a corresponding over travel effect was not observed despite the greatly reduced key strike force for the longer over travel distance. This discrepancy may be explained by the greater finger movement that was observed with increased over travel. Although there was no apparent improvement in short-term discomfort from fatigue when over travel was increased, this study did not consider the potential long-term health benefits from reduced key strike force.

1. Introduction

Key switch force and travel are design factors recognized as important for the prevention of localized muscle fatigue and musculoskeletal disorders in intensive keying tasks (Rose 1991, Armstrong *et al.* 1994, Feuerstein *et al.* 1994, Rempel *et al.* 1994, Smutz *et al.* 1994, Gerard *et al.* 1996). Relevant key switch design parameters include make force and travel. *Make force* is the minimum force needed to activate the key switch. *Make travel* is the displacement of the key associated with the make force, and *over travel* is the maximum distance that the key switch can displace beyond the make point.

Previous investigations have found that key strike force is directly related to key switch make force (Armstrong *et al.* 1994, Feuerstein *et al.* 1994, Rempel *et al.* 1994,

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Gerard *et al.* 1996). Pascarelli and Kella (1993) observed injured keyboard operators and noted that 26% hit the keys with particular vigour and rapidly pressed the keys to the end-points. These keyboard operators were termed 'clackers'. Pascarelli and Kella (1993) argued that since computer keyboards have a sudden and definite end-point, they are capable of producing injury by striking the keys hard to their travel limits.

A recent study by Radwin and Jeng (1997) of a repetitive key tapping task observed that peak key strike force decreased by 15% when the make force was reduced from 0.71 to 0.31 N, and that the peak key strike force decreased by 24% when the key switch over travel distance was increased from 0.0 to 3.0 mm. Although the experiment did not directly study typing, the results suggest that key switch design parameters could have a dramatic effect on keying exertions. The implications of this magnitude of force reduction on short-term effects such as hand and forearm discomfort and localized muscle fatigue, or long-term effects such as upper extremity musculoskeletal disorders in keyboard use are not yet understood. The goal of the current study was to investigate the short-term effects of key switch design on localized fatigue and discomfort using a highly-controlled repetitive key tapping task. This experiment considers key switch make force and over travel distance and their relationship to finger exertions, keying rate and indices of localized muscle fatigue.

Fatigue in frequent and sustained keyboard usage has long been recognized (Lundervold 1958, Komoike and Horiguchi, 1971, Fergusson and Duncan 1974). Gerard *et al.* (1996) studied typists using two keyboards that were identical except for the make force which was 0.28 N or 0.83 N. More fatigue was observed on the 0.83 N keyboard during 2 h of continuous typing, but the trends were not consistent.

The psychophysical approach has been used extensively for studying subjective discomfort in fatigue associated with physical design factors in manual tasks. Snook pioneered this method and has utilized psychophysics for investigating the relative effects of posture, repetition and force in manual materials handling as well as upper limb repetitive motion tasks (Snook 1985, Snook *et al.* 1995). Discomfort from localized muscle fatigue may be quantified using psychophysical scales through cross-modality matching of perceived discomfort on a visual analogue scale (Corlett and Bishop 1976). The method has been applied to physical stress factors including repetition and posture (Krawczyk *et al.* 1992, Ulin *et al.* 1993a), force and posture (Ulin *et al.* 1993b), and force, posture and repetition (Lin *et al.* 1997). The current study uses a similar approach for understanding the relationship between key switch parameters and short-term discomfort in repetitive key tapping.

Localized muscle fatigue may also be measured objectively from the recruitment pattern of fatigued muscle fibres. Electromyography (EMG) can be used for quantifying localized muscle fatigue by observing increased RMS amplitude in the EMG for a controlled static exertion (DeVries 1968) or from frequency shifts in EMG spectral characteristics (Chaffin 1973). The current study measures localized muscle fatigue by comparing EMG RMS amplitude for constant index finger exertion in the same posture used for key tapping before and after the task.

2. Methods

Subjects repetitively tapped a simulated key switch instrumented to directly measure key strike force using strain gauge load cells. The apparatus contained a single key that controlled the key switch force-displacement characteristics using varied width leaf springs. Miniature strain gauge load cells directly measured key strike force exerted against the key cap. A detailed description of the experimental apparatus and hand posture used in this may be found in Radwin and Jeng (1997).

A Daytronic™ (Miamisburg, OH) model 9878A strain gauge conditioner provided the load cell excitation and amplification. The output was low-pass filtered with a cut-off frequency set to 200 Hz. An i386 microcomputer and a MetraByte™ (Cleveland, OH) model DASH-16 12-bit data acquisition board digitized and sampled the force signal at a 400 Hz sample rate. A representative sample of key strike force in repetitive key tapping is shown in figure 1.

Key activation was controlled through software. A successful key stroke occurred when exerted force exceeded a specific make force. Key travel and associated force were dependent on the particular spring constant used. When make force was achieved the computer generated auditory feedback using a clicking sound and visual feedback by displaying a character on a monitor viewed by the subject in order to simulate tapping on a computer keyboard. The software was programmed so that there was practically no delay (< 1 ms) between the make force event and the initiation of auditory and visual feedback. Successive key strokes could not occur until the key was released below a specific break force. Break force was fixed at 80% of the make force.

EMG signals were measured superficially over the extensor digitorum and the flexor digitorum muscles prior to the experiment and immediately following the tapping task. The percentage increase of average EMG RMS amplitude was used to indicate the magnitude of localized muscle fatigue for each muscle group. The EMG signals were amplified using a differential instrumentation amplifier and transformed

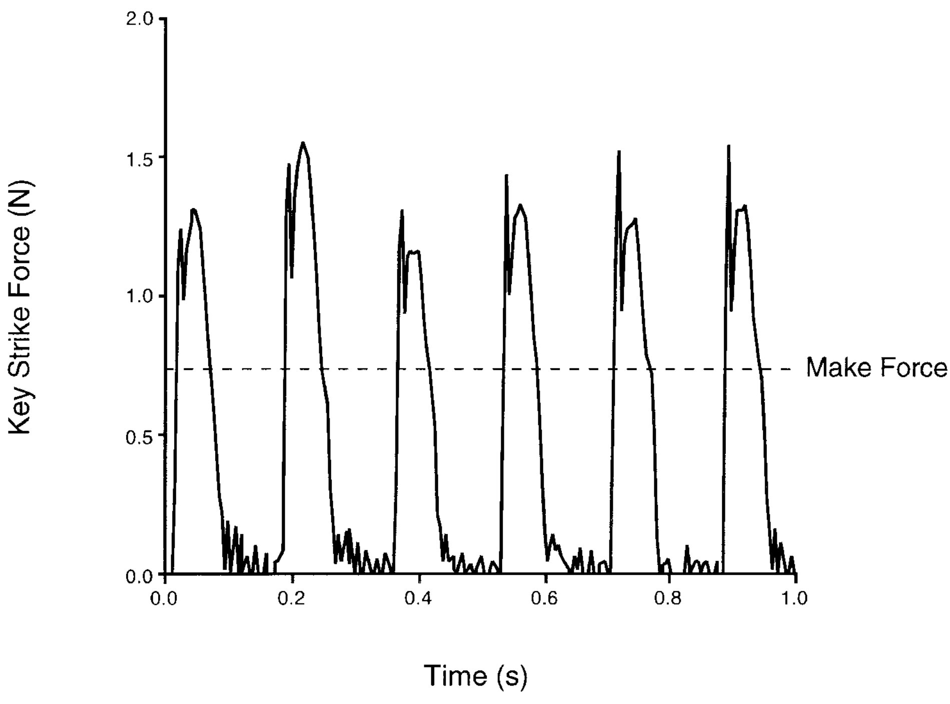

Figure 1. Representative key strike force record.

into an RMS signal using an Analog Devices (Norwood, MA) AD536 integrated circuit which uses exponential filtering to calculate real-time RMS with a 24 ms accumulation time constant for reaching 90% of the peak value. The RMS signal was digitized using a 12-bit analogue-digital converter and sampled at a 400 Hz sample rate. Disposable Ag-AgCl electrodes (ConMed^{TM}, Utica, NY, model 1620-003) were used to record the EMG signal from the anterior and posterior forearm. The specific placement of the electrodes was determined by palpation. Two active electrodes were used in a bipolar fashion along the long axis of the respective muscle groups. The distance between the active electrodes was approximately 25 mm. A ground electrode was placed on the side of the Olecranon process. EMG data was recorded after it was observed to be stable for several repetitions of pushing on the instrumented beam before the experimental period. The electrodes remained in place during the entire experiment.

EMG signals were recorded while subjects performed a static finger exertion of 50% maximum voluntary contraction (MVC) against a strain gauge dynamometer (Radwin *et al.* 1991) located and oriented adjacent to the key switch so the subject could assume the same position for EMG data collection as for the tapping task. This was done so that EMGs were recorded from the same muscles used for the tapping task. The dynamometer was angled at 6.2° with respect to the horizontal and the key top height was 73.5 cm from the floor, which were the same as for the keying apparatus. The EMG signal was recorded for a duration of 3 s.

At the beginning of each experimental session, subjects performed a MVC using the index finger in the same position used for the tapping task. They were instructed to press as hard as they could against the key in a single exertion. The maximum force exerted was taken as the MVC. An oscilloscope provided a visual indication of the finger force exerted against the dynamometer during the EMG data collection. It was calibrated so that the beam was centred on the screen when 50% MVC was achieved. EMG data was collected before performing the tapping task and immediately following the task. EMG signals were averaged over a 3-s period and compared against the pre-test average amplitude.

Perceived localized fatigue in the hands and forearm were measured on a 10 cm visual analogue scale anchored from NONE to VERY HIGH. A mark was made across the scale line by the subject in order to indicate the perceived level of localized muscle fatigue. Each subject was provided with the same definition of fatigue, which included soreness, aching, tingling and pain.

The experiment included two key make forces (0.31 and 0.71 N) and two over travel distances (0.5 and 4.5 mm) for a full-factorial experimental design (see figure 2). Since Radwin and Jeng (1997) found that make travel had no significant effect on key force applied, make travel was fixed at 2.5 mm because it was considered typical for many keyboards. All conditions were randomized within and between subjects. Every subject returned for four experimental sessions on different days at least 24 h apart. This allowed the subject sufficient time to recover from residual fatigue from the previous experimental session, but was soon enough so that the task would be still familiar and training would not be extinguished.

At the start of each session subjects were given time to practise and become comfortable with the new experimental condition. Subjects were instructed to tap the key as fast as possible. The key tapping task was then performed for 15 s followed by a 10-s rest period. The task-rest period was repeated 20 times for a total period of 500 s (8.3 min). Key strike force was continuously sampled during each 15 s key

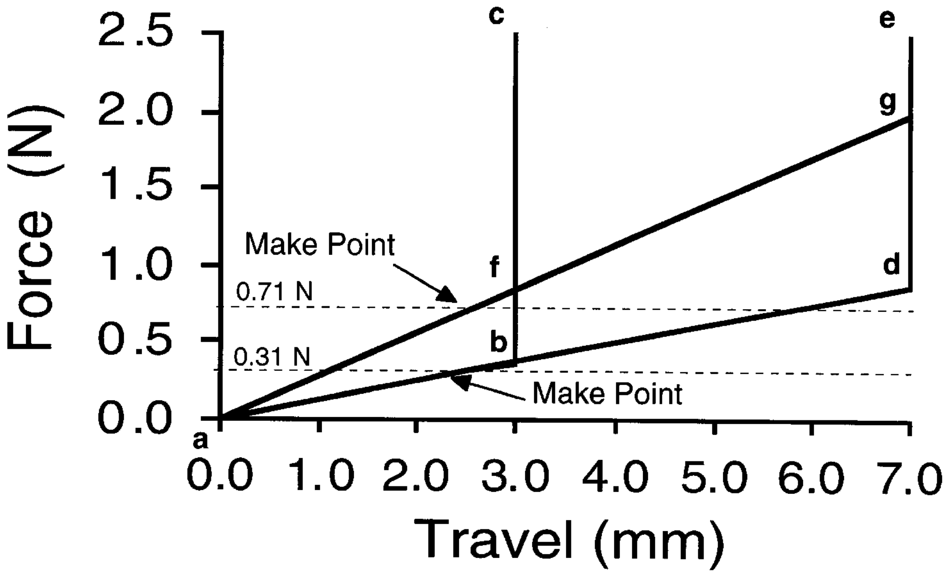

Figure 2. Force-displacement characteristics for the four experimental conditions, make point 0.31 N and 0.5 mm over travel (a-b-c), make point 0.31 N and 4.5 mm over travel (a-d-e), make point 0.71 N and 0.5 mm over travel (a-f-c), and make point 0.71 N and 4.5 mm over travel (a-g-e).

tapping period. The peak force exerted for every successful key stroke was averaged over each continuous 15 s interval of keying. Keying rate (keys/s) was based on the average time interval between peaks for every continuous 15 s keying interval.

Notices were posted at various locations on campus to recruit subjects. Each candidate completed a demographic questionnaire. Criteria for inclusion as a subject included an appropriate response to items indicating that they were free of hand conditions, disorders or injuries that could affect their typing performance in order to qualify as subjects. Nine subjects participated. The group consisted of three females and six males. The mean average age was 24.6 years (SD = 1.87 years) with a range of 22 to 27 years. All subjects provided informed consent for the study, which was approved by the University of Wisconsin-Madison human subjects review board. Subjects were paid a nominal fee for participating in the study.

3. Results

Peak exerted key strike force stabilized within 100 s and remained relatively unchanged ($F(19,152) = 1.39$, $p > 0.05$) throughout the duration of the experimental session (figure 3). Average peak key strike force increased ($F(1,8) = 8.68$, $p < 0.05$) from 0.75 N (SD = 0.50 N) to 1.10 N (SD = 0.38 N) when the key switch make point force was increased from 0.31 N to 0.71 N. Average peak key strike force decreased ($F(1.8) = 54.67$, $p < 0.01$) from 1.22 N (SD = 0.47 N) to 0.62 N (SD = 0.24 N) when the key switch over travel distance was increased from 0.5 to 4.5 mm. No significant interactions were observed. The minimum average key strike force occurred when make force was 0.31 N and over travel was 4.5 mm (table 1). The maximum average key strike was observed when make force was 0.71 N and over travel was 0.5 mm.

Average keying rate decreased ($F(1,8) = 6.11$, $p < 0.05$) slightly from 6.30 keys/s (SD = 0.75 keys/s) to 6.13 keys/s (SD = 0.77 keys/s) when the key switch make force was increased from 0.31 to 0.71 N. Although these results were *statistically* significant, there were no practical differences observed. The interaction between make force × time was also statistically significant ($F(19,152) = 1.79$, $p < 0.05$), where keying rate slightly increased after 100 s when make force was 0.31 N (figure 3). Keying rate was not significantly affected by key switch over travel ($F(1,8) = 0.03$, $p > 0.10$).

Subjective localized discomfort reported 500 s after the key tapping task began was 3.3 cm (SD = 2.1 cm) on a 10 cm scale when the make force was 0.31 N and 4.0 cm (SD = 2.0 cm) when the make force was 0.71 N ($F(1,8) = 5.87$, $p < 0.05$). However, no significant ($F(1,8) = 0.123$, $p > 0.10$) increase in subjective localized discomfort was observed when the key switch over travel was increased from 0.5 to 4.5 mm. Also no significant interaction between make force × over travel was observed ($F(1,32) = 0.04$, $p > 0.10$).

Table 1. Key strike force and resulting key travel (nine subjects).

Over travel (mm)	Make point force (N)	Mean ± SD peak key strike force (N)	Resulting key travel* (mm)
0.5	0.31	1.09 ± 0.50	2.1 – 3.0†
0.5	0.71	1.34 ± 0.39	2.5 – 3.0†
4.5	0.31	0.40 ± 0.05	2.6 – 3.9
4.5	0.71	0.85 ± 0.07	2.6 – 3.4

*5th percentile to 95th percentile key travel based on key switch displacement/force coefficient and mean peak key strike force and SD. †Maximum key travel possible when key strikes bottom.

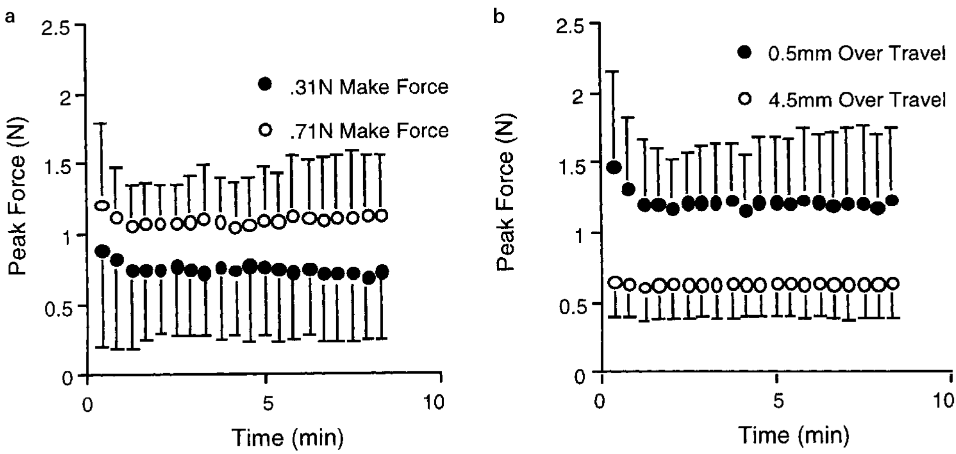

Figure 3. (a) Peak key force averaged over the two make force conditions and plotted against time (nine subjects). (b) Peak key force averaged over the two over travel conditions and plotted against time (nine subjects).

Flexor EMG RMS increased significantly from the beginning to the end of the trials for all conditions; however the differences were not significant between force and over travel conditions. Forearm flexor EMG RMS amplitude, averaged over all experimental conditions, increased by 15.9% (SD= 3.0%) from the pre-trial level to the level measured 500 s after the trial commenced (F(1.8= 29.73, $p < 0.001$). Average flexor EMG RMS amplitude increased by 18.5% (SD= 14.4%) when the key switch make force was 0.31 N, and 13.3% (SD= 16.2%) when the make force was 0.71 N; however there was no significant ($F(1.8)= 0.89$, $p > 0.05$) difference between the two make force levels. Similarly there was no significant ($F(1,8)= 1.57$, $p > 0.05$) difference in the average flexor EMG RMS amplitude with respect to over travel; when the key switch over travel was 0.5 mm there was an 18.2% (SD= 19.7%) increase in the average flexor EMG RMS amplitude, and when over travel was 4.5 mm there was a 13.6% (SD= 9.3%) increase from the pre-trial to the post-trial levels.

Extensor RMS EMG followed a similar trend as the flexor EMG. The average forearm extensor EMG RMS amplitude, averaged over all experimental conditions, increased by 32.8% (SDS = 4.1%) from the pre-trial level to the level measured 500 s after the trial commenced ($F(1.8)= 52.95$, $p < 0.001$). No significant ($F(1.8)= 0.26$, $p > 0.1$) extensor EMG amplitude effect was observed with regards to make force where average extensor EMG RMS amplitude increased by 31.3% (SD= 22.0%) when the make force was 0.31 N and 34.4% (SD= 20.3%) when the make force was 0.71 N. Similar to make force, there was no significant ($F(1.8)= 0.16$, $p > 0.1$) difference in average extensor EMG amplitude where average forearm extensor EMG RMS amplitude increased by 34% (SD= 20.3%) when over travel was 0.5 mm and 31.7% (SD= 22.0%) when over travel was 4.5 mm.

4. Discussion

This study observed a similar relationship between key strike force and key switch parameters as previously observed by Radwin and Jeng (1997). In the current study, key strike force decreased by 32% when the key switch make force was reduced from 0.71 to 0.31 N, which was a greater force reduction than previously observed. Similarly, key strike force decreased by 49% when the key switch over travel was increased from 0.5 to 4.5 mm. Since the minimum over travel in the current study was 0.5 mm greater, and the maximum over travel was 1.5 mm greater than the over travel used in Radwin and Jeng (1997), it could explain the larger main effect for make force and over travel even though the make force levels were the same as the previous study.

Although subjective localized fatigue increased when the key switch make force was greater, no corresponding fatigue effect was observed when the key switch over travel distance was reduced. This may seem surprising since the effect on average key strike force was even greater for over travel than it was for make force (figure 3). The discrepancy can be explained by considering not just the exerted force, but also the motion associated with each of the key switch parameters. Since the experimental apparatus leaf spring was a linear elastic device, key travel was directly proportional to key strike force within the static limits of deflection. Hence it was possible to estimate the amount of key travel associated with the key strike force observed for each experimental condition based on the elastic modulus of the key. Key strike forces greater than the static limits of deflection correspond to when the key strikes bottom, which was the controlled over travel in this experiment (figure 2). Based on the distribution of key strike forces measured, the 5th percentile to 95th percentile key displacement was computed for each experimental condition and is presented in table 1.

The greatest key strike forces occurred when the over travel distance was small. In addition when over travel was small, the key stroke distance was frequently (85% for the low make force and 78% for the high make force) the maximum displacement possible (3.0 mm) causing the key to strike bottom (table 1). Therefore when over travel was small, key strike force was high but finger motion was limited by the maximum displacement of the key. Conversely when over travel was large, key strike force was small but finger motion was considerably greater than for the small over travel condition. Since localized fatigue is a function of force and motion, the effect of reduced key strike force for greater over travel may possibly have been cancelled out by the associated increased finger movement. This was particularly the case for the condition where make force was small and over travel was large. Decreasing force with increasing over travel suggests ballistic movement. Consequently, fatigue may not have been affected by over travel.

The experimental task required subjects to repetitively tap a key using just one finger as fast as possible. This had the effect of accelerating fatigue onset in a laboratory experiment in order to compare key design parameters. Consequently the finger motion and repetition associated with actual typing were not considered in the current study and a corresponding effect should be investigated for typing. Since EMG signals were recorded superficially using surface electrodes it is possible that the muscles involved in the static reference exertions were different muscles than the ones actually used for the keying task. This may help to explain why, although subjective localized discomfort decreased when make force decreased, no corresponding EMG effect was observed.

A practical way of reducing total finger travel while maintaining sufficient over travel is to minimize key switch make travel displacement. Radwin and Jeng (1997) did not observe any significant increase in key strike force for 1.0, 2.5 or 4.0 mm key switch make travel distances. Furthermore, the keying rate increased when make travel was small, so less make travel displacement should not have an adverse effect on keying performance. Therefore the make point travel distance may be minimized in order to reduce finger movement and still maintain a considerable over travel distance.

The larger over travel distance in this experiment was 4.5 mm. That much over travel should not be necessary in practice since the key did not displace more than 4.0 mm 95% of the time (table 1). Since make travel was 2.5 mm, an over travel distance of 1.5 mm (2.5 mm make travel+ 1.5 mm over travel = 4.0 mm) should result in the same finger strike force for key switches with similar make forces. A reduced make travel of 1 mm and an over travel of 1.5 mm could limit the maximum finger movement to just 2.5 mm and may result in less fatigue. This needs to be tested experimentally.

Localized discomfort in repetitive motion tasks is dependent on force, movement and repetition frequency (Lin *et al.* 1997). Rose (1991) concluded that increased keying rates will accelerate the onset of muscle fatigue and that this incresae could be a sufficient cause for muscle overuse. In the current experiment the subjects were instructed to tap as fast as possible. The actual key tapping rate observed was slightly greater when the key switch make force was small, which is consistent with the findings of Radwin and Jeng (1997). They also observed a slight increase in key tapping rate when over travel distance was increased. A similar increase was not observed in the current study. Consequently there was no appreciable repetition frequency effect confounding the fatigue effect for the different key switch parameters.

Although EMG revealed fatigue after 500 s through increased RMS amplitudes, no significant differences in EMG were observed between key switch parameters. Gerard *et al.* (1996) observed increased fatigue for the greater make force keyboard for individual subjects but the trends did not hold for all subjects. They concluded that EMG may not be sufficiently sensitive to indicate fatigue for low force/high repetition work.

Morelli *et al.* (1995) had typists use various keyboards for a period of time and then respond to a psychophysical questionnaire. Their results for actual typing showed that there were indeed significant differences in fatigue ratings for 'tiredness from keying'. Although the repetition rate was high in the current study, the duration of the test was relatively short. Therefore it is necessary to consider a keyboard in an actual typing task in order to truly understand short-term fatigue effects of key make force and over travel. Future research should develop working prototype keyboards that have improved over travel and make force characteristics as recommended by Radwin and Jeng (1997) so key force and fatigue effects can be measured during actual typing tasks over the course of an actual work period.

A plot of peak force versus time (figure 3) shows that a certain amount of adaptation occurred during the first 100 s when over travel was 0.5 mm, but this effect was not observed when over travel was 4.5 mm. Feedback from pounding the keys against the key bottom when over travel was 0.5 mm may have been responsible for this effect. Although auditory and visual feedback was provided, the experimental apparatus did not provide any tactile snap characteristic of most keyboards. The role of tactile feedback should be explored.

Taylor and Berman (1982) conducted an experiment using momentary contact keys where resistance was adjusted independently of displacement for make travel distances ranging between 2 and 10 mm and make forces ranging between 1 to 15 N. Subjects performed a paced keying task for different experimental conditions varying make travel, make force, use of gloves and number of fingers. Increased make force and longer make travel were associated with prolonged response time and reduced errors. Gloves had no effect on response time and errors even though they presumably reduced tactile feedback and restricted motion, although the authors admit that the keying rates they used were relatively slow compared with skilled typists in continuous data entry. Since gloves are known to impair manual dexterity and tactility, their findings suggest that the key parameters have a more dramatic effect on keying performance than gloves.

Although the current study examined the short-term effects of localized fatigue and discomfort, long-term health effects from exerting less key strike force were not addressed. Pascarelli and Kella (1993) studied injured keyboard operators and categorized keyboard operators who strike the keys vigorously as 'clackers'. A total of 71% of the 'clackers' had evidence of extensor and flexor forearm pain, 36% had DeQuervains disease, and 21% had carpal tunnel syndrome (CTS). Based on these observations, Pascarelli and Kella suggested better cushioning is needed of the end-point in computer keyboards. Increased over travel has the effect of cushioning the key end-point as the authors recommended.

Jeng *et al.* (1994) reported that when rapidly pinching and releasing a strain gauge dynamometer, CTS patients exerted 82% more force than control subjects free of CTS. It is not yet known if this behaviour is causative or a symptom resulting from impaired sensory feedback in CTS. Most researchers agree, however, that a reduction in force and repetitive motion should reduce the risk of a musculoskeletal disorder and prevent localized fatigue and discomfort.

The current study revealed statistically significantly less discomfort when make force was reduced. Only inferences can be drawn as to the practical significance of the magnitude of the reduction in discomfort observed in this laboratory-controlled study since the task in this experiment was not actual typing. This observed trend implies that measurably less discomfort results when the make force is reduced within practical levels. Furthermore, when key strike force was reduced by increasing key over travel, a corresponding reduction in subjective discomfort was not observed. This discrepancy may be explained by the greater finger movement that was observed with increased over travel. Future studies will involve actual typing tasks in order to reveal the practical limits of these findings.

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