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Differences in typing forces, muscle activity, wrist posture, typing performance, and self-reported comfort among conventional and ultra-low travel keyboards

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ABSTRACT

This study investigated the relative impact of ultra-low travel keyboards on typing force, muscle activity, wrist posture, typing performance, and self-reported comfort/preference as compared to a conventional keyboard. In a repeated-measures laboratory-based study, 20 subjects were invited to type for 10 min on each of five keyboards with different travel distances of 0.5, 0.7, 1.2, 1.6 (ultra-low travel keyboards), and 2.0 mm (a conventional keyboard). During the typing sessions, we measured typing force; muscle activity in extrinsic finger muscles (flexor digitorum superficialis and extensor digitorum communis), shoulder (trapezius) and neck (splenius capitis); wrist posture; typing performance; and self-reported comfort/preference. While using the ultra-low travel keyboards, subjects typed with less force and wrist extension, and had more ulnar deviation (p's < 0.0001) compared with conventional keyboard. However, these differences in typing forces were less than 0.5 N and less than 4° for both wrist extension and ulnar deviation. The general trend of data did not show any consistent or substantial differences in muscle activity (less than 2 %MVC) and typing performance (< 5 WPM in speed; < 3% in accuracy), despite the observed statistical difference in the finger flexors and extensors muscle activity (p's < 0.19) and typing performance ($p < 0.0001$). However, the subjects preferred using conventional keyboards in most of the investigated self-reported comfort and preference criteria (p's < 0.4). In conclusion, these small differences indicate that using ultra-low travel keyboards may not have substantial differences in biomechanical exposures and typing performance compared to conventional keyboard; however, the subjective responses indicated that the ultra-low keyboards with the shortest key travel tended to be the least preferred.

1. Introduction

Although the degree of association varies by studies, many previous studies have shown an association between computer keyboard use and upper extremity musculoskeletal disorders (MSDs) (Andersen et al., 2011; Bergqvist et al., 1995; Garza et al., 2012; Gerr et al., 2002). Among the possible risk factors, highly repetitive movements and awkward postures during computer keyboard typing are known to be risk factors for computer-related MSDs (Jensen et al., 2002; Joe Chang et al., 2009). Accumulation of micro trauma over long duration of time is known to be a underlying injury mechanism for computer-related MSDs in the upper extremities (IJmker et al., 2007; Jensen et al., 2002; Punnett and Wegman, 2004).

The physical characteristics of computer keyboards have found to affect biomechanical risks for musculoskeletal symptoms (Armstrong et al., 1994; Garza et al., 2012; Gerard et al., 1999; Kim et al., 2014; Lee et al., 2009; Radwin and Ruffalo, 1999; Rempel et al., 1997a, 1997b; Rempel et al., 1999). These studies have shown that key travel distance (Kim et al., 2014; Lee et al., 2009) and activation force (Armstrong et al., 1994; Gerard et al., 1999; Lee et al., 2009; Radwin and Ruffalo, 1999; Robert G. Radwin and Jeng, 1997) affect muscle activity, muscle fatigue and discomfort in the upper extremities.

As computer keyboards are gravitating towards thinner designs to increase portability and have a more visually appealing design, the key travel distances have substantially decreased from 4.0 mm (conventional detachable desktop keyboards) to less than 2.0 mm (ultra-low travel keyboards) (Sisley et al., 2017). Although changes in key travel distance can alter force-displacement characteristics that affect biomechanical risk factors and usability, there has been little research to investigate the effects of such ultra-low key travel distances on the

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biomechanical exposure measures and usability. Previous studies on the key travel distance were mainly on traditional keyboards with longer (≥2.5 mm) key travel distances (Lee et al., 2009; Radwin and Ruffalo, 1999). These studies showed that longer key travel was associated with decreased typing force (Lee et al., 2009; Radwin and Ruffalo, 1999). A few recent studies with current, shorter travel keyboards (~2.0 mm) showed that typing forces decreased as key travel decreased (Hughes et al., 2011; Hughes and Johnson, 2014; Kim et al., 2014). Hoyle et al. (2013) found that key travel distance was negatively correlated with typing performance, discomfort, and preference.

Due to the recent introduction of the ultra-low travel keyboards as part of laptop and tablet computers, and with designs gravitating towards thinner keyboards, there is relatively little research on the user comfort, usability, and typing performance associated with these ultra-low travel keyboards. Therefore, existing literature is not sufficient to determine MSD-related physical risks associated with ultra-low travel keyboards. To address this current research gaps, the goal of this study was to evaluate relative biomechanical exposures including typing forces, muscle activity on extrinsic finger muscles, shoulder and neck muscles, wrist postures, typing performance, self-reported comfort and preference between a conventional keyboard and a series of ultra-low travel keyboards.

2. Methods

2.1. Subjects

A total of 20 subjects (10 male and 10 female) were recruited to participate in this study via e-mail solicitations and printed flyers. The sex of the subjects was balanced to properly represent the general population. All subjects were touch typists who could type faster than 40 WPM and had no history of upper extremity musculoskeletal disorders. Eighteen subjects were right-handed and two subjects were left-handed. Their average (SD) age and computer experience was 29.5 (7.5) and 17.8 (6.1) years, respectively. The experimental protocol was approved by the University's Institutional Review Board and all subjects gave their written consent prior to their participation in the study.

2.2. Experimental protocol

Prior to the experiment, the chair and desk were adjusted based on anthropomorphic measures per ANSI/HFES standards (2007). Briefly, the chair was adjusted so that the subject's thighs were parallel to the ground and the cushion was adjusted such that the subject could fit two fingers between the end of the seat pan and their calf (Fig. 1). The keyboards were placed 7 cm from the edge of the work place and at the center of subjects' bodies. The workstation height was adjusted at 2 cm below sitting elbow height. Then, subjects had a practice session typing on a neutral, non-study keyboard to become familiar with the typing program interface used throughout the experiment (Mavis Beacon Teaches Typing Platinum – 25th Anniversary Edition; Broderbund Software Inc.; Eugene, OR, USA). To control the difficulty of the text, five chapters from Grimm's Fairy Tale stories were randomly selected for the typing tasks. These stories were rated as a 5.1–5.7 on the Flesch-Kincaid grade, which indicates that the text would be easily understood by an average twelve year old.

After the practice session, in a repeated-measures laboratory experiment, subjects typed for 10 min on each of the five keyboards that have relatively similar key activation force (0.5–0.6 N), key size (height x width = 15 × 15 mm), and key pitch (19 mm), with different key travel distance (Fig. 2). These keyboards included a conventional keyboard with a 2.0 mm travel distance (A1234; Apple; Cupertino, CA) and four ultra-low travel keyboards with key travel distances of 1.6 mm or less: 0.5 mm (MacBook; Apple; Cupertino, CA); 0.7 mm (Thin Touch; Synaptics; San Jose, CA); and 1.2 mm (Magic Keyboard; Apple; Cupertino, CA); 1.6 mm (Surface Typecover; Microsoft; Redmond, WA).

Fig. 1. Experimental setup.

The order in which the keyboards were used was randomized and counterbalanced to minimize any potential confounding due to keyboard testing order. Throughout the typing sessions, subjects were instructed to type with their normal typing speed and achieve a balance between accuracy and speed. Typing speed (words per minute) and accuracy (% key correctly typed) were measured by the typing program. Between typing sessions, a 5-min break was given to minimize residual fatigue effects of the previous keyboard testing condition. After typing on each keyboard, subjective comfort and preference ratings were collected using a slightly modified Likert scale questionnaire adapted from the ISO keyboard comfort questionnaire (ISO9241-410; 2008).

2.3. Typing forces

Typing force were measured at a sampling rate of 500 Hz using a triaxial force platform that has been validated and used in previous studies (Kim et al., 2014; Kim and Johnson, 2012). The absolute mean force measurement errors over a 0–4 N range is less than 10% over the full area of the force platform (Kim and Johnson, 2012). The keyboards were located on the force plate so that the "H" key was positioned on the center of the force place. A polyoxymethylene frame was constructed surrounding the force plate at the same height to create a continuous work surface for the subjects. Subjects were instructed not to rest their hands and wrists on the force plate or keyboards to minimize potential for unwanted, static forces to be superimposed on the typing force data. The presiding experimenter observed the hand posture of the subjects through the experiments to minimize the potential for the superimposition of the unwanted static typing forces.

Prior to each typing session, the force plate was zeroed to offset the weight of the keyboard being tested. Perpendicular, downward, z-axis typing forces applied to the alphanumeric portion of the keyboard were investigated. A custom-built typing force program (LabVIEW, 2016b; National Instruments; Austin, TX, USA) identified and categorized the individual force profiles associated with each keystrokes by simultaneously saving the keyboards digital signals, which were unique to each key, parallel with the force data. Typically, the digital signal started when the forces applied to the keys were above 0.4N and ended when the forces descended below 0.4 N. In addition, to be considered as an individual keystroke, the force profile had to be between 16 and 250 ms long and the peak force had to occur in first half of force profile (Rempel et al., 1997a, 1997b). Typing force data was summarized using median and peak forces.

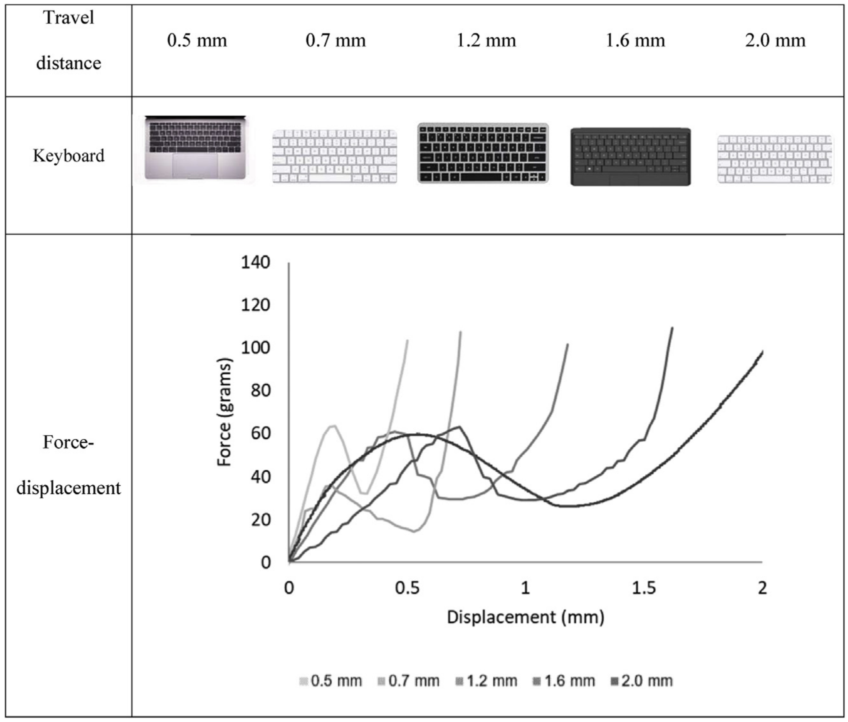

Fig. 2. Five tested keyboards with different key travel distance levels and representative examples of force-displacement profiles of the five tested keyboards.

2.4. Muscle activity

The muscle activities of Extensor Digitorum Communis (EDC), Flexor Digitorum Superficialis (FDS), Trapezius (TRAP), and Splenius Capitis (SPL) on the right side of subjects were measured by surface electromyography (EMG). The ECD and FDS muscle identification was done according to the previous studies (Basmajian and De Luca, 1985; Perotto and Delagi, 1994). Because previous studies with similar experiment settings showed no significance differences in muscle activities between dominant and non-dominant sides in these muscle groups, muscle activity was unilaterally collected (Garza et al., 2012; Kim and Johnson, 2012). Briefly, the EDC was located by having the participants move their fingers and identifying the muscle by palpating the dorsal side of the forearm, one-third of the forearm's length distally from the lateral epicondyle. The FDS was located by touching the muscle on the palmar side and then palpating one-third the length of the forearm distal to the medial epicondyle. Ground electrodes were then placed on the lateral and medial epicondyles, respectively. Electrodes for the TRAP muscle were placed 2 cm lateral to the halfway point between the C7 vertebral process and the right acromion process; the ground electrode was then placed on the C7 vertebral process (Jensen et al., 1993).

Prior to attaching electrodes, the electrode sites were shaved and cleaned using razors (Medline; Mundelein, IL, USA) and alcohol pads (Dynarex; Orangeburg, NY, USA) to reduce skin impedance. Then, disposable Ag/AgCl surface electrodes with an 8-mm diameter pick up area (Blue Sensor N-00-S; Ambu; Ballerup, Denmark) were placed with a 20-mm inter-electrode spacing over the three muscles. Then, skin impendence was measured and considered acceptable when the impedance was less than 10 kΩ. Muscle activity was recorded using a digital data logger (Mega ME6000; Mega Electronics; Kuopio, Finland) at a sample rate of 1000 Hz.

The raw EMG data were processed with a band pass filter of 10–350 Hz. The filtered EMG data from the EDC, FDS, and TRAP muscles were normalized relative to Maximum Voluntary Contractions (%MVC). In order to measure MVCs, at the end of the experimental session, subjects were instructed to extend their fingers up against isometric resistance (EDC) and flex their fingers down against isometric resistance (FDS) (Kim et al., 2014). To measure TRAP MVCs, subjects were instructed to shrug their shoulders against isometric resistance with their arms at their sides and avoiding bending or twisting at the hips/waist (Harms-Ringdahl et al., 1996; Kim et al., 2014; Schuldt and Harms-Ringdahl, 1988). The MVCs from SPL were collected during the maximal neck extension (Almosnino et al., 2009). Each contraction was administered for three seconds with verbal encouragement and MVC measurement for each muscle was repeated for three times with two-minute break between the trials. Of the three collected MVC data, the maximum RMS signal over a period of 1 s was identified and used to normalize the data. Normalized EMG data were summarized with amplitude probability density function: 10th (representing static muscle activity), 50th (representing median muscle activity), and 90th (representing peak muscle activity) percentile (Jonsson, 1982).

2.5. Wrist posture

To measure wrist flexion/extension and radial/ulnar deviation, a biaxial electrogoniometer (Model SG-75; Biometrics Ltd; Newport, UK) was attached on the right hand in according to the methods prescribed by Johnson (Johnson et al., 2002; P. Jonsson and Johnson, 2001). The raw goniometer data were synchronously collected with the EMG signals at 1000 Hz using the aforementioned data logger (Mega ME6000; Mega Electronics; Kuopio, Finland). After data collection, the raw goniometer data were parsed and down-sampled to 20 Hz (Kim et al., 2014). The 5th, 50th, and 95th percentile values were then calculated for the flexion/extension and radial/ulnar deviation planes (Blackstone et al., 2008). The 5th and 95th percentiles represented the extreme wrist postures while the 50th percentile represented the central tendency of the wrist posture.

2.6. Self-reported comfort and preference

After each typing session, self-reported comfort, preference, usability, and productivity were measured using a modified 7-point Likert scale questionnaire adapted from the ISO keyboard comfort questionnaire (ISO 9241–410; 2008) with 1 being least comfortable and 7 being most comfortable. Verbal anchors were used at both ends of each scale.

2.7. Data analysis

The Normality of the outcome variables was formally examined by goodness-of-fit tests in JMP 12 (Version 12.0.1; SAS Institute Inc., Cary, SC, USA). For normally distributed data, parametric statistical methods (mixed linear model in JMP 12) were used; otherwise for non-parametric data, either *Friedman* test or *Skillings-Mack* test (generalized *Friedman* test for data sets with missing values) was used to analyze the data in R (R 3.3.2, Development Core Team). A mixed linear model with restricted maximum likelihood estimation (REML) was used to investigate the differences in wrist flexion/extension and typing speed between the keyboards. Due to non-normality, *Friedman* test was used to determine whether there were differences between the keyboards in muscle activity (EMG), perceived fatigue, typing accuracy, and wrist radial/ulnar deviation. Due to a few missing values in the typing force data, *Skillings-Mack* test was used to compare the typing force between the keyboards. Per statistical guidelines for health science journals (Altman et al., 1983), non-normal data were summarized with median and interquartile ranges. Any statistical significance ($p < 0.05$) was followed up with post-hoc multiple comparisons with *Bonferroni* correction.

3. Results

3.1. Typing forces

The median and peak typing force were significantly different (p's < 0.0001) across the keyboards (Table 1) Despite the statistical differences in median forces between the keyboards, the differences were less than 0.1 N. The peak force applied to the 2.0 mm keyboard was higher than all the ultra-low keyboards ($p < 0.0001$). However, post-hoc multiple comparisons indicated that the differences between the conventional (2.0 mm) and two ultra-low travel (0.5 and 0.7 mm) keyboards did not reach statistical significance ($p < 0.5$).

3.2. Muscle activity

The peak (90th percentile) Extensor Digitorum Communis (EDC) muscle activity significantly differed across keyboards ($p = 0.0005$), while the differences in the static (10th percentile) and median (50th percentile) EDC muscle activity approached ($p = 0.10$ and 0.19, respectively) but did not reach significance (Table 2). The 50th and 90th percentile Flexor Digitorum Superficialis (FDS) muscle activity were significantly different across keyboards ($p = 0.0005$ and $p < 0.0001$, respectively), while the 10th percentile FDS muscle activity between the keyboards approached significance ($p = 0.11$). Despite the statistical significance, no consistent and substantial differences in finger muscle activity were found across the keyboards (less than 2% MVC); however, the trends in typing forces across keyboards somewhat mirrors the trends in the finger muscle activity. Finally, no differences in Trapezius (TRP) and Splenius Capitis (SPL) muscle activity were found across the keyboards (p's > 0.45) (Table 2).

Table 1
Comparisons of typing force median and peak (Median [25th, 75th]) across five different key travel distance levels. The values not sharing the same letters indicate significant differences at $\alpha = 0.05$ [N = 20].

	Travel distance (mm)					P-Value
	0.5	0.7	1.2	1.6	2.0	
Median Force	1.2 ^{a} [1.0,1.2]	1.1^{a} [1.0,1.2]	1.0 ^{ab} [1.0,1.1]	1.0 ^{b} [1.0,1.1]	1.1 ^{a} [1.0,1.1]	< **0.0001**
Peak Force	2.1 ^{a} [1.9,2.4]	2.0 ^{a} [1.8,2.3]	1.8 ^{bc} [1.7,1.9]	1.7 ^{b} [1.6,1.9]	2.3 ^{a} [2.1,2.4]	< **0.0001**

3.3. Wrist posture

The conventional (2.0 mm) keyboard showed greater wrist extension (9.9 ± 2.1) than ultra-low travel keyboards ($p < 0.0001$) (Fig. 3 (a)). With the exception of the 1.6 mm travel keyboard, the results showed that wrist extension decreased as the travel distance decreased. In addition, there were differences in wrist ulnar deviation, but with no real systematic differences across the keyboards (Fig. 3 (b)).

3.4. Typing performance

The average net typing speed and accuracy across all of the keyboards were 63 ± 3 WPM and with an accuracy 94.9 ± 0.5 percent. There were significant differences in the net typing speed and accuracy across the keyboards ($p < 0.0001$) (Fig. 4). Despite the statistical significance, the differences between the conventional and the ultra-low keyboards were practically small (< 5 WPM in speed; < 3% in accuracy).

3.5. Self-reported comfort and preference

The usability measures indicated that the conventional (2.0 mm) keyboard was preferred to the ultra-low travel keyboard (Table 3). As the key distance increased, the preferences increased in terms of the easiness, typing performance (speed and accuracy), tactile feedback (feel of key pressing and activation force) and adaptation. However, no differences were found in self-reported comfort in hand/wrist and neck/shoulder.

4. Discussion

This study evaluated the relative impact of using ultra-low travel keyboards (key travel distance ≤ 1.6 mm) on typing force, upper extremity muscle activity, wrist posture, typing performance, and self-reported fatigue. This impact was compared to a conventional keyboard with the travel distance of 2.0 mm. The results indicated that ultra-low travel keyboards do not appear to have any substantial effects on biomechanical exposures and usability measures, given the relatively small differences between the conventional and ultra-low keyboards. However, the subjective responses indicated that there were some preference differences within the ultra-low keyboards and that the shortest travel keyboards tended to be the least preferred. Typically, the conventional keyboard with 2.0 mm travel was most preferred but this higher preference may somewhat be due the subjects' familiarity with this keyboard.

The study results showed that there were significant differences in typing forces between the ultra-low travel keyboards and the conventional keyboard ($p < 0.0001$). The ultra-low travel keyboards had lower peak typing forces as compared to the conventional keyboard. This is consistent with previous studies on shorter travel keyboards that have shown the positive relationships between key travel distance and typing force (Kim et al., 2014). However, as these differences in median typing forces between the conventional and ultra-low travel keyboards were less than 0.1 N, a careful interpretation should be made.

There were no consistent differences in the finger extensor and flexor muscle activity across the keyboards. Although some differences were statistically significant ($p < 0.0001$), the differences between the keyboards were less than 2% MVC. Previous studies have also shown small effects of travel distance on finger extensor, flexor, and shoulder muscle (Kim et al., 2014; Lee et al., 2009; Radwin and Ruffalo, 1999). Kim et al. (2014) study showed small (1 %MVC) but statistically significant increase in finger extensor and flexor muscle activity in the keyboard with long travel distance (4.0 mm) compared to a short travel

Table 2
Comparisons of normalized muscle activity in Extensor Digitorum Communis (EDC) and Flexor Digitorum Superficialis (FDS) (a) and Trapezius (TRAP) and Splenius Capitis (SPL) (b) across five different key travel distance levels. The values not sharing the same labels indicate significant differences at (α = 0.05) [N = 20].

Muscle	Percentile	Key Travel					P-value
		0.5 mm	0.7 mm	1.2 mm	1.6 mm	2.0 mm	
EDC	10th	8.0 [6.0, 10.0]	8.0 [6.0, 10.0]	8.0 [7.0, 10.0]	7.5 [6.0, 10.0]	8.0 [6.3, 10.0]	0.10
	50th	12.0 [10.0, 17.5]	12.0 [11.0, 17.3]	12.0 [11.0, 17.3]	11.5 [10.0, 16.8]	12.5 [10.3, 17.3]	0.19
	90th	20.0 [b] [16, 27]	21.0 [ab] [16.3, 28.3]	20.0 [ab] [16.0, 27.0]	19.0 [b] [15.5, 25.5]	21.0 [a] [17.5, 27.8]	**0.0005**
FDS	10th	2.0 [1.3, 3.8]	2.0 [1.3, 3.8]	2.0 [1.0, 3.8]	2.0 [1.0, 3.0]	2.0 [1.0, 3.8]	0.11
	50th	6.0 [a] [4.0, 10.0]	6.0 [a] [4.0, 11.0]	6.0 [ab] [3.0, 10.0]	5.0 [b] [3.0, 8.0]	5.0 [ab] [4.0, 9.0]	**0.0005**
	90th	18.0 [a] [8.0, 23.0]	17.0 [a] [9.0, 24.0]	16.0 [b] [10.0, 23.0]	17.0 [b] [9.0, 23.0]	17.0 [ab] [10.0, 23.0]	< **0.0001**
TRAP	10th	6.5 [5.3, 10.5]	7.5 [6.0, 12.3]	7.5 [5.0, 12.3]	7.5 [6.0, 10.8]	7.0 [4.3, 11.0]	0.093
	50th	10.0 [8.3, 15.5]	11.0 [8.3, 16]	10.5 [8.3, 15.8]	10.5 [9.3, 17.5]	11.0 [7.3, 16.0]	0.63
	90th	14.5 [12.3, 21.0]	15.0 [12, 20.0]	14.0 [10.5, 23.0]	15.5 [12.3, 23.5]	15.5 [11.3, 20.8]	0.45
SPL	10th	11.5 [8, 24.3]	13.0 [8.0, 19.8]	13.0 [8.0, 19.0]	12.0 [8.0, 18.0]	12.0 [8.0, 20.5]	0.70
	50th	15.0 [11.5, 31.5]	16.5 [9.8, 26.8]	17.0 [10, 26.5]	17.5 [9.8, 24.3]	17.0 [11, 26]	0.69
	90th	19.0 [14.5, 40.8]	21.0 [12, 35.5]	20.5 [13, 34.0]	22.0 [13, 30.5]	23.0 [13.8, 34.0]	0.47

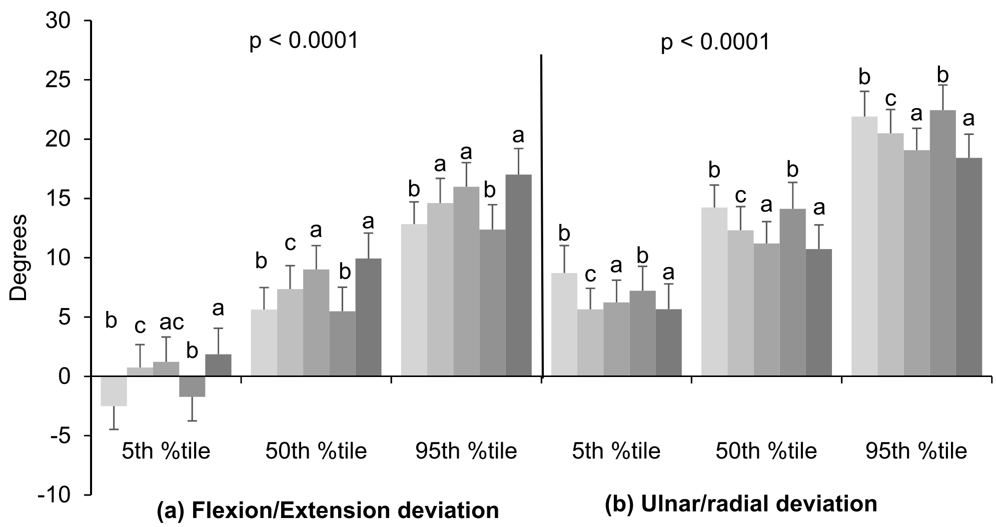

Fig. 3. Comparisons of the wrist ulnar/radial deviation and flexion/extension across five different key travel distance levels. The bars not sharing the same labels indicate significant differences at (α = 0.05) [N = 20].

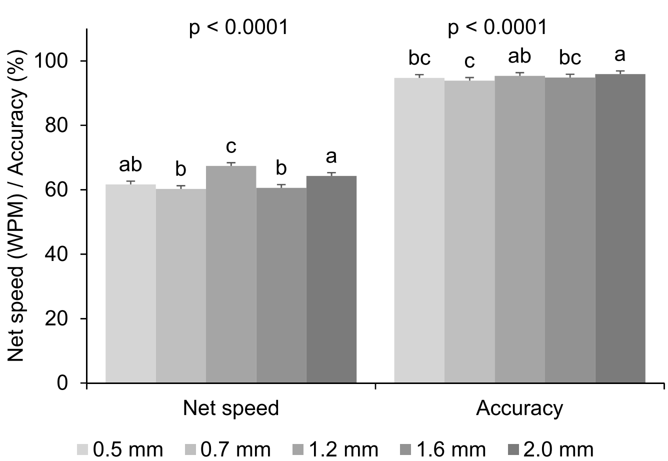

Fig. 4. Comparisons of the typing performance across five different key travel distance levels. The bars not sharing the same labels indicate significant differences at (α = 0.05) [N = 20].

keyboard (1.8 mm). These small differences in muscle activity across the ultra-low travel keyboards and the lack of difference with the conventional keyboard indicate that using ultra-low travel keyboards do not increase or change the exposures to the finger flexor and extensor muscles. On the other hand, shoulder muscle activity increased as key travel distances decreased, but these differences were not statistically significant. No consistent differences were seen in neck muscle activity. The differences in shoulder muscle activity between the keyboards were less than 1.5 %MVC. However, such small differences in muscle activity may be influential over a long period of using the keyboard due to an accumulation of the additional muscle activity (Cook et al., 1999; Pereira et al., 2013). This result indicates that ultra-low travel keyboards may slightly increase muscular loads in the shoulder region when compared to the conventional keyboards with longer travel distances.

Wrist posture data showed that less wrist extension was observed as key travel distance decreased. This inverse relationship may be because subjects had to hold up their wrists more with longer key travel keyboard (higher profile) as compared the ultra-low travel keyboards. A previous study also showed lower wrist extension while using laptops when compared to a conventional keyboard that has a longer travel distance (Rempel et al., 2007). In their study, the 50th percentile of the wrist extension ranged between 5.5° for the laptop keyboard to 9.9°for the conventional keyboard, which was lower than 15° of maximum wrist extension recommend for an hour of computer use. The 15° threshold for wrist extension was recommended in order to keep carpal

Table 3
Mean (SE) self-reported comfort and preference across five different key travel distance levels. A seven point Likert Scale was used with 1 indicating least preferable/ and 7 the most preferable. The values with different labels indicated significant difference at (α = 0.05) [N = 20].

	Travel distance (mm)					P-Value
	0.5	0.7	1.2	1.6	2.0	
Hand/Wrist comfort	4.5 (0.3)	4.2 (0.2)	4.8 (0.3)	4.4 (0.3)	4.7 (0.2)	0.40
Arm/Shoulder comfort	4.1 (0.2)	4.2 (0.2)	4.35 (0.3)	3.95 (0.3)	4.60 (0.3)	0.22
Typing accuracy	3.5 ^{bc} (0.2)	3.2 ^{b} (0.2)	4.7 ^{c} (0.3)	4.1 ^{d} (0.2)	5.1 ^{a} (0.2)	< **0.0001**
Typing speed	3.8 ^{b} (0.3)	3.7 ^{b} (0.2)	5.0 ^{a} (0.3)	4.2 ^{b} (0.2)	5.0 (0.2)	**0.002**
Ease of use	3.85 ^{b} (0.2)	3.6^{b} (0.2)	4.9 ^{c} (0.3)	4.3 ^{b} (0.3)	5.4 ^{a} (0.2)	**0.0001**
Reachable	4.3 ^{b} (0.3)	4.4 ^{ab} (0.2)	4.9 ^{ab} (0.2)	4.3 ^{b} (0.3)	5.3 ^{a} (0.3)	**0.02**
Feel of pressing keys	2.9 ^{b} (0.2)	3.3 ^{c} (0.4)	4.9 ^{a} > (0.2)	4.5 ^{d} > (0.3)	5.4 ^{a} (0.3)	**0.0001**
Activation force	3.5 ^{b} (0.3)	4.0 ^{c} (0.3)	4.9 ^{a} (0.2)	4.4 ^{c} (0.3)	5.0 ^{a} (0.4)	< **0.0001**
Adaptation speed	3.8 ^{bc} (0.3)	3.6 ^{d} (0.2)	4.8 ^{b} (0.2)	4.0 ^{c} (0.2)	5.3 ^{a} (0.2)	**0.004**

tunnel pressures at low levels (Rempel et al., 2008). The levels of wrist extension measured in this study were lower than the previous studies on the keyboards with longer travel distance (Honan et al., 1996; Rempel et al., 2007; Sommerich et al., 1996). This indicates that the ultra-low travel keyboard can reduce wrist extension and may therefore lower carpal tunnel pressures (Keir et al., 1998; Rempel et al., 1997a, 1997b), flexor and extensor tendon force (Kursa et al., 2006), and/or discomfort. The 50th percentile of ulnar deviation varied between 10.7° and 14.1°, which was compatible with previous studies on wrist postures while typing (Honan et al., 1996; Rempel et al., 2007; Sommerich et al., 1996) and within recommended range for wrist deviation (Rempel et al., 2008). Previous studies have shown that there is no evidence that these levels of wrist postures will increase risks of developing musculoskeletal disorders while typing (Hünting and Grandjean, 1981; Serina et al., 1999; Weiss et al., 1995).

Although there were significant differences in typing performance across keyboards, the differences appeared to be practically small (< 5 WPM in net speed; < 3% in accuracy). This indicates that using ultra-low travel keyboard may not substantially alter typing performance. This is consistent with the previous studies where no significant difference or general trend in typing performance associated with travel distance was found (Hoyle et al., 2013; Hughes et al., 2011; Kim et al., 2014).

The results on the self-report comfort in the hand, wrist, arm, and shoulder did not show any differences across the keyboards (Table 3). This is consistent with objective measurements of muscle activity and typing force during the 10-min typing sessions, as no differential effect associated with using ultra-low keyboard was observed. Similar to previous studies (Hoyle et al., 2013; Kim et al., 2014), the overall results on the perceived usability and preference showed that the subjects preferred to use the conventional 2.0 mm keyboard; however, there were also different within the ultra-low travel keyboards. The shortest (0.5 and 0.7 mm) ultra-low travel keyboards were the least preferred. Some of these differences may be due to more subject familiarity with conventional keyboards.

Despite the well-controlled laboratory experiment, this study has several limitations. In this study, the subjects were asked not to rest their wrists on the keyboards to avoid the superimposition of the unwanted static forces to the typing forces. This instruction may have resulted in alteration in muscle activity and wrist posture data. However, since this instruction was consistent across all of the typing sessions, we were able to compare different levels of travel distance. Second, although we intended to select the keyboards in our study to be different only in key travel distance level by choosing the keyboards with the same key size, pitch, and activation force, there were some minor differences in physical characteristics and tactile feedback. For example, 1.6 mm keyboards had smaller gaps (gutters) between the keys as compared to the other keyboards, which may explain that 1.6 mm keyboard did not follow the overall trend in some dependent variables. Third, the typing speed was not controlled in this study for comparing realistic typing performance across the keyboards that can influence the typing force (Sommerich et al., 1996). However, the measured typing speed showed that the typing speed differences across keyboards were relatively small (less than 7 WPM). Fourth, typing session was the relatively short (10 min) on each keyboard. Although previous studies showed that this duration can be sufficient to characterize biomechanical responses during typing (Kim et al., 2014; Pereira et al., 2013), the study does not provide information on MSD-relate risk associated with long-term use of ultra-low travel keyboards. Furthermore, because ultra-low travel keyboards by nature can be used anywhere that is different from a desk as tested in this study, the study results especially in typing force, muscle activity, and posture may not reflect realistic biomechanical exposures during real use of these keyboards; therefore, the results should be carefully interpreted. Nonetheless, given small differences between ultra-low travel keyboards and a conventional keyboard in biomechanics, performance, and perceived comfort and usability measures, accumulated risk of MSDs from long-term use of ultra-low travel keyboard is expected to be similar to long-term use of conventional computer keyboards found in previous studies (IJmker et al., 2007; Jensen et al., 2002; Punnett and Wegman, 2004).

In conclusion, this study demonstrated that there were some small differences between ultra-low travel keyboards and a conventional keyboard in typing force, muscle activity, wrist postures, typing performance, perceived comfort and usability. These findings indicated that the ultra-low key travel keyboards may not have any substantial effects on physical exposures and typing performance as compared to a conventional keyboard, but subjectively the shortest travel ultra-low keyboards were less preferred.

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