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# Differences in typing forces, muscle activity, comfort, and typing performance among virtual, notebook, and desktop keyboards

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ABSTRACT

The present study investigated whether there were physical exposure and typing productivity differences between a virtual keyboard with no tactile feedback and two conventional keyboards where key travel and tactile feedback are provided by mechanical switches under the keys. The key size and layout were same across all the keyboards. Typing forces; finger and shoulder muscle activity; self-reported comfort; and typing productivity were measured from 19 subjects while typing on a virtual (0 mm key travel), notebook (1.8 mm key travel), and desktop keyboard (4 mm key travel). When typing on the virtual keyboard, subjects typed with less force ($p$'s $< 0.0001$) and had lower finger flexor/extensor muscle activity ($p$'s $< 0.05$). However, the lower typing forces and finger muscle activity came at the expense of a 60% reduction in typing productivity ($p < 0.0001$), decreased self-reported comfort ($p$'s $< 0.0001$), and a trend indicating an increase in shoulder muscle activity ($p$'s $< 0.10$). Therefore, for long typing sessions or when typing productivity is at a premium, conventional keyboards with tactile feedback may be more suitable interface.



## 1. Introduction

Computer keyboard characteristics can affect computer users' risks for developing upper extremity musculoskeletal disorders (MSDs). Previous studies have shown that a keyboard's key activation force, travel distance, force-displacement characteristics, and tactile feedback can affect typing forces, muscle activity, muscle fatigue and discomfort in the upper extremities (Gerard et al., 1999; Lee et al., 2009; Marcus et al., 2002; Martin et al., 1996; Radwin and Ruffalo, 1999; Rempel et al., 1997; Rempel et al., 1999). Although the strength of relationships between key activation force and typing force varies across studies (Sommerich et al., 1996a), typing forces have been shown to be directly associated with keyboard key activation force (Armstrong et al., 1994; Lee et al., 2009; Radwin and Jeng, 1997; Radwin and Ruffalo, 1999; Rempel et al., 1999). These previous studies have found that typing forces increase with higher key activation forces and that the higher typing forces resulted in increased muscle activity, muscle fatigue and discomfort in the upper extremities.

As tablet use is becoming increasingly common, conventional keyboards are being replaced by virtual, touchscreen keyboards with no physical key feedback. Due to the increased presence of tablets and the associated increase in virtual keyboard use, it is important to understand how the use of a virtual keyboard may affect typing productivity and the physical risk factors associated with MSDs. A touchscreen keyboard is completely different from conventional physical keyboards in terms of key feedback characteristics. Since most standard physical keyboards have a narrow range of activation forces, typically between 0.5 and 0.8 N, users can rest their fingers on the keyboard keys. However, because keys on a virtual keyboard are activated by any physical contact with the skin, users are unable to rest their fingers on the keyboard and must float their fingers, hands, and wrist to avoid accidental key activation. As this hand and finger floating could lead to prolonged static loading in the finger/forearm extensors and shoulder muscles, the associated risks for MSDs may increase whilst using a virtual keyboard. Furthermore, because a virtual keyboard provides limited tactile

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feedback without key travel and force-displacement characteristics, there may be differences in typing productivity and typing forces relative to conventional keyboards which provide users with some sort of tactile feedback.

With the relatively recent introduction of tablets, there has been very little research on how a touchscreen virtual keyboard may affect typing force exposures, muscle activity, user comfort, and typing performance. Young et al. (2013) examined the wrist posture and forearm muscle activity during touchscreen tablet use and found that a touchscreen table use can increase risks for MSDs. Another study (Shin and Zhu, 2011) evaluated the physical risk factors associated with touchscreen keyboard use in a desktop computer setting. They showed that using a touchscreen increased muscle activity in the shoulder and neck muscles, and increased self-reported discomfort in the fingers, shoulder and neck. However, it is still unknown whether using a virtual keyboard affects typing forces and the load on finger flexor, extensor, and shoulder muscles differently than a conventional computer keyboard. Therefore, the purpose of this study was to determine whether there are differences in typing forces, finger and shoulder muscle activity, self-reported comfort and typing productivity between a virtual keyboard which has no tactile-based switches and physical key travel and conventional computer keyboards with tactile (force–displacement) feedback.

## 2. Method

### 2.1. Subjects

A total of 19 subjects (10 male and 9 female) were recruited to participate in the study through e-mail solicitations. Seventeen subjects were right hand dominant and all subjects were experienced touch typists with no history of upper extremity musculoskeletal disorders. The average (SD) age and typing speed for all subjects was 24.3 (6.4) years and 62.7 (9.8) words per minute (WPM), respectively. The typing speed was collected using an online typing test program (http://www.typeonline.co.uk) with subject's own conventional keyboard during subject recruitment. Their average (SD) experience using computer was 14.1 (5.5) years; and all subjects were current virtual keyboard users with either smart phones or tablets. The experimental protocol was approved by the University's Human Subjects Committee and all subjects gave their written consent prior to their participation in the study.

### 2.2. Experimental design

Before evaluating the various keyboards, the chair and work surface was adjusted to match each subject's anthropometry in accordance with ANSI/HFES standards (2007). In addition, subjects were allowed to familiarize themselves with the typing software used in the experiment (Mavis Beacon Teaches Typing Platinum – 25th Anniversary Edition; Broderbund Software Inc.; Eugene, OR, USA) using a non-test virtual keyboard. Twelve randomly-selected chapters from a Grimm's Fairy Tales were used as the text for the typing. This text had a Flesch-Kincaid grade level of 5.1–5.7 indicating the text would easily be understandable by an average twelve year old.

In the repeated-measures laboratory experiment, participants typed for two five-minute sessions on each of the three keyboards used in the experiment. As shown in Fig. 1, two conventional keyboards were tested: a desktop keyboard with 4.0 mm of key travel (DT528AT; Hewlett Packard Inc.; Houston, TX, USA) and a notebook computer with a keyboard with 2.0 mm of key travel (Envy; Hewlett Packard Inc.; Houston, TX, USA); along with a notebook computer with a touch screen interface with 0 mm of key travel (Iconia; Acer Inc.; Taiwan). The force-displacement characteristics of the two conventional keyboards are shown in Fig. 1. The key spacing (center-to-center distance) was approximately 19 mm on all the keyboards and all conformed ANSI (ANSI/HFES 100, 2007) and ISO standards (ISO9241-410, 2008).

During the typing sessions, typing accuracy and adjusted typing speed (the product of gross typing speed and accuracy) were recorded by the typing software program. The order of the keyboards used was randomized and counterbalanced to minimize any potential confounding due to keyboard testing order. The various sections of the text used for the typing tasks were also randomized and counterbalanced. Finally, between the use of each keyboard, a 5-min break was provided to reduce any residual fatigue effects of the previous condition. The duration of the typing task was determined based on previous studies that evaluated typing exposures on various keyboards (Gerard et al., 1999; Gerard et al., 2002; Pereira et al., 2013a).

### 2.3. Typing forces

During keyboard use, typing forces were measured using a force platform (Fig. 2). The force platform consisted of a 36 cm × 18 cm × 0.64 cm (14.17 in × 7.09 in × 0.25 in) aluminum plate mounted to six degree of freedom force/torque load cell (Mini40E; ATI Inc.; Apex, NC, USA) which allowed detection of forces in three dimensions (Kim and Johnson, 2012). A previous study validated the accuracy of the force platform and showed the absolute mean force measurement errors over a 0–4 N range were less than 10% over the full area of the force platform (Kim and Johnson, 2012). The devices were placed on the force platform such that the "H" key of each keyboard was positioned in the center of the force platform. Only the downward, *z*-axis (i.e. perpendicular to the face of the keyboard being tested) were analyzed. To create a flat, continuous work surface, a polyoxymethylene frame which matched the height of the force platform was constructed to surround the force plate. Subjects were also instructed to type without resting their hands or wrists on either the device being tested or the force platform since these resting forces would artificially increase the measured typing forces. The experimenter observed the subjects to ensure they did not rest their hands and wrists on the devices or force platform when typing. Subsequent analysis of the typing force data (forces returning to near zero Newtons between keystrokes) verified that subject did not rest their hand on the device and/or force platform.

A LabVIEW program (Version 2009; National Instruments; Austin, TX, USA) was used to record force data at a rate of 500 Hz (Kim and Johnson, 2012). Prior to each typing task, the force platform was zeroed to offset the weight of the device being tested. The program also simultaneously recorded the digital signals from the keyboard. These digital signals were used by a subsequent LabVIEW-based typing force analysis program to identify individual keystroke force profiles. Only keystroke force profiles associated with the alphanumeric and punctuation portions of the keyboard were evaluated; keystrokes associated with Caps Lock Shift, Ctrl, Alt and Windows keys were not evaluated. The typing force program categorized typing forces as individual keystrokes when the force profile identified by the keyboard digital signal rose above, peaked and then descended below 0.4 N; the force profile had to be between 16 and 250 ms (ms) long, and the peak force had to occur in the first half of the force profile (Rempel et al., 1994). An upper limit of 250 ms was used for keystroke duration, as key rollover (where the letter is repeatedly typed when the key is held down) occurs at durations greater than 250 ms. Over the entire duration of each typing session, median (50th percentile) and peak (90th percentile) typing forces were calculated. In addition, from the individual

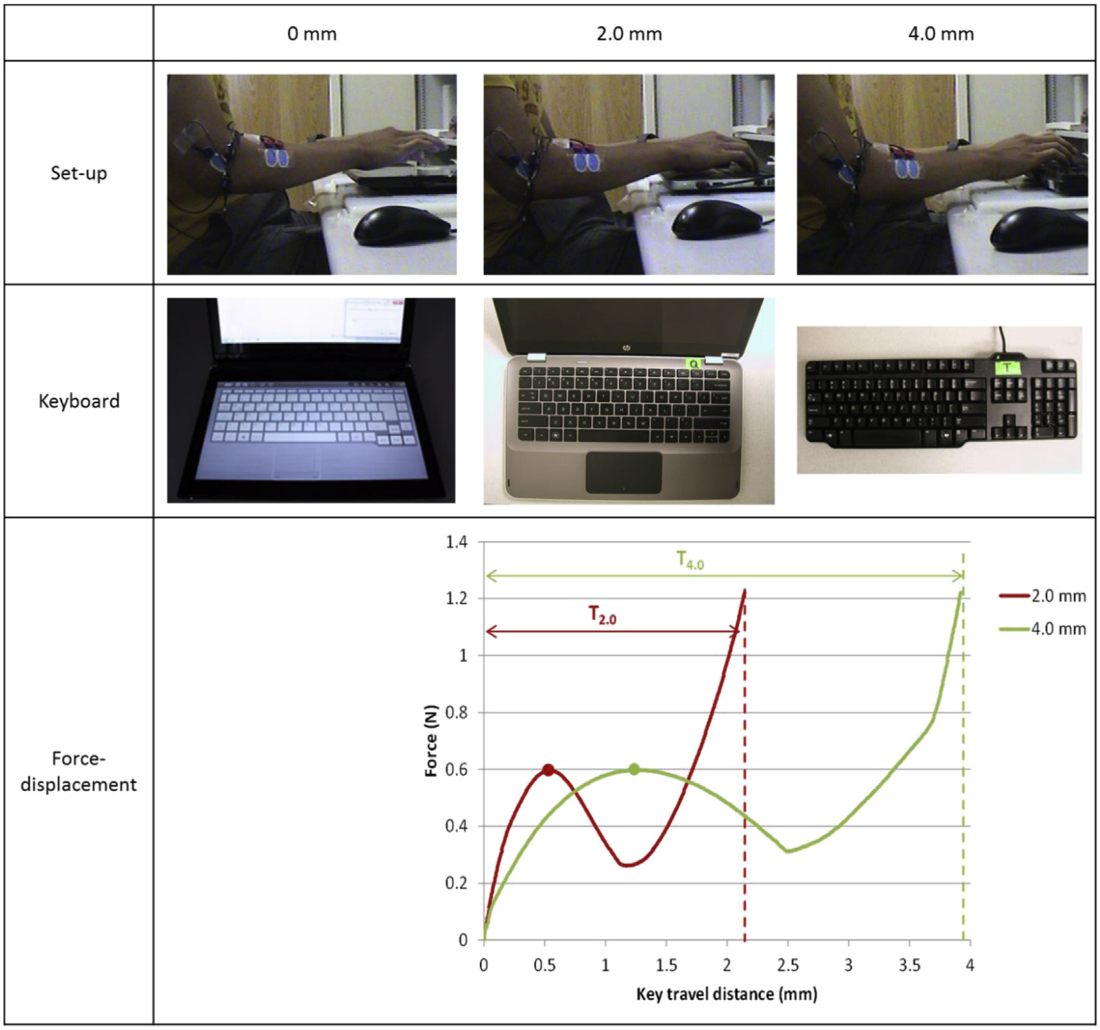


**Fig. 1.** Three keyboards tested in the study and force-displacement curves of two conventional keyboards: the notebook computer with 2.0 mm of key travel and the desktop keyboard with 4.0 mm of key travel. The solid dots and dashed lines indicate the activation forces (make point) and the travel distances, respectively.

keystroke profiles, mean and peak forces, and keystroke duration were calculated.

### 2.4. Muscle activity

Muscle activity was recorded from the right extensor digitorum communis (EDC), right flexor digitorum superficialis (FDS), and right trapezius (TRAP) muscle (Fig. 2). The EDC was identified by palpating the muscle on the dorsal side of the forearm one third of the way up the forearm and having the subject wiggle their fingers. The electrodes were located where the muscle contractions could be felt (Basmajian and De Luca, 1985; Perotto and Delagi, 1994). Similarly, the FDS was located by touching the muscle on the palmar side one third of the way up the forearm and locating the electrodes where the muscle contractions could be felt (Basmajian and De Luca, 1985; Perotto and Delagi, 1994). The ground electrodes for EDC and FDS muscle were placed on the lateral and medial epicondyles, respectively. The active electrodes for the TRAP muscle were placed 2 cm lateral to the halfway point between C7 and the right acromium process while the ground was placed on C7 (Jensen et al., 1993).

Prior to applying EMG electrodes to the skin, the electrode contact area was prepared by shaving hair with a razor (Medline; Mundelein, IL, USA) and cleaning skin surface with Alcohol Prep 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. EMG signals were recorded using a digital data logger (Mega ME6000; Mega Electronics; Kupio, Finland) at a sample rate of 1000 Hz.

After collecting the raw EMG data, a band pass filter of 10–350 Hz was applied. The filtered EMG data from the EDC, FDS, and TRAP muscles were normalized relative to Maximum Voluntary Contractions (%MVC) and the 10th (static), 50th (median) and 90th (peak) muscle activities were calculated (Jonsson, 1982). To obtain the MVCs, subjects were instructed to extend their wrists and fingers up against isometric resistance (EDC) and to flex their fingers down against isometric resistance (FDS) with verbal encouragement. To obtain TRAP MVCs, isometric resistance was applied as subjects performed a continuous single shoulder shrug with their arms at their sides and without bending or twisting at the hips/waist (HarmsRingdahl et al., 1996; Schuldt and Harmsringdahl, 1988). Each contraction time lasted for three to five seconds (Soderberg and Knutson, 2000). Three MVCs were collected from which the maximum RMS signal over a 1 s period was identified and used to normalize the EMG data.

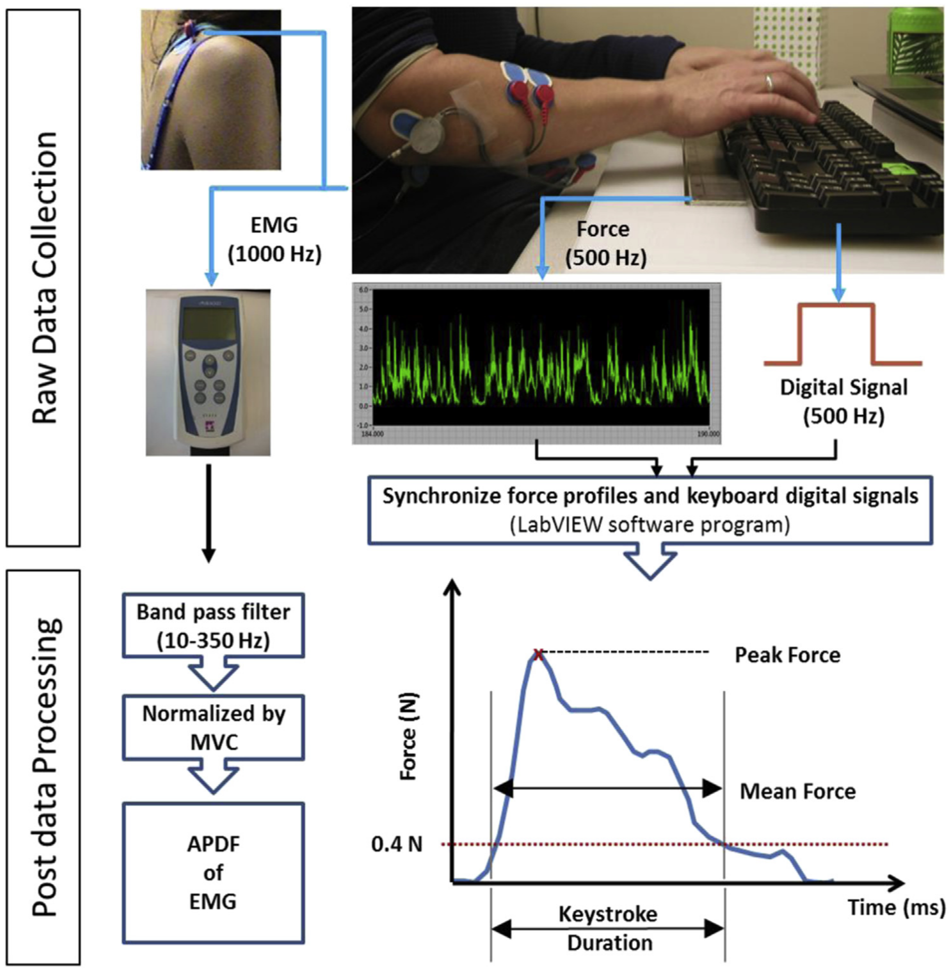


**Fig. 2.** Experimental setup.

### 2.5. *Self-reported comfort and preference*

After typing on each keyboard, self-reported comfort and preference ratings were collected using a slightly modified Likert scale questionnaire adapted from the ISO keyboard comfort questionnaire (ISO9241-410, 2008). The ISO keyboard comfort questionnaire measures self-reported comfort on variable aspects including upper extremity comfort, usability and productivity with a 7-point scale (1 being least comfortable and 7 being most comfortable). Verbal anchors were used at both ends of each scale.

### 2.6. *Data analysis*

The statistical analysis was conducted in JMP (Version 9; SAS Institute Inc.; Cary, SC, USA). A *mixed model* with *restricted maximum likelihood estimation* (REML) was used to test our hypotheses that there were differences between a virtual and conventional keyboards in terms of typing forces, muscle activity, and typing performance. Any statistical significance was followed-up with a *Tukey–Kramer* post-hoc test to determine whether there were significant differences between keyboards. Friedman tests with post-hoc multiple comparison in R (R 2.13.2, Development Core Team) were used to determine whether there were any differences between keyboards in self-reported comfort, typing performance, and preference. All data are presented as mean and standard error; and significance was noted when Type I error was less than 0.05 and probabilities less than 0.10 were used to indicate trends that approached significance.

## 3. Result

### 3.1. *Typing performance*

Compared to conventional keyboards, adjusted (net) typing speed on the virtual keyboard was approximately 60% slower ($p < 0.0001$) while there was no difference between notebook and desktop keyboards (Fig. 3). Subjects typed with 95% accuracy on the notebook and desktop keyboards whereas accuracy was significantly lower on the virtual keyboards averaging 84% ($p < 0.0001$).

### 3.2. *Typing forces*

When median (50th %tile) and peak (90th %tile) typing forces were calculated from the complete ten minute time series of the force data, there were significant differences between the keyboards (Fig. 4). The median typing force on the virtual keyboard was significantly lower ($p < 0.0001$) while no differences were found between the notebook and desktop keyboards ($p = 0.96$). The peak typing forces were significantly different across all the keyboards and the virtual keyboard had a lower peak typing force compared to the other keyboards ($p < 0.0001$); the peak force on the desktop keyboard was higher than the notebook keyboard ($p = 0.02$).

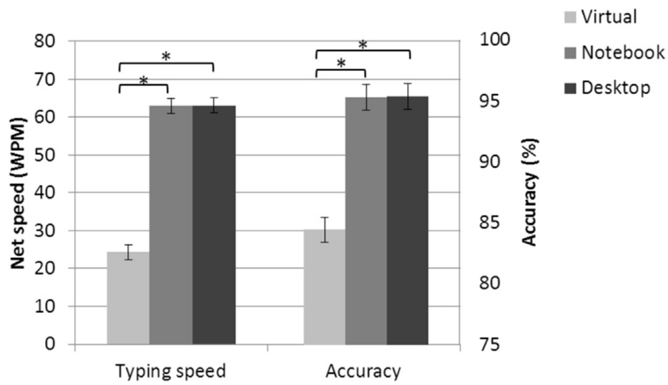


**Fig. 3.** Comparisons of mean adjusted (net) typing speed and accuracy by keyboard. Asterisks denote statistical significance at $\alpha = 0.05$ [$n = 19$]. The error bars represent standard errors.

From the individual keystroke force profiles, mean and peak keystroke forces, and keystroke durations were calculated. The mean keystroke force on the virtual keyboard was lower than the other keyboards ($p < 0.0001$) while the desktop keyboard had a greater mean keystroke forces ($p = 0.02$) when compared to the notebook keyboard (Fig. 4). Peak keystroke forces were lowest on the virtual keyboard and highest on the desktop keyboard ($p < 0.0001$). Based on the keystroke durations calculated of the individual keystroke profiles, the virtual keyboard had shorter keystroke durations compared to the other keyboards ($p < 0.0001$) while no differences in keystroke duration were found between the notebook and desktop keyboards ($p = 0.94$).

### 3.3. Muscle activity

Due to technical difficulties, one of the participant's EMG data was not recorded; therefore, the EMG results are based on 18 subjects.

#### 3.3.1. Finger extensor

The results indicated that there were differences in extensor digitorum communis (EDC) muscle activity between keyboards (Fig. 5). The desktop keyboard showed consistently higher EDC activities for 10th, 50th and 90th percentile muscle activity, compared to the other keyboards. The desktop keyboard had significantly higher median (50th percentile) and peak muscle activity (90th percentile) compared to the virtual and notebook

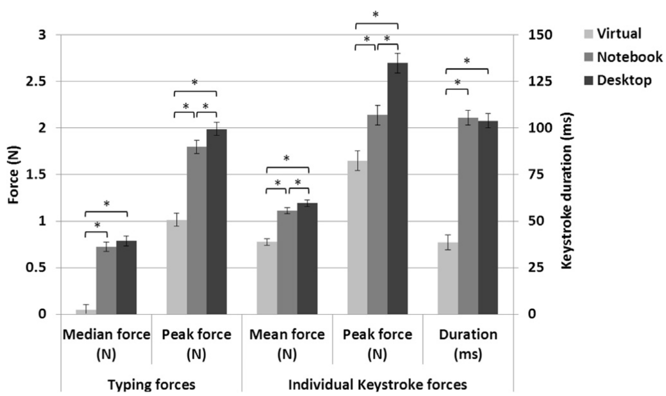


**Fig. 4.** Comparisons of typing and individual keystroke forces by keyboard. Asterisks denote statistical significance at $\alpha = 0.05$ [$n = 19$]. The error bars represent standard errors.

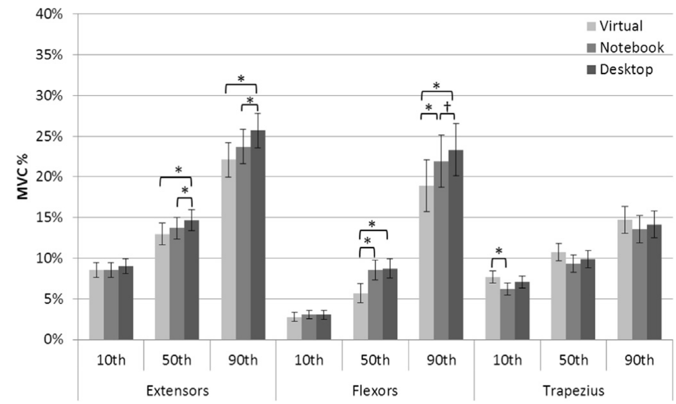


**Fig. 5.** Comparison of 10th, 50th, and 90th %tile muscle activity of the finger extensor (extensor digitorum communis), flexor (Flexor digitorum superficialis), and Trapezius muscles by keyboard. Asterisks and † denote statistical significance at $\alpha = 0.05$ and 0.10, respectively [$n = 18$].

keyboard ($p < 0.0001$) whereas there were no differences between the virtual and notebook keyboard.

#### 3.3.2. Finger flexor

There were significant differences in median and peak flexor digitorum superficialis (FDS) muscle activity across keyboards with the virtual keyboard having lower median ($p < 0.0001$) and peak ($p < 0.0001$) muscle activity. The results showed a trend ($p$'s $< 0.10$) for FDS muscle activity increasing with key travel distances.

#### 3.3.3. Trapezius

The results showed that the virtual keyboard had the highest trapezius muscle activity compared to the other keyboards (Fig. 5). The virtual keyboard had higher static muscle activity (10th percentile) when compared to the notebook keyboard ($p = 0.007$) whereas there were no muscle activity differences between the notebook and desktop keyboards.

### 3.4. Self-reported comfort and preference

Self-reported comfort, productivity and preference ratings showed that the virtual keyboard consistently received the lowest (least preferable) ratings in all three categories whereas there were no differences between the notebook and desktop keyboards (Table 1). The notebook keyboard received the highest comfort rating on the arm and shoulder while the desktop keyboard had the highest productivity and ease of use ratings including typing accuracy, typing speed, and time needed to adapt to using the keyboard ($p$'s $< 0.0001$). Similarly, the perceived activation force on the virtual keyboard was substantially lower than the other

**Table 1**
Mean (SE) self-reported comfort and preference ratings. A seven point Likert Scale was used with 1 indicating least preferable and 7 the most preferable. The values with different superscripts across rows indicate significant differences [$n = 19$].

| | Virtual | Notebook | Desktop | $p$-value |
|---|---|---|---|---|
| Hand/wrist comfort | 2.9 (1.7)$^a$ | 5.4 (1.1)$^b$ | 5.4 (1.2)$^b$ | $<0.0001$ |
| Arm/shoulder comfort | 3.4 (1.7)$^a$ | 5.3 (1.2)$^b$ | 4.9 (1.2)$^b$ | $=0.0007$ |
| Easy-of-use | 1.7 (1.3)$^a$ | 5.7 (1.1)$^b$ | 5.8 (1.1)$^b$ | $<0.0001$ |
| Typing accuracy | 1.5 (1.0)$^a$ | 5.6 (1.1)$^b$ | 5.9 (0.9)$^c$ | $<0.0001$ |
| Typing speed | 1.7 (1.3)$^a$ | 5.6 (0.9)$^b$ | 5.6 (0.9)$^c$ | $<0.0001$ |
| Activation force | 2.4 (1.6)$^a$ | 3.9 (1.7)$^b$ | 4.5 (1.3)$^b$ | $=0.0009$ |
| Adjustment speed | 2.4 (1.4)$^a$ | 5.5 (1.3)$^b$ | 6.0 (0.9)$^b$ | $<0.0001$ |
| Preference | 1.6 (1.1)$^a$ | 5.5 (1.2)$^b$ | 5.6 (1.3)$^b$ | $<0.0001$ |

keyboards ($p = 0.0009$) whereas there were no differences in the perceived activation force between the notebook and desktop keyboard.

## 4. Discussion

As the use of virtual keyboard is becoming more prevalent, it is important to understand the effects that these keyboards have on a user's physical exposures, comfort, and typing performance. Therefore, the present study evaluated whether there were differences between a virtual keyboard, a short travel notebook keyboard, and a long travel desktop keyboard in terms of typing forces, muscle activity, productivity, and user preferences. This study found that, relative to the notebook and desktop keyboards, the virtual keyboard had lower finger flexor/extensor muscle activity, but this came at the expense of typing productivity and decreased self-reported comfort in the upper extremities.

The results showed that the 50th and 90th percentile typing forces as well as the mean and peak keystroke forces were significantly lower on the virtual keyboard compared to the other keyboards. Previous studies showed that typing forces can be affected by typing speed (Sommerich et al., 1996b) and keyboard's physical characteristics including key activation force and travel distances (Armstrong et al., 1994; Lee et al., 2009; Radwin and Jeng, 1997; Radwin and Ruffalo, 1999; Rempel et al., 1999). Sommerich et al. (1996b) showed the relationship between typing speed and typing force in a certain condition; however, they did not find any relationships between typing speed and typing force when subjects typed at their preferred speed. As the present study allowed subjects to type at their preferred speed, typing force was more likely affected by key activation force than the typing speed.

Typing forces have been shown to be positively correlated with key activation forces (Armstrong et al., 1994; Lee et al., 2009; Radwin and Jeng, 1997; Radwin and Ruffalo, 1999; Rempel et al., 1999); that is, higher activation forces can lead to higher typing forces applied to a keyboard. The activation forces of the notebook and desktop keyboards were the same and approximately 0.6 N (Fig. 1). However, the virtual keyboard had no force threshold for key activation as the virtual keyboard had capacitive key sensors which allow key activation with a minimal physical contact. This substantial difference in activation force was likely the reason for the differences between the virtual and conventional keyboards in typing forces.

Interestingly, although the notebook and desktop keyboard had similar activation forces, the 4-mm desktop keyboard showed higher mean and peak keystroke forces as compared to the 1.8-mm notebook keyboard (Fig. 4). Previous studies have shown that typing forces are affected by keys stiffness (slope of force-displacement curves) and key travel distances (Gerard et al., 1999; Martin et al., 1996; Radwin and Ruffalo, 1999; Rempel et al., 1997; Rempel et al., 1999). Therefore, the differences in mean and peak keystroke forces between the notebook and desktop keyboard may have been the result of the substantial differences in the force-displacement curves between the keyboards. This reinforces the importance of considering other force-displacement characteristics such as key travel in addition to key activation force when a keyboard is designed.

The EMG results indicated that the desktop keyboard had consistently higher mean and peak muscle activity in the finger extensor (EDC) and flexor (FDS) muscles than the virtual keyboard, and that the notebook keyboard's muscle activity tended to be intermediate (Fig. 5). In addition, the virtual keyboard had consistently lower finger flexor and extensor muscle activity compared to the conventional keyboards although some of differences were not significant. This was corroborated by the typing forces, in that the virtual keyboard had lower typing forces than the conventional keyboards (Fig. 4). However, as Gerard et al. (1994) found that typing speed affected muscle activity, typing speed may also have contributed to the lower finger flexor/extensor muscle activity since subjects typed 60% slower with the virtual keyboard. As a result, the direct comparison of static (10th percentile) and median (50th percentile) muscle activity between the keyboards may be problematic due to the different typing speeds.

Different from EDC and FDS muscle activity, TRAP muscle activity on the virtual keyboard was marginally higher than the other keyboards, especially for static (10th %tile) TRAP muscle activity (Fig. 5). Although the differences were relatively small (~1% MVC), these small exposure differences could be important when they accumulate over time (Pereira et al., 2013b). A previous study (Shin and Zhu, 2011) has shown that TRAP muscle activity was higher during the virtual keyboard use, this was thought to be a result of participants not being able to rest either their fingers or hands during typing so as to avoid accidental key activation. Because a function of the TRAP muscle is to support the arms, floating the hands and forearms while typing on the virtual keyboard may have increased the static loading in the TRAP muscle and consequently resulted in higher muscle activity. The prolonged static muscle loading is a risk factor for musculoskeletal disorders (Chang et al., 2007; Ijmker et al., 2007; Jensen et al., 2002); thus, using a virtual keyboard for long periods of time may increase the risk for musculoskeletal discomfort and/or disorders in the shoulder. However, given the small differences (~1% MVC) in TRAP muscle activities between keyboards and the study condition where subjects were directed to float their forearms and wrists, further clarification should be made in future studies to draw conclusive information.

Although virtual keyboard resulted in lower typing force and finger muscle (EDC and FDS) activity than other conventional keyboards, the virtual keyboard's self-reported comfort ratings in the hand and wrist were less favorable compared to the other keyboards. Typing forces and muscle activity are known to be directly associated with key activation forces (Armstrong et al., 1994; Lee et al., 2009; Radwin and Jeng, 1997; Radwin and Ruffalo, 1999; Rempel et al., 1999). The negligible force needed to activate the capacitive interface of the virtual keyboard may have resulted in lower typing forces. The lower typing forces with slower typing speed on the virtual keyboard may have also contributed to the lower muscle activity. However, the virtual keyboard's lower force and muscle activity did not result in more favorable self-reported comfort ratings in the hand and wrist; this is likely due to the complex interaction between the subjective perception of comfort registered by the central nervous system and the physical comfort registered by the peripheral nervous system. Previous studies (Greening and Lynn, 1998; Valencia, 1986) have shown that the subjective sense of physical loading is not necessarily synchronized with the corresponding direct biomechanical measurement.

Self-reported measures of typing productivity were consistent with the corresponding objective measures. The subjective typing speed and accuracy on the virtual keyboard was lowest while the conventional keyboards had substantially higher typing speed and accuracy (Table 1). Some of the keyboard-based differences in the typing productivity may be due to subjects' lack of familiarity with the virtual keyboard. Although the subjects reported that they regularly used virtual keyboards, since conventional keyboards have been in existence longer and are predominantly used when working with computers, they were more likely more familiar with the conventional keyboards. Given the completely different interface and short periods of typing (10 min), it was not unexpected to find lower typing productivity levels with the virtual keyboard. In addition, the slower typing on the virtual keyboard was likely the result of subjects having to look at the virtual keyboard keys while typing.

Finally, the present study has a few limitations. Although the study found that the virtual keyboard had lower muscle activity on the finger flexor/extensor muscles than the other conventional keyboards, typing speed may have contributed to the lower finger muscle activity since subjects typed 60% slower with the virtual keyboard. Due to the typing speed differences between devices, it may be beneficial to have a condition where typing speed is fixed to the lowest common denominator typing speed (typing speed on the slowest keyboard). Controlling the typing speed can minimize any biases in the EMG data due to typing productivity differences. Furthermore, subjects were instructed not to rest their fingers on devices during typing since these resting forces would artificially increase the measured typing forces; consequently, muscle activity measured on finger extensor and shoulder muscles may have been overestimated since user's can usually rest their hands on the device itself or work surface. Nonetheless, because this study compared muscle activity under identical conditions across all the keyboards, the results should provide meaningful comparison of muscle activity across devices.

Lastly, median typing force and keystroke durations on the virtual keyboard (Fig. 4) may have been underestimated. One challenge with the virtual keyboard on the notebook computer we tested was that the notebook screen wobbled slightly while subjects typed on the virtual keyboard and this added some noise (i.e. oscillations) to the force data. These force oscillations may have caused an underestimation in the virtual keyboard's keystroke duration and median typing forces. In future studies, adding weight to the underside of the notebook computers can move the notebook computer's center of mass away from the screen area, increase the resonant frequency of the keyboard, reduce force oscillations, and improve the quality of the typing force data.

In conclusion, the study demonstrated that there were differences between conventional keyboards and a virtual keyboard in typing forces, muscle activity, productivity, and preference. The lower typing forces and muscle activity in the finger flexor and extensor muscles may imply that using a virtual keyboard may be less detrimental in terms of physical exposures. However, the lower typing forces and finger muscle activity came at the expense of a 60% reduction in typing productivity, and increased self-reported discomfort. Due to the dual vision demands of the notebook computer with the virtual keyboard (viewing the text on the vertical screen and having to also look at the keys on the horizontal virtual keyboard), the typing speed on the virtual keyboard tested in this study is likely slower than on tablets where the display and virtual keyboard are on one screen. Given the increased self-reported discomfort and the substantial reduction in typing productivity while typing on the virtual keyboard, when engaging in long typing sessions or when typing productivity is at a premium, conventional keyboards may be more suitable; however, for shorter typing sessions when typing productivity is not at a premium, the virtual keyboard is a suitable interface.

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