The Effect of Key Size of Touch Screen Virtual Keyboards on Productivity, Usability, and Typing Biomechanics

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Objective: We investigated whether different virtual keyboard key sizes affected typing force exposures, muscle activity, wrist posture, comfort, and typing productivity.

Background: Virtual keyboard use is increasing and the physical exposures associated with virtual keyboard key sizes are not well documented.

Method: Typing forces, forearm/shoulder muscle activity, wrist posture, subjective comfort, and typing productivity were measured from 21 subjects while they were typing on four different virtual keyboards with square key sizes, which were 13, 16, 19, and 22 mm on each side with 2-mm between-key spacing.

Results: The results showed that virtual keyboard key size had little effect on typing force, forearm muscle activity, and ulnar/radial deviation. However, the virtual keyboard with the 13-mm keys had a 15% slower typing speed ($p < .0001$), slightly higher static (10th percentile) shoulder muscle activity (2% maximum voluntary contractions, $p = .01$), slightly greater wrist extension in both hands (2° to 3°, $p < .01$), and the lowest subjective comfort and preference ratings ($p < .1$).

Conclusions: The study findings indicate that virtual keyboards with a key size less than 16 mm may be too small for touch typing given the slower typing speed, higher static shoulder muscle activity, greater wrist extension, and lowest subjective preferences.

Applications: We evaluated the effects of virtual keyboard key sizes on typing force exposures, muscle activity, comfort, and typing productivity.

Keywords: typing biomechanics, human–computer interface, electromyography, electrogoniometer

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INTRODUCTION

The touch screen interface has become prevalent on mobile devices, such as phones, tablets, and even notebook computers, because of its advantages, such as intuitiveness and no need for additional input devices (Irwin et al., 2011; Park & Han, 2010b; Scott & Conzola, 1997). In 2012, 144.5 million tablets were sold and the number is going to increase more than fivefold by 2017 (International Data Corporation, 2013; Jones, 2013). According to market projections, tablets are expected to dominate the entire PC market, including desktops and notebook computers, by 2015 (International Data Corporation, 2013). Recently, with an increased prevalence of tablet use, conventional tactile keyboards have been replaced by touch screen virtual keyboards on the tablets themselves. From an ergonomics standpoint, the touch screen virtual keyboard has the advantage that key size and key spacing can be adjusted according to users' anthropometry.

However, as tablets gravitate toward smaller and smaller key sizes for better portability, the key sizes on a virtual keyboard are often smaller than the 18- to 20-mm key sizes recommended for physical keyboards in the American National Standards Institute (ANSI) and International Organization for Standardization (ISO) standards (ANSI/HFES 100-2007, 2007; ISO 9241-410, 2008). In addition, compared to conventional keyboards, virtual keyboards do not provide any tactile feedback, such as tactile cues for key location or tactile feedback when the keys are pressed. In a recent study in which typing performance was compared between virtual and conventional keyboards (Kim, Aulck, Bartha, Harper, & Johnson, 2012), subjects were shown to type 60% slower on the virtual keyboard. A major factor behind the virtual keyboard's typing decrement was the lack of tactile feedback.

Computer keyboard geometry, including key spacing and key size, may alter the risk factors associated with computer-related musculoskeletal disorders (MSDs; Jindrich, Balakrishnan, & Dennerlein, 2004a, 2004b; Pereira et al., 2012; Rempel, Nathan-Roberts, Chen, & Odell, 2009; Yoshitake, 1995). Different key sizes may change the degrees of finger abduction/adduction, wrist flexion/extension, and radial/ulnar deviation. Those different postures are known to change the biomechanics of hand and fingers, change applied finger forces, and affect muscle activity, which are well-known risk factors for MSDs (Armstrong, Foulke, Martin, Gerson, & Rempel, 1994; Feuerstein, Armstrong, Hickey, & Lincoln, 1997; Gerard, Armstrong, Franzblau, Martin, & Rempel, 1999; Jindrich et al., 2004a, 2004b; Rempel, Serina, et al., 1997; Wu et al., 2008). Unfortunately, despite a few existing guidelines on physical keyboard design (ANSI/HFES 100-2007, 2007; ISO 9241-410, 2008), no consistent recommendations for key sizes on touch screen keyboard interfaces are available (Sesto, Irwin, Chen, Chourasia, & Wiegmann, 2012). Therefore, it is important to understand how different virtual keyboard key sizes affect typing biomechanics and to determine optimal key sizes to minimize physical risk factors for fatigue and MSDs while not adversely affecting typing productivity.

There has been research into how altering key sizes on a touch screen interface can affect performance, usability, and preference (Colle & Hiszem, 2004; Kwon, Lee, & Chung, 2009; Lee & Zhai, 2009; Lewis, 1993; MacKenzie, Zhang, & Soukoreff, 1999; O'Brien, Rogers, Fisk, & Richman, 2008; Park & Han, 2010a, 2010b; Scott & Conzola, 1997; Sears, 1991; Sears, Revis, Swatski, Crittenden, & Shneiderman, 1993) as well as applied force (Irwin et al., 2011; Sesto et al., 2012). For example, Colle and Hiszem (2004) showed that on a touch screen keypad, a bigger key size (20 mm) gave better speed and accuracy with higher preferences compared to smaller key sizes (10 and 15 mm). On the basis of previous empirical findings, Lewis (1993) suggested that the key width of a touch screen keyboard should be larger than 22 mm, considering adults' finger width. Irwin et al. (2011) and Sesto et al. (2012) found that exerted peak forces were significantly affected by a key size on a touch screen kiosk.

Despite numerous studies on the performance effects associated with touch screen key size, there is a lack of research into how different key sizes affect typing biomechanics and physical exposures during virtual keyboard use. The human–computer interfaces are substantially different between touch screen devices and conventional tactile keyboards (i.e., lack of tactile or other forms of feedback). A recent study showed that due to the lack of tactile feedback, the typing performance on a virtual keyboard is 60% slower when compared to a conventional keyboard (Kim et al., 2012). Due to the completely different interface, previous findings on the relationships between conventional keyboard characteristics and physical exposures may not be directly applicable to a touch screen virtual keyboard (Armstrong et al., 1994; Gerard et al., 1999; Lee, Kuo, Jindrich, & Dennerlein, 2009; Marcus et al., 2002; Martin et al., 1996; Radwin & Jeng, 1997; Radwin & Ruffalo, 1999; Rempel, Serina, et al., 1997; Rempel, Tittiranonda, Burastero, Hudes, & So, 1999). Therefore, the goal of this study was to determine whether virtual keyboard key sizes had any influence on typing productivity, biomechanics (typing forces, muscle activity, and wrist posture), and usability (subjective comfort and preference).

METHODS

Subjects

A total of 21 subjects (12 males and 9 females) were recruited to participate in the study through e-mail solicitations. All subjects were experienced touch typists whose typing speed was faster than 40 words per minute (WPM), with no history of upper-extremity MSDs, and 19 subjects were right-hand dominant. The average age for all subjects was 24.5 years, ranging from 18 to 49 years old; their average experience using computers was 14.1 (SD = 5.5) years; and all had prior experience using tablets and/or smartphones with touch interfaces. 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.

Experimental Protocol

Prior to the start of the experiment, a chair and work surface were adjusted based on subject's anthropometry in accordance with ANSI standards (ANSI/HFES 100-2007, 2007). The chair was adjusted so the subject's thighs were parallel to the floor and their feet rested firmly on the floor. Then, the height of the workstation was adjusted so the table height was set at approximately 2 cm below elbow height with approximately 90° elbow angles. Finally, the virtual keyboard was placed so the spacebar was centered on the subject's body and 7 cm from the front edge of the work surface. Demographic and hand anthropometric data, including index finger length and index finger width, were collected. Index finger length was measured from palmar proximal metacarpophalangeal crease to tip of finger, and index finger width was measured at the proximal interphalangeal joint.

To allow subjects to familiarize themselves with the virtual keyboard and the virtual keyboard typing program, subjects typed on a non-test device (virtual keyboard with 16 × 16 mm keys) until they felt they were comfortable with the program's interface. The typing program and virtual keyboard with programmable key sizing/spacing was created using LabVIEW (Version 2009; National Instruments; Austin, TX, USA). Text with a Flesch-Kincaid grade level of 5.1 to 5.7 with a reading level of 83.2 to 87.6 (equivalent to a fifth-grade reading level) were used in both the practice session and the experiment.

After the practice session, a repeated-measures laboratory experiment was conducted in which each subject typed for two 5-min sessions on each of four different virtual keyboards (Figure 1). The four virtual keyboard key sizes evaluated were 13, 16, 19, and 22 mm (width and height). The virtual keyboard was created on a notebook computer with a 14-in. dual capacitive touch screen interface (Iconia; Acer Inc., Taiwan). The virtual keyboard provided both audio and visual feedback when keys were activated, with no discernible delay. To minimize potential confounding due to different gutter sizes between the keys, both horizontal and vertical gutters were kept constant at 2 mm. Although the ANSI standard recommends the between-key spacing to be at least 3.2 mm for conventional keyboards, 2 mm was chosen because this was the typical spacing on many of the commercially available tablets. Accordingly, the four keyboards had a horizontal and vertical center-to-center key spacing of 15, 18, 21, and 24 mm. The key size and spacing were chosen to be greater and less than the 18- to 19-mm center-to-center key spacing recommended in the ANSI and ISO standards for keyboards (ANSI/HFES 100-2007, 2007; ISO 9241-410, 2008).

During the typing sessions, the LabVIEW-based typing program recorded the subjects' gross typing speed (number of words per minute), accuracy (as determined by the percentage of characters in the same text position as the displayed text), and adjusted typing speed (the product of gross typing speed and accuracy). Eight sets of text (2 sessions × 4 key sizes) were utilized for the typing sessions; the order of text sets and key sizes was randomized and counterbalanced to reduce potential confounding effects. The text was displayed above the virtual keyboard on the same screen that contained the virtual keyboard. Subjects were instructed to type texts with their normal speed and achieve a balance between speed and accuracy. After each typing session, subjects rated their levels of perceived comfort and preference using Likert scales adapted from the ISO keyboard comfort questionnaire (ISO 9241-410, 2008). The ISO keyboard comfort questionnaire measures subjective 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*). Finally, a 5-min break was given between each virtual keyboard size to minimize any residual fatigue effects of the previous condition.

Typing Forces

Typing forces were measured with a force platform that consisted of a 36 cm × 18 cm × 0.64 cm aluminum plate mounted on top of a 6 degree-of-freedom force/torque load cell (Mini40E; ATI Inc., Apex, NC, USA) during the entire typing sessions (Figure 2). Detailed

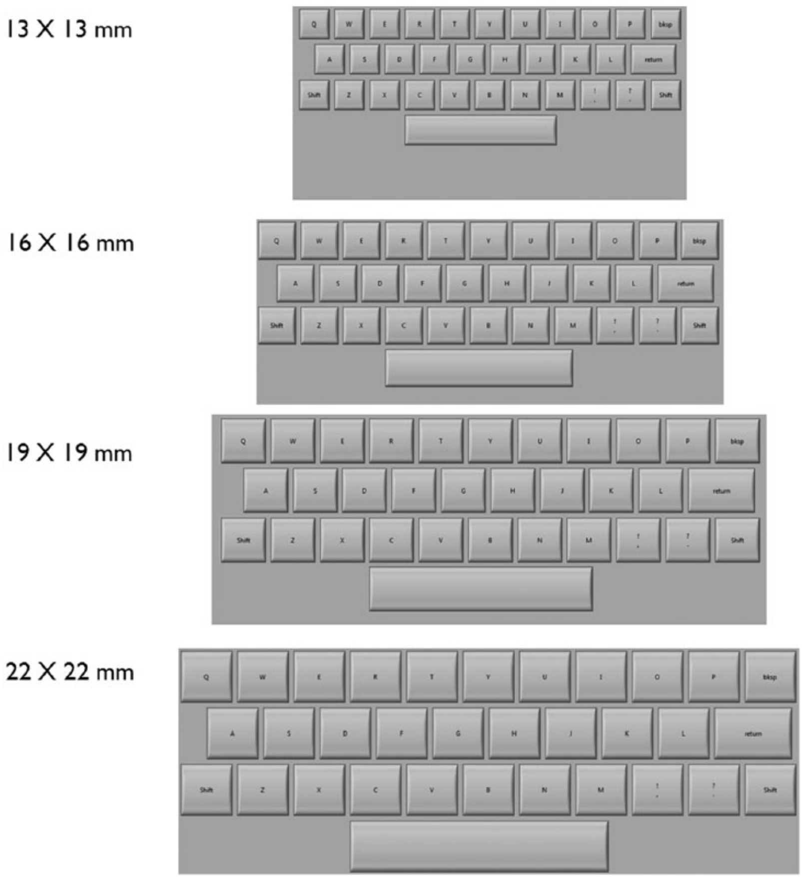

Figure 1. The four virtual keyboards evaluated. The keys were square and had a height and width of 13, 16, 19, and 22 mm. Across all keyboards, the spacing/gutters between keys was fixed at 2 mm. The printed letters on the keys are the same size across all keyboards.

information on the force platform construction can be found in Kim and Johnson (2012). The notebook computer with the virtual keyboard was placed on the force platform such that the *H* key of each keyboard was positioned in the center of the force platform and directly over the force/torque load cell. Only the *z*-axis typing forces (forces perpendicular to the face of the keyboard) were analyzed. In order to measure typing forces without artificial force effects from resting their wrists on the virtual keyboard, subjects were not allowed to rest their wrists on the virtual keyboard during typing.

A LabVIEW program (Version 2009; National Instruments, Austin, TX, USA) was used to record force data at a rate of 500 Hz. Prior to each typing task, the force platform was zeroed to offset the weight of the notebook computer with the virtual keyboard interface. Similar to our previous work (Kim et al., 2012; Kim & Johnson, 2012), an automated typing force program identified individual keystrokes, which were based on when the keystroke force profile rose above 0.4 N, peaked in the first half of the keystroke force profile, and then descended below 0.4 N (Rempel, Dennerlein, Mote, & Armstrong, 1994). The force profile had to be at least 0.4 N and between 16 and 250 ms long to be accepted as a viable keystroke. Keystroke durations longer than 250 ms were excluded since these longer keystrokes were likely to be nonballistic (Chang et al., 2009; Kim et al., 2012; Kim & Johnson, 2012).

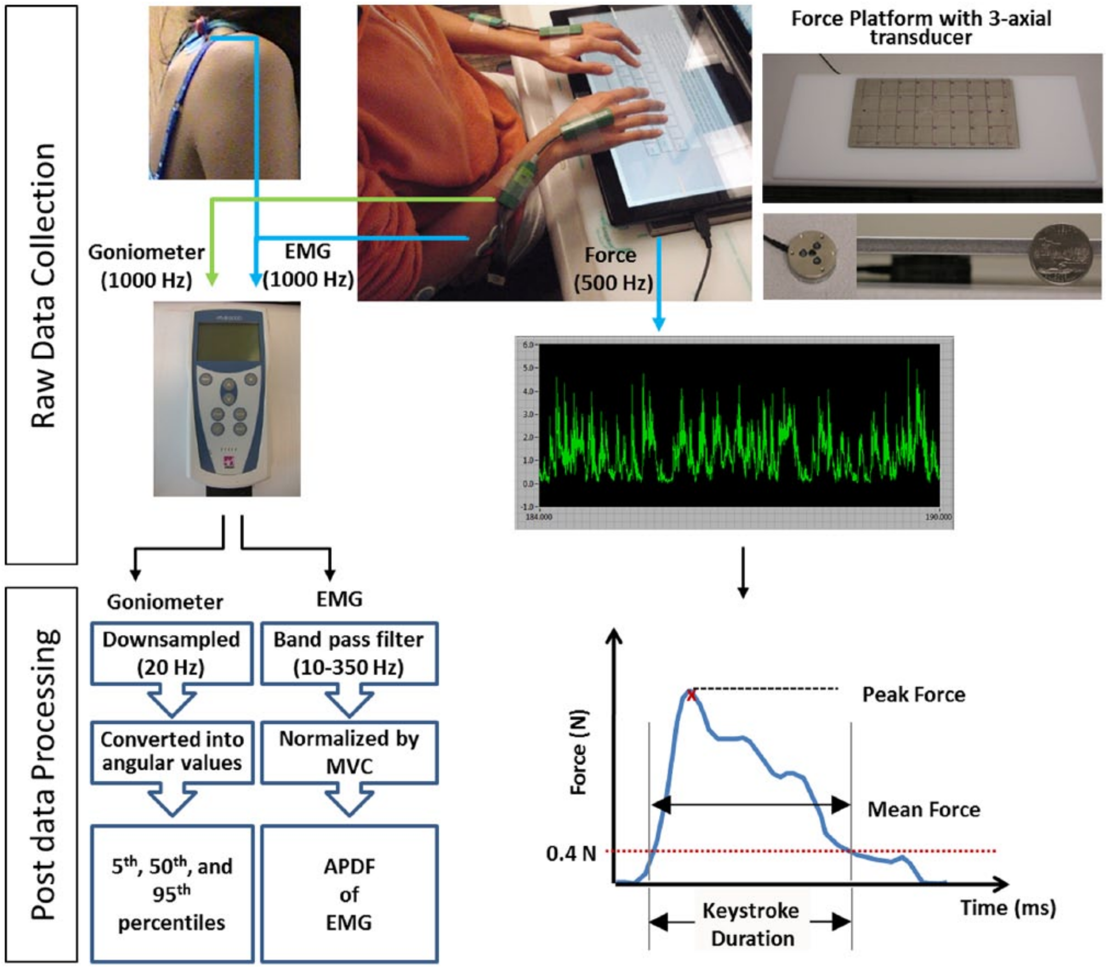

Figure 2. Experimental setup.

Muscle Activity

Muscle activity was recorded from the right extensor digitorum communis (EDC), right flexor digitorum superficialis (FDS), and right trapezius (TRAP) muscle with the use of a data logger (ME6000; Mega Electronics, Kupio, Finland) at a sampling rate of 1000 Hz during the entire typing session. The EDC and FDS muscle identification and electrode placement were performed according to the methods by Basmajian and De Luca (1985) and Perotto and Delagi (1994), and electrode placement for TRAP muscle was done using the methods prescribed by Jensen, Vasseljen, and Westgaard (1993).

After collecting the raw electromyography (EMG) data, a band pass filter of 10 to 350 Hz was applied. The filtered EMG data from the EDC, FDS, and TRAP muscles were normalized as a percentage of the maximum voluntary contraction (MVC); the 10th percentile (static), 50th percentile (median), and 90th percentile (peak) amplitude probability density function (APDF) muscle activities were calculated (Jonsson, 1982). To obtain the MVCs, subjects were instructed to extend their wrists and fingers up against resistance (EDC) and to flex their fingers down against resistance (FDS) with verbal encouragement. TRAP MVCs were obtained using the methods prescribed by Schuldt and Harmsringdahl (Harmsringdahl, Ekholm, Schuldt, Linder, & Ericson, 1996; Schuldt & Harmsringdahl, 1988). Subjects were asked to

TABLE 1: Demographics and Anthropometry Measures of Study Population (N = 21)

Variable	Male (n = 12)	Female (n = 9)	p
Age (years)	23.8 (5.2)	25.4 (9.5)	.62
Computer use (years)	15.0 (2.6)	15.8 (4.3)	.64
Height (cm)	181.0 (6.8)	169.9 (7.1)	.002
Weight (kg)	80.8 (12.8)	68.3 (7.7)	.02
Chair height (cm)	48.0 (0.8)	45.2 (1.0)	.04
Elbow height (cm)	68.0 (1.1)	65.7 (1.3)	.29
Desk height (cm)	66.3 (0.6)	62.9 (0.6)	.002
Finger length (mm)			
Index	75.9 (5.2)	68.6 (4.2)	.003
Middle	84.6 (4.5)	76.4 (4.8)	.0001
Ring	79.6 (4.0)	70.2 (4.1)	<.0001
Little	65.0 (4.0)	55.8 (4.7)	.0001
Finger width (mm)			
Index	18.9 (1.1)	17.0 (0.9)	.0004
Middle	19.5 (1.0)	17.3 (1.0)	<.0001
Ring	18.8 (1.5)	16.7 (1.0)	.0013
Little	17.0 (1.0)	14.9 (0.8)	<.0001

Note. Means shown with standard errors in parentheses.

practice their MVCs before the actual measurement. Each contraction time lasted for 3 s (Soderberg & Knutson, 2000) with a 3- to 5-s break between contractions. Three MVCs were collected from each muscle; the maximum of the highest root mean square signal over a 1-s period was identified and used to normalize the EMG data. To confirm that maximum activity was elicited, we visually monitored the data logger. However, we were not able to numerically confirm the MVC in real time.

Wrist Posture

Wrist postures, including flexion/extension and radial/ulnar deviation, were measured from both hands using biaxial electrogoniometers (Model SG-75; Biometrics Ltd., Newport, UK) during the entire typing session. The attachment and calibration of the electrogoniometers were performed using the methods prescribed by Johnson (Johnson, Jonsson, & Hagberg, 2002; Jonsson & Johnson, 2001). The calibration was performed to reduce offset errors. The raw goniometer data were synchronously collected with the EMG signals at 1000 Hz using the same aforementioned digital data logger (Mega ME6000; Mega Electronics, Kupio, Finland). After data collection, the raw goniometer data were parsed and down-sampled to 20 Hz. The 5th, 50th, and 95th percentile values were then calculated for the flexion/extension and radial/ulnar deviation planes (Blackstone, Karr, Camp, & Johnson, 2008). The 5th and 95th percentiles represented the extreme wrist postures, and the 50th percentile represented the central tendency of the wrist posture. Last, the ranges of motion in the flexion/extension and radial/ulnar deviation planes were calculated based on 5th and 95th percentiles during keyboard typing (Blackstone et al., 2008).

Data Analysis

A mixed model with restricted maximum likelihood estimation (REML) in JMP (Version 9; SAS Institute Inc., Cary, SC, USA) was used to determine whether key sizes affected typing forces, muscle activity, wrist posture, and typing performance. Any statistical significance was followed up with a Tukey-Kramer post hoc test to determine whether there were significant differences between key sizes. 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 subjective 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.

RESULTS

Study subjects' demographic and anthropometric data are summarized in Table 1. There were no gender-related differences in age and computer experience, whereas males' anthropometry measures were significantly greater than the females' measures. Anthropometric data were not significantly different when compared to the corresponding U.S. population data (ADULTDATA, 1998). Also, subjects' anthropometry covered from 20th to 100th percentile U.S. adult

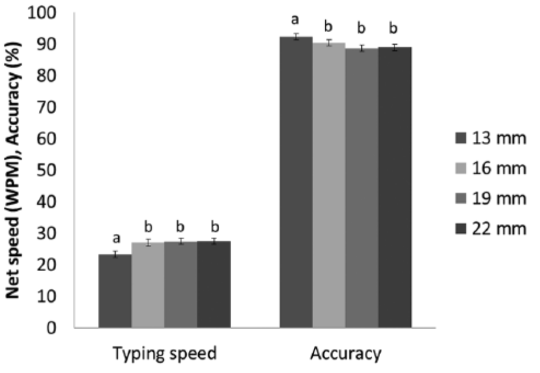

Figure 3. Mean (*SE*) comparison of adjusted typing speed and accuracy by key size. The different superscripts indicate significant difference between key sizes ($N = 21$).

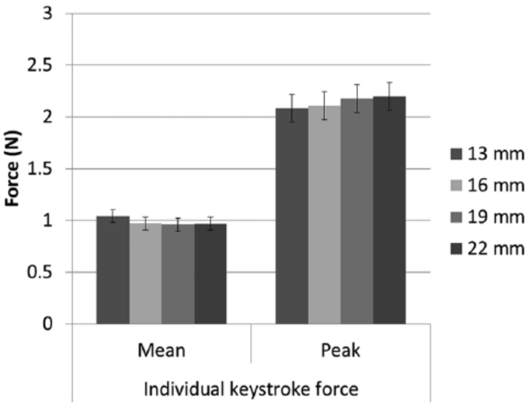

Figure 4. Mean (*SE*) comparison of individual keystroke forces across the four different key sizes ($N = 20$).

TABLE 2: Pearson's Product-Moment Coefficients Between Index Finger Width and Typing Performance ($N = 20$)

	Accuracy		Adjusted WPM	
Keyboard	*r*	*p*	*r*	*p*
13 mm	–.04	.74	–.20	.09
16 mm	–.29	.01	.13	.27
19 mm	–.24	.04	–.18	.11
21 mm	–.30	.01	.02	.87

Note. WPM = words per minute.

population. Therefore, the study population was thought to be representative of the U.S. population in terms of their anthropometry.

Typing Performance

As shown in Figure 3, adjusted typing speed ($M \pm SE$) on the 13-mm virtual keyboard (15-mm center-to-center spacing) was approximately 15% slower (23.3 ± 1.0 WPM) compared to the other virtual keyboards ($p < .0001$), whereas no significant difference existed between the other keyboards. Accuracy ($M \pm SE$) on 13-mm virtual keyboard was 4.5% higher (92.3% ± 1.0) than the other virtual keyboards ($p = .004$) and likely a product of the slower typing speed.

The Pearson's product-moment coefficients between index finger width and typing performance are shown in Table 2. The results showed typing accuracy was negatively correlated with index finger width on 16-, 19-, and 22-mm keyboards ($p = .01$, .04, and .01, respectively); that is, typing accuracy declined as index finger width increased. Although no statistically significant relationship was found between index finger width and adjusted typing speed, a negative correlation was identified on the 13-mm keyboard ($p = .09$).

Typing Forces

Due to technical difficulties, typing forces were recorded from 20 of 21 subjects. As shown in Figure 4, key size of the virtual keyboard did not alter mean and peak individual keystroke forces ($p = .30$ and .60, respectively).

Muscle Activity

Due to technical difficulties, EMG data from 2 subjects were not recorded; therefore, the EMG results were based on 19 of 21 subjects. The static (10th percentile), median (50th percentile), and peak (90th percentile) muscle activity levels collected from each muscle were compared across the four key sizes (Figure 5).

Finger flexor and extensor muscle activity. The results indicated that virtual keyboard key size had little effect on FDS and EDC muscle activity (Figure 5). Peak (90th percentile) muscle activity from the FDS muscle was slightly higher with the virtual keyboards with the larger

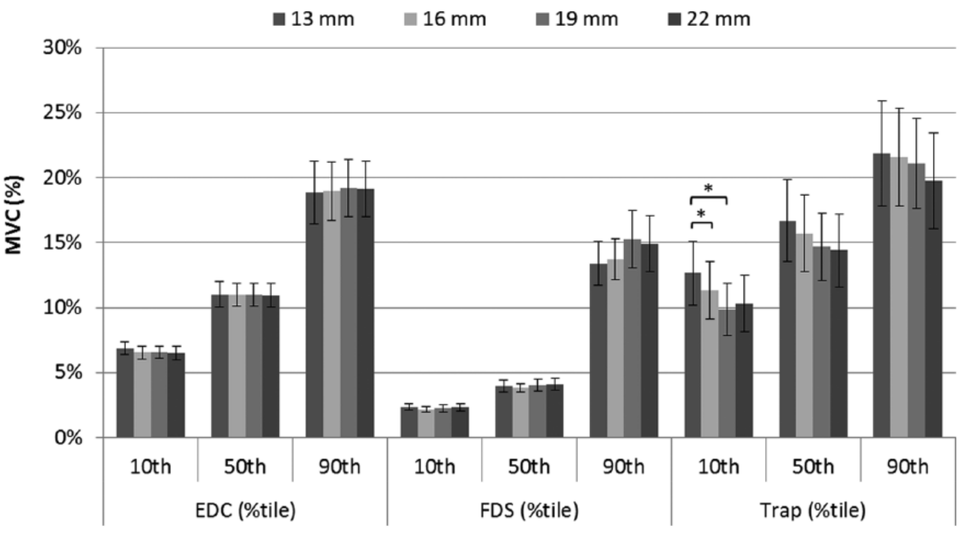

Figure 5. Mean (*SE*) 10th, 50th, and 90th percentile muscle activity the EDC (extensor digitorum communis), FDS (flexor digitorum superficialis), and TRAP (trapezius) muscles. The brackets with asterisks indicate significant differences between key sizes (N = 19).

keys (19 and 22 mm); however, differences were not significant (p = .19).

TRAP muscle activity. As shown in Figure 5, the results showed an inverse relationship between key sizes and TRAP muscle activity, especially for static (10th percentile) muscle activity. The virtual keyboard with the 13-mm keys had greater static TRAP muscle activity compared to the virtual keyboards with the 19- and 22-mm keys (2% MVC, p = .01). Although no significant differences in median (50th percentile) and peak (90th percentile) muscle activity were present across the four virtual keyboard key sizes, median and peak TRAP muscle activity gradually increased as the virtual keyboard key size decreased.

Wrist Posture

Similar to the EMG data, electrogoniometer data from 2 subjects were not recorded; therefore, the wrist posture results were based on measurements from 19 of 21 subjects. The results showed that virtual keyboard key size affected wrist extension and flexion, whereas radial/ulnar deviation was not influenced by key size (Table 3). The central tendency of wrist posture, represented by 50th percentile indicated that smaller key sizes (13 and 16 mm) tended to have more wrist extension (p < 0.01). The 5th percentile wrist angles indicated that smaller key sizes (13 and 16 mm) had less extreme wrist flexion by 2° to 4° (p < .0001), whereas the 95th percentile wrist angles indicated wrist extension was greater in the left hand when using the virtual keyboard with the smallest (13-mm) keys (p = .01).

When looking at the differences in ranges of wrist motion (95th to 5th percentile) between the virtual keyboards, we found that the virtual keyboards with the larger keys (19 and 22 mm) required greater ranges of motion in radial/ulnar deviation (0.1° to 2.7°, p = .02) and flexion/extension (1.8° to 3.5°, p < .0001) in the right hand, whereas there were no range-of-motion differences in the left hand (Table 3).

Subjective Comfort and Preference

The results showed that the 13-mm virtual keyboard consistently had the lowest comfort ratings on the upper extremities, whereas no differences on comfort ratings were found across the 16-, 19-, and 22-mm virtual keyboards (Table 4). Hand/wrist comfort ratings showed that typing on the virtual keyboard with the 13-mm keys was the most uncomfortable (p = .002), whereas no differences on hand/wrist

TABLE 3: Mean 5th, 50th, and 95th Percentile Wrist Angles (in degrees) in Flexion/Extension (F/E) and Radial/Ulnar Deviation (R/U) (N = 19)

		Keyboard				
Percentile	Hand	13 mm	16 mm	19 mm	22 mm	p
F/E						
5th	Left	–4.3 (1.6)[a]	–6.2 (1.6)[b]	–8.0 (1.6)[c]	–8.1 (1.6)[c]	<.0001
	Right	–3.0 (3.1)[a]	–3.6 (3.1)[a]	–6.9 (3.1)[b]	–6.6 (3.1)[b]	<.0001
50th	Left	5.2 (1.7)[a]	3.5 (1.7)[a,b]	2.0 (1.7)[b]	2.7 (1.7)[b]	.003
	Right	6.4 (3.1)[a,b]	6.8 (3.1)[a]	4.1 (3.1)[b]	4.6 (3.1)[a,b]	.01
95th	Left	13.9 (1.8)[a]	12.7 (1.8)[a,b]	10.9 (1.8)[b]	11.5 (1.8)[a,b]	.01
	Right	15.5 (3.3)[a]	16.4 (3.3)[a]	14.9 (3.3)[a]	15.4 (3.3)[a]	.47
R/U						
5th	Left	9.9 (1.6)[a]	10.0 (1.6)[a]	10.5 (1.6)[a]	10.3 (1.6)[a]	.91
	Right	8.3 (1.8)[a]	6.4 (1.8)[a]	7.2 (1.8)[a]	6.8 (1.8)[a]	.18
50th	Left	16.9 (1.5)[a]	17.3 (1.5)[a]	17.4 (1.5)[a]	16.6 (1.5)[a]	.53
	Right	13.0 (1.7)[a,b]	12.5 (1.7)[a]	12.6 (1.7)[a]	12.6 (1.7)[a]	.70
95th	Left	22.2 (1.5)[a]	22.8 (1.5)[a]	23.1 (1.5)[a]	22.5 (1.5)[a]	.27
	Right	17.3 (1.8)[a]	17.2 (1.8)[a]	18.1 (1.8)[a]	18.5 (1.8)[a]	.08

Note. Standard errors shown in parentheses. Negative values indicate flexion and radial deviation and positive values indicate extension and ulnar deviation. The values with different superscripts across rows indicate significant differences.

TABLE 4: Mean Subjective Comfort and Preference Ratings (N = 21)

	Keyboard				
Measure	13 mm	16 mm	19 mm	22 mm	p
Hand/wrist comfort	2.3 (0.2)[a]	3.3 (0.3)[b]	3.6 (0.3)[b]	3.4 (0.3)[b]	.002
Arm/shoulder comfort	2.7 (0.3)[a]	3.2 (0.3)[a,b]	3.6 (0.3)[c]	3.6 (0.3)[b,c]	.002
Typing speed	2.1 (0.2)[a]	3.0 (0.3)[b]	3.3 (0.3)[b]	2.9 (0.3)[b]	.003
Typing accuracy	2.4 (0.3)[a]	3.5 (0.3)[b]	3.7 (0.3)[b]	3.7 (0.3)[b]	.03
Adjustment speed	3.0 (0.4)[a]	4.0 (0.3)[a]	4.1 (0.3)[a]	3.9 (0.3)[a]	.09
Ease of use	2.2 (0.4)[a]	3.7 (0.4)[b]	4.0 (0.3)[b]	4.0 (0.3)[b]	<.0001
Reaching keys	2.7 (0.3)[a]	3.8 (0.3)[a,b]	4.3 (0.3)[b]	3.9 (0.3)[a,b]	.047

Note. Standard errors shown in parentheses. A 7-point Likert scale was used with 1 indicating *least preferable* and 7 *most preferable*. The values with different superscripts across rows indicate significant differences.

comfort were found across the other keyboards. Arm/shoulder comfort data demonstrated that the virtual keyboard with the 13-mm keys also had lower comfort ratings (p = .002) compared to the virtual keyboards with the larger keys (19 and 22 mm).

Preference ratings demonstrated that the virtual keyboard with the 13-mm keys was least preferred in terms of typing performance and usability. Subjective performance measures (Table 4) also indicated the virtual keyboard with the 13-mm keys was rated as the worst in terms of typing speed and accuracy (p = .003 and .03, respectively), which was similar to the objective performance measures except for the accuracy (Figure 3). Time to adjust to using the virtual keyboard with the 13-mm keys was perceived to take longer compared to the virtual keyboard with the 16-mm keys (p = .09). The virtual keyboard with the 13-mm keys was rated as the most difficult keyboard for subjects to type on (p < .0001) and to reach the keys (p = .05), whereas no differences in ease of use was found between the other keyboards.

DISCUSSION

Despite the prevalent use of virtual keyboards on touch screen devices, there has been a lack of research and guidelines for key sizes on such touch screen interfaces. Currently, virtual key sizes range from 9 mm on smaller devices to as large as 18 mm on larger devices. As such, we investigated whether different key sizes on a touch screen virtual keyboard affected typing biomechanics, wrist posture, typing productivity, and subjective comfort and usability. Based on the anthropometrics (finger width and length) of our study population, which spanned the 20th to 100th percentile U.S. adult population, our results indicated that the virtual keyboard with the 13-mm keys (15-mm center-to-center key spacing) may not be an appropriate key size for a virtual keyboard, given slower typing speed, higher static shoulder activity, greater wrist extension, and lowest subjective preferences.

Both objective (Figure 3) and subjective (Table 4) typing proficiency measures showed that the virtual keyboard with the 13-mm keys had a reduced typing proficiency compared to the other keyboards. The slower typing speed with the smaller key sizes is in line with those reported by previous studies (Colle & Hiszem, 2004; Lee & Zhai, 2009; Pereira et al., 2012; Sears, 1991; Sears et al., 1993; Sears & Zha, 2003; Yoshitake, 1995). Yoshitake (1995) and Pereira et al. (2012) showed that typing speed decreased when key spacing of a conventional keyboard with tactile feedback was 16 mm or smaller. Other studies have also shown that reducing key sizes on virtual keyboards decreased typing speed (Lee & Zhai, 2009; Sears et al., 1993; Sears & Zha, 2003). These studies demonstrated that key spacing may be limited by finger width and that typing productivity significantly decreased when key size and/or center-to-center key spacing were less than finger width.

The present study also showed that typing accuracy and speed had a negative relationship with finger width (Table 2); that is, subjects with wider fingers showed less typing accuracy on most virtual keyboards and slower typing speed especially for the smallest virtual keyboard key size (13 mm). As pointed out in Pereira's studies (Pereira et al., 2012; Pereira, Hsieh, Laroche, & Rempel, 2013), the slower typing speed on smaller key sizes may be due to a lack of clearance between keys when compared relative to the subject's finger width. Since the average finger width of this study population was approximately 18 mm (Table 1), the 15-mm center to-center key spacing on the virtual keyboard with the 13-mm keys may have caused interference between fingers when typing, with the end result being a slower typing speed. As shown in Table 4, this limited clearance on the virtual keyboard with 13-mm keys may have contributed to the poor subjective ratings associated with reaching the keys.

The forearm muscle activity showed that virtual keyboard key size had a limited impact on EDC and FDS muscle activity (Figure 5). Pereira et al. (2012) also found that center-to-center key spacing of conventional keyboards had a minimal effect on forearm muscle activity. Despite the limited effect of key sizes, peak (90th percentile) FDS and EDC muscle activity showed a trend that larger key sizes were associated with higher muscle activity. The slightly higher muscle activity with larger key sizes may have been due to slightly faster typing speed and slightly higher typing forces, which occured during the use of virtual keyboards with larger key sizes.

On the other hand, compared to the virtual keyboards with larger keys, static (10th percentile) shoulder muscle activity was higher (2% MVC) when using the virtual keyboard with the 13-mm keys (Figure 5). Although the difference of 2% MVC seems to be small, this small difference may become important when we consider longer exposure time (Pereira et al., 2012). Previous studies suggested that virtual keyboard use could increase the visual demands to locate the keys and therefore increase shoulder muscle activity (Shin & Zhu, 2011). Since visual demands are known to increase as a target size decreases, the smaller key size may have increased the visual demands and therefore increased shoulder muscle activity. This increased shoulder muscle activity was accompanied by the lowest comfort ratings for the arm and shoulder regions (Table 4).

The wrist goniometer data showed that virtual keyboard key size had a minimal effect on radial/ulnar deviation, whereas wrist extension was affected by the different key sizes, especially in the left wrist. The 50th percentile and 95th percentile wrist angles showed that the virtual keyboard with the 13-mm keys caused slightly more wrist extension during typing. Pereira et al. (2012) also found greater wrist extension with smaller key spacing. The greater wrist extension with smaller keys may be due to users having to extend their wrists to see the smaller keys. Although the wrist extension differences between the key sizes were less than 5°, prolonged virtual keyboard use with less neutral wrist posture may increase biomechanical loads. Given that users cannot rest their fingers on the touch screen keys, small non-neutral wrist postures, in combination with more awkward finger postures, may increase carpal tunnel pressure (Keir, Bach, & Rempel, 1998; Rempel, Keir, Smutz, & Hargens, 1997), flexor and extensor tendon force (Kursa, Lattanza, Diao, & Rempel, 2006), and/or discomfort. Indeed, the subjective comfort rating indicated that the virtual keyboard with the 13-mm keys was less comfortable than the keyboards with the larger keys (Table 4).

The present study showed that 50th percentile ulnar deviation was between 12.5° and 17.4° with 4° to 5° greater ulnar deviation on the left wrist. This finding agreed with the previous studies where average ulnar deviation ranged from 7° to 25° (Blackstone et al., 2008; Honan, Jacobson, Tal, & Rempel, 1996; Nakaseko, Grandjean, Hunting, & Gierer, 1985; Simoneau, Marklin, & Monroe, 1999; Sommerich, 1994; Sommerich, Marras, & Parnianpour, 1996). Previous studies (Hedge & Powers, 1995; Simoneau et al., 1999) also showed that ulnar deviation was a few degrees greater on the left wrist compared to the right wrist. On the other hand, 50th percentile wrist extension was between 2.0° and 6.8° and substantially lower compared to previous studies in which wrist extension angles ranged between 13° and 33° (Blackstone et al., 2008; Hedge & Powers, 1995; Honan et al., 1996; Sommerich, 1994). Since virtual keyboards may have keys that are lower in height than tactile keyboards and have capacitive key sensors that can be accidentally activated with physical contact, the lower degree of wrist extension with the virtual keyboard may be due to the lower key height and less opportunity for wrist support when typing.

We hypothesized that different key sizes and key spacing may affect typing forces because previous studies have shown that finger postures affect finger joint characteristics and therefore determine applied finger forces during keyboard typing (Jindrich et al., 2004a, 2004b; Wu et al., 2008). However, the results showed that there were no differences in keystroke forces between the four key sizes. As the study did not measure finger posture, it was unclear if the virtual keyboard key size affected finger posture. However, the measured differences in wrist postures between the different key sizes indicated that subjects had to change the wrist postures to accommodate the different key sizes.

Finally, the present study has some limitations. In order to measure typing forces without artificial force effects from resting their wrists on the virtual keyboard, we did ask subjects to not rest their wrists on the virtual keyboard during typing. If the subjects typed with their wrists unsupported for a larger percentage of time compared to real situations outside of this lab-based experiment, this may have resulted in overestimation of shoulder muscle activity. Nonetheless, as the present study compared muscle activity under controlled identical conditions across all the virtual keyboard key sizes, the muscle activity comparisons should still provide valid and meaningful information. Another limitation was the relatively short exposure duration: two 5-min typing sessions on each virtual keyboard key size. However, all the subjects were familiar with virtual keyboards as they owned either smartphones, iPads, or tablets. In addition, a subsequent analysis of the data by order indicated there was no improvement in typing speed between the first typing session and the last session. Therefore, it appears the learning effect, if present in this experiment, was small.

Furthermore, previous studies evaluating typing on various keyboards (Gerard et al., 1999; Gerard, Armstrong, Rempel, & Woolley, 2002; Pereira et al., 2012) have shown that the keyboard-use duration in this study should be sufficient to provide stable results over time. Nonetheless, in future studies, when feasible, it would be worthwhile to give longer practice sessions or even to use the testing device for a period before the experiment. Last, the breaks between MVCs were relatively shorter (3 to 5 s) than the widely accepted duration (2 min). However, although the short duration may affect our absolute percentage MVC values and comparability of our EMG results to other studies, it will not affect our between–key size EMG comparisons in this study.

In conclusion, this study demonstrated that virtual keyboard key size had a minimal effect on typing force, forearm muscle activity, and ulnar/radial deviation, whereas virtual keyboard key size affected typing speed, static (10th percentile) shoulder muscle activity, wrist extension, and subjective comfort and preferences. The use of the virtual keyboard with 13-mm keys resulted in 15% slower typing speed, slightly higher static shoulder muscle activity (2% MVC), slightly more wrist extension (2° to 3°), and the lowest subjective comfort and preference ratings. These findings suggested that 13-mm key size for virtual keyboards may not be an appropriate size for touch typing.

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KEY POINTS

- In this study, virtual keyboard key size had a minimal effect on typing force, forearm muscle activity, and ulnar/radial deviation.
- Thirteen millimeters of virtual keyboard key size (15-mm center-to-center key spacing) showed 15% slower typing speed, slightly higher static shoulder muscle activity (2% MVC), slightly more wrist extension (2° to 3°), and the lowest subjective comfort and preference ratings.
- The study findings indicate that virtual keyboards with a center-to-center key spacing less than 16 mm may be less appropriate for touch-typing.

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