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ARTICLE

Influence of virtual keyboard design and usage posture on typing performance and muscle activity during tablet interaction

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ABSTRACT
This study aimed to determine the effects of virtual keyboard designs and postures on task performance and muscle activity during tablet use. Eighteen healthy adults were randomly assigned to one of three postures (DESK, LAP, BED) to complete six sessions of 60-minute typing on a tablet with three virtual keyboards (STD, WIDE, SPLIT) twice in an experimental laboratory. Keystroke dynamics and muscle activity of the forearm and neck-shoulder regions were measured by electromyography. The split virtual keyboard was found to be associated with faster typing speed (SPLIT vs STD, $p = .015$; SPLIT vs WIDE, $p < .001$) and decreased muscle activity of extensor digitorum communis (SPLIT vs STD, $p = .021$). Lap posture was associated with faster typing speed ($p = .018$) and higher forearm muscle activity ($p < .05$). Typing performance decreased ($p < .001$) with elevated neck extensor muscle activity ($p = .042$) when the task duration prolonged. The split virtual keyboard showed potential to improve tablet ergonomics under various postures.

Practitioner Summary: Tablets have become widely used for a variety of tasks and have gradually expanded into the realm of mobile productivity and education. Adequate designs of virtual keyboards for tablets show the potential for increased task performance and decreased muscle activity pertinent to typing activity and posture constraints imposed by non-traditional work positions.

Abbreviations: WPM: words per minute; IKI: inter-key press interval; EMG: electromyography; EDC: extensor digitorum communis; FDS: flexor digitorum superficialis; CES: cervical erector spinae; UT: upper trapezius; EA: electrical activity; MVC: maximum voluntary contraction; APDF: amplitude probability distribution function

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Introduction

Since Apple introduced its first touchscreen tablet in 2010, the market for tablet computers experienced rapid growth, with the total shipments in 2017 accounting for 164 million units worldwide (Liu 2019). With years of design improvements, tablets have evolved from a device used mainly for media consumption to a mobile computing platform with potential in the commercial and education fields. A recent Australia survey among children in a socio-educationally advantaged school showed that the average daily use of tablets is high and substantially surpasses that of other information technology devices (e.g. television, mobile phone, desktop and laptop computer) in grades 5–9 (Straker et al. 2018). Inevitably, there have been concerns about possible adverse effects of tablet use on the users' musculoskeletal system and visual health (Shan et al. 2013; Toh et al. 2017; Straker et al. 2018).

It is already known that non-neutral postures, highly repetitive movements, and extended usage durations are considered risk factors for neck and upper extremity musculoskeletal symptoms associated with computer work (Gerr, Monteilh, and Marcus 2006; Waersted, Hanvold, and Veiersted 2010; Coenen et al. 2019). Because of their unique portable design and integration of display and input functions on a single touchscreen, tablets are mainly operated via hand-gesture interfaces and are likely to be used while moving or in work positions that are uncommon in office settings. Therefore, previous findings based on traditional desktop computers may not be readily applicable to situations involving contemporary mobile touchscreen

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devices. For example, the work of Xie et al. (2016) showed that texting on a smartphone was associated with higher activity in the neck extensor and thumb muscles compared with that during typing on a physical computer keyboard. A large-scale survey of adolescents in China (Shan et al. 2013) also suggested that tablet use and other factors (e.g. sitting time after school, academic stress) were significantly associated with a high prevalence of neck and shoulder pain. Therefore, as the use of mobile touchscreen devices becomes pervasive in everyday life, there is a clear need for more studies to help researchers and the general public to gain a better understanding of the relationships between tablet use and physical demands imposed on the human body (Coenen et al. 2019). However, only limited research has been conducted to explore how tablet interaction and configuration affect musculoskeletal outcomes (Toh et al. 2017).

To alleviate adverse health problems related to prolonged keyboarding work, alternative geometric designs of physical computer keyboards (e.g. opening angle, slope angle, and title angle) have been proposed and extensively investigated (Marklin and Simoneau 2004; Rempel et al. 2009). The aforementioned studies generally suggested that more neutral postures (e.g. less wrist extension, less ulnar deviation, and less forearm pronation) will be assumed if users type on a split physical keyboard rather than a standard computer keyboard. Furthermore, reduced muscle activity of some forearm or shoulder muscles has been reported when a physical keyboard with split geometry was used in comparison to its straight counterpart (Gerard et al. 1994; Strasser, Fleischer, and Keller 2004). However, it is still unclear whether similar beneficial health effects can be achieved when adopting features of the alternative geometry used in physical keyboards into the design of virtual keyboards for tablets.

Trudeau et al. (2013) suggested that when typing with thumbs in a two-hand grip posture, the tablet's keyboard configuration could affect the amount of thumb reaching and task performance. When examining the effects of the virtual keyboard design based on touch typing, using a virtual split-design keyboard was shown to be associated with a lesser degree of ulnar deviation and body discomfort perceived in the upper extremities compared to the standard straight layout (Lin et al. 2015). However, previous research regarding the effects of tablet use on muscle activity mainly focussed on the effects of screen size (Pereira et al. 2013; Kietrys et al. 2015), tilt angle (Chiu et al. 2015), grip shape (Pereira et al. 2013), task type (Young et al. 2013; Chiu et al. 2015), or swipe gesture (Coppola et al. 2018). The effect of travel distance or key-activated mechanism on typing productivity and user preference has also been investigated using tablet's virtual (onscreen) keyboards and external physical keyboards designed for tablet usage (Chaparro, Phan, and Jardina 2013; Hoyle et al. 2013; Chaparro et al. 2014). Nevertheless, how the geometric design of the virtual keyboard influences the extent of muscle activity during text entry using tablets largely remains to be determined (Toh et al. 2017). Werth and Babski-Reeves (2014) examined the physical loading elicited while typing on a laptop, notebook, and tablet and found no difference in the muscle activity of the flexor carpi radialis and extensor carpi radialis across the three devices; however, typing speed on the tablet was approximately four times slower than that observed on the other two portable devices. Their results may imply that muscle activity during the active cycle of typing on a virtual keyboard could actually be higher than that experienced using its physical counterpart (Gerard et al. 2002). Therefore, tablet users might be exposed to considerable physical strain or muscle fatigue after prolonged use of virtual keyboards, which is a phenomenon that has been reported by previous computer studies involving continuous typing (Lin et al. 2004).

Furthermore, with their lightweight and versatile design, tablets provide users more opportunities for mobile computing in usage postures that could be substantially different from those commonly assumed in office settings. The previous work of (Young et al. 2012; Young et al. 2013; Werth and Babski-Reeves 2014) indicated that working with a tablet while seated on a sofa generally resulted in non-neutral wrist, elbow, and neck postures compared to working while seated at a desk. Relative to desk posture, Vasavada et al. (2015) also observed an increase in neck flexion and the gravitational demand on the neck musculature when typing with a tablet on the lap. A study performed at our laboratory further reported that the geometric designs of virtual keyboards for tablets could affect the upper limb postures and perceived usability associated with unconventional work positions (Lin et al. 2015). The posture difference associated with positions of tablet use, however, may not always be in accordance with the change in muscle activity experienced (Toh et al. 2017). For example, notwithstanding the significant difference in wrist extension, similar levels of muscle activity of the flexor carpi radialis, flexor carpi ulnaris, and extensor carpi radialis were found when participants performed email reading and responding tasks with a tablet held on their laps compared to on a desk surface (Young et al. 2013). Moreover, to our knowledge, there has been no specific investigation of how virtual keyboard designs and usage postures affect muscle activity and task performance during an extended period of tablet typing. A research gap exists in published ergonomics standards and guidelines for contemporary screen work in mobile environments (Woo et al. 2016). To enhance the understanding of the health and safety of tablet interaction, it is imperative to conduct more research to establish usage and design recommendations for tablets that favour musculoskeletal outcomes, physiological responses, and high levels of usability.

The goal of this study was to determine the influence of the virtual keyboard design on typing performance and muscle activity of the fingers and neck-shoulder region across usage postures while typing with a tablet supported on a surface. It was hypothesised that superior performance and lower muscle activity were associated with the split virtual keyboard design compared to the standard and wide keyboard designs. It was also expected that varying the geometric design of virtual keyboards would have different effects for participants who assumed different usage postures during tablet typing. When the task duration was prolonged, we expected that the typing performance and the extent of muscle activity would change to reflect the workload accumulated throughout that time period.

Materials and methods

Participants

A total of 18 right-hand-dominant participants (9 males and 9 females) ranging from 20 to 31 years of age (males: 24.8 ± 3.5; females: 23.1 ± 0.9; years) were recruited to complete tablet typing tasks in the laboratory for the present study. All participants were free from any type of musculoskeletal disorders and had no history of notable pain or injury in the neck, shoulder, back, buttocks, and extremities for at least 6 months. Moreover, they were able to touch type at a speed more than 35 words per minute (WPM), owned smartphones with touchscreens, and had limited experience with tablets. Based on the results of a 10-minute typing performance examination conducted using a 14-inch laptop computer during the recruitment session, no significant gender difference in either the typing speed (males: 44.3 ± 5.5 WPM; females: 45.5 ± 7.6 WPM) or the typing accuracy (males: $95.9 \pm 2.3\%$; females: $95.8 \pm 1.2\%$) was observed, based on the results of a Mann-Whitney *U* test.

Experimental design

The study was conducted using a 3×3 mixed design in a laboratory setting. The first manipulated factor was the usage posture of the tablet under three conditions (DESK, LAP, and BED), which was designed to simulate a scenario in which individuals placed a capacitive touchscreen tablet (9.7-inch iPad; Apple, Cupertino, CA, USA) on a desk, on the top of the lap, or on the thighs while 'crook sitting' on bed. Eighteen participants were randomly assigned to one of three groups of usage postures (i.e. six participants per group). Those in the desk group were first instructed to sit on an office chair and then adjust its height so that their thighs were parallel to the floor while sitting. The tablet was then placed in the landscape direction on a 74-cm-high desk with its central line matched with the midline of the participants' trunks. No additional footrest was provided. During the typing session, participants were required to have their forearms partially supported by the desk surface with the elbow angle remain between 70 and 135 degree (Figure 1(a)). This practice allowed them to shift their body slightly with regard to the tablet location during typing to avoid posture rigidity. For the lap posture group, participants had to sit on an adjustable piano chair and place the lower back against the backrest with thighs parallel to the floor and feet firmly on the ground. The tablet rested flat on the lap while typing (Figure 1(b)). Participants in the bed group were instructed to sit with a customised seat frame on a medical examination bed (Figure 1(c)). The padded seat frame allowed participants to assume an inclined sitting posture on bed while typing on the tablet. Participants were allowed to use their hands/wrists to better secure the tablet on the anterior surface of the thighs.

The second manipulated factor was the design of the virtual keyboard. A customised typing application (app) was created using the Xcode development environment (v.4.31; Apple); three different keyboard configurations (STD, WIDE, and SPLIT) could be selected for the tablet typing tasks. These virtual keyboards adopted the same QWERTY layout, but the key size and between-key spacing varied. The standard design (STD) referred to a keyboard layout identical to the default onscreen keyboard provided by iOS 5.1 with a key size of 15×14 mm (height x width), along with 3 mm horizontal and 2 mm vertical between-key spacing (Figure 2(a)). The wide keyboard design (WIDE)

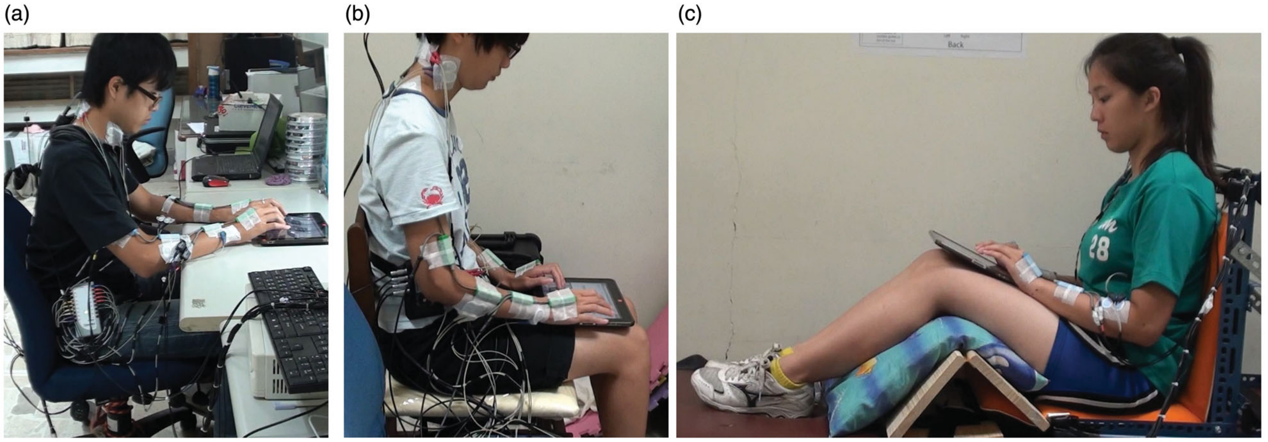

Figure 1. The three postures of tablet usage evaluated. (a) DESK posture, participants seated on an adjusted chair with the tablet on the desk. (b) LAP posture, participants seated on an adjusted chair with the tablet on the laps. (c) BED posture, participants seated on a bed with knees bent and the tablet on the thighs.

had a reduced key size (9 × 11 mm) with widened horizontal and vertical between-key spacing set to 7 mm and 3 mm, respectively (Figure 2(b)). Because early research suggested that key size and spacing of the touchscreen interfaces could significantly affect typing productivity and usability ratings (Kim et al. 2014b; Pereira et al. 2014), this particular keyboard geometry was chosen to extend the current understanding of touchscreen interaction outside traditional office settings. Finally, participants were asked to perform tablet typing on a virtual keyboard with the split design. The split configuration (SPLIT) was created by separating the original QWERTY layout from the edge of the T, G, and, B keys into two halves (Figure 2(c)). An opening angle of 15 degrees between the two keypads was chosen because this type of angled geometry has shown the potential to reduce wrist deviation in studies of physical keyboard designs (Rempel et al. 2009). During the typing session, the app displayed the text to be transcribed in the upper area of the screen and the keys pressed by the participant in the middle area. The AutoCorrect setting was disabled. To confirm the successful key activation, the key colour changed from light-gray to dark-gray. Neither auditory nor haptic feedback was provided. The typescripts consisted of English words randomly selected from the book *The Lord of the Rings* (written by J. R. R. Tolkien), with grammatical linkages and punctuation marks removed.

Typing performance

All events that occurred on the touchscreen interface were automatically recorded with corresponding timestamps in a log file by the typing app. The gross average typing speed (WPM), average typing accuracy (%), average keystroke duration (ms), and average inter-key press interval (ms) were then computed from the information stored in the log files. The keystroke duration was the time difference between the activation and release of a keystroke detected by the touchscreen interface of the tablet. In contrast, the time difference between the activation timings of two consecutive key presses was defined as the inter-key press interval (IKI). Previous research has found temporal changes in keystroke durations and, to a lesser extent, in IKI when the typing duration is prolonged (Liang, Hwang, and Chang 2008; Chang et al. 2009). The observed phenomena have been attributed to fatigue-compensated measures that reflect the tendency to rest the fingers on unused keycaps to alleviate physical loads required for maintaining the desired level of finger extension during consecutive typing (Liang, Hwang, and Chang 2008).

Muscle activity

During the entire typing session, a wireless surface electromyography (EMG) system (BioRadio 150; Great Lakes NeuroTechnologies, Independence, OH, USA) was used to record electrical muscle activity at a sampling rate of 960 Hz from the extensor digitorum communis (EDC) and flexor digitorum superficialis (FDS) bilaterally, as well as the right side of the cervical erector spinae (CES) and upper trapezius (UT). Individual muscle identification and the placement of surface electrodes were carefully performed according to established guidelines (Hermens 1999) and previous research (Lin et al. 2004; Szeto, Straker, and O'Sullivan 2009; Xie et al. 2016). A ground electrode was placed on the olecranon process of the right ulna bone. These superficial muscles were selected because they are either the major muscles

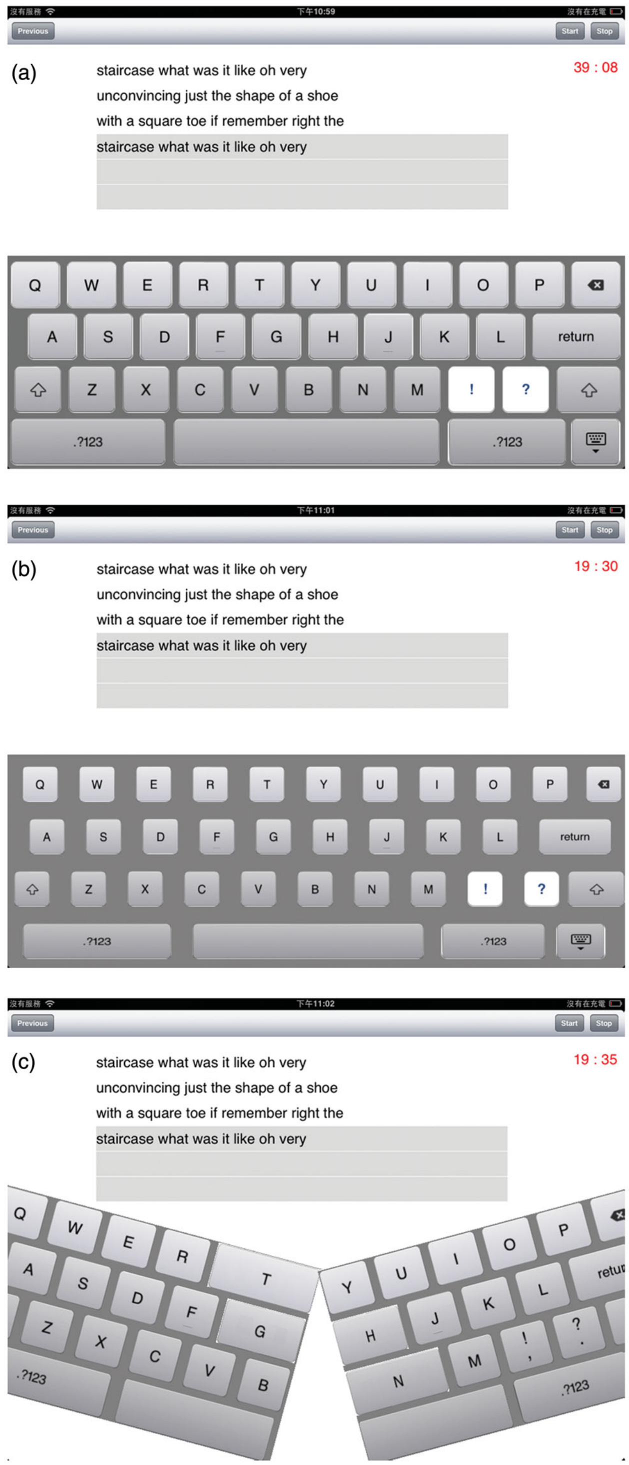

Figure 2. The three different designs of virtual keyboard investigated. (a) STD design, the default layout provided by the tablet's operation system. (b) WIDE design, the layout with broaden spacing between keys. (c) SPLIT design, the layout formed by two angled half keyboards.

controlling the finger movements during typing or the postural muscles of the neck and shoulder region commonly involved in sedentary activities (Young et al. 2013; Kim et al. 2014a; Werth and Babski-Reeves 2014; Chiu et al. 2015; Xie et al. 2016). Standard skin preparation procedures for the located electrode sites were conducted; hair was shaved and skin was cleaned using skin preparation gel and alcohol wipes. The electrode impedance was checked to ensure that an acceptable level was achieved (<5 Kohms). Silver/silver chloride surface electrodes (Ambu Neuroline 720) were placed using a bipolar arrangement on the aforementioned six muscles with an inter-electrode distance fixed at 20 mm.

A 10- to 450-Hz bandpass filter was digitally applied to the recorded EMG signals in MATLAB (R2014a; The MathWorks, Natick, MA, USA). After full-wave rectification, the filtered EMG data was used to calculate an amplitude measure, electrical activity (EA) (Basmajian and Deluca 1985) with a time window of 200 ms and further normalised as a percentage of the isometric maximum voluntary contraction (%MVC). Three trials of MVC testing were performed for each muscle. Each contraction lasted 5 seconds, with a 2-minute break between contractions. To obtain reference values to normalise muscle activity recorded from the EDC muscle, participants first needed to have the test side of the forearm supported on a desk surface in full pronation. They were then coached to gradually extend the fingers against a dynamometer placed on the dorsal surfaces of the proximal phalanges when the wrist was maintained in its neutral position (Lin et al. 2004; Cram and Criswell 2010). With the wrist fully supinated, MVC testing for the FDS muscle was obtained by the same protocol, but with the finger flexion manoeuvre. To test the MVC of CES and UT muscles, the methods described by Szeto, Straker, and O'Sullivan (2009) were adopted. The dynamometer reading was used to validate the reproductivity of force production during MVC testing trials. For individual muscles, the maximum EA value during the middle 3-second period of the MVC trials was identified and used to normalise the EMG data.

Protocols

Before data collection, experimental procedures and typing task requirements were explained to all participants in detail, and signed informed consent forms approved by the Intuitional Review Board of the National Cheng Kung University (A-ER-101-042) were obtained. To familiarise themselves with all virtual keyboard designs and experimental setups, participants were required to type on each keyboard in the assigned postures for 10 minutes and learned how to perform a series of MVC tests for all muscles that were monitored. The first formal typing session was then scheduled within two days. During the formal session, the participant was first attached to the surface EMG system, followed by conducting three MVC test trials for each monitored muscle. After assuming the assigned posture, the participant was instructed to perform a 60-minute typing task on the tablet using one of the three virtual keyboards examined in this study. The tablet was placed in the landscape orientation, with the spacebar centred on the participant's upper torso. The participant completed two replications of 60-minute typing sessions under the same keyboard-posture condition within the same day. A 30-minute break was provided between two sessions to minimise residual fatigue. The identical experimental protocol was used to conduct the remaining typing sessions for the same participant for the other two virtual keyboards with the same usage posture on two different days. Therefore, each participant had to complete a total of six typing sessions with the same usage posture using three different virtual keyboards twice. The order of three virtual keyboards examined for participants was counterbalanced within each posture group.

Data management and statistical analyses

For each 60-minute typing session, the data logs of keystrokes and EMG signals recorded during two time periods, the interval between minutes 10 and 15 and the interval between minutes 55 and 60, were used to quantify the typing performance and muscle activity for further statistical analyses. Normalised electrical activity (EA) values measured from individual muscles during corresponding time periods were summarised as the 10th, 50th (median), and 90th percentile of the amplitude probability distribution function (APDF; Jonsson 1982). Moreover, the APDF range, defined as the difference between the 10th percentile and 90th percentile of APDF, was also calculated to evaluate the dynamic variation of muscle activity during the corresponding time period (Dennerlein and Johnson 2006; Szeto, Straker, and O'Sullivan 2009). Differences in typing performance and APDF variables of muscle activity between conditions were evaluated using a repeated-measures analysis of variance (rANOVA) with linear mixed models in SAS (v9.4; SAS Institute, Cary, NC, USA). Box-Cox transformation was performed for typing speed, typing accuracy, and IKI because the data was not normally distributed. In the rANOVA, the keyboard configuration and time effect (10–15 minutes and 55–60 minutes) were treated as within-subject fixed factors, whereas the posture during tablet usage and gender were treated as between-subject fixed factors. We also added a random participant factor in each rANOVA model to account for the effect of individual differences. Tukey's post hoc test was performed across levels of the significant fixed factors, indicated by the omnibus F-test results. Significance was considered at $p < .05$.

Results

Typing performance

Significant differences in typing speed ($p = .022$, Cohen's $f^2 = 0.10$) and keystroke durations ($p = .046$, Cohen's $f^2 = 0.05$) were shown between usage postures. The lap posture was associated with faster average typing speeds and shorter average keystroke durations than the bed posture (typing speeds: 27.0 ± 4.7 WPM [LAP] and 23.3 ± 3.8 WPM [BED], $p = .018$, Cohen's d = 0.86; keystroke duration: 109 ± 19 ms [LAP] and 137 ± 41 ms [BED], $p = .040$, Cohen's d = 0.88). However, the observed posture effects were further influenced by the virtual keyboard design, as indicated by the significant posture-keyboard interactions (typing speed: $p = .016$, Cohen's $f^2 = 0.21$; keystroke duration: $p < .001$, Cohen's $f^2 = 0.21$). Discrepancies in the average typing speed between the lap posture and the other two postures were most obvious when the standard virtual keyboard was used (LAP > DESK, LAP > BED) (Figure 3(a)). Similarly, the aforementioned differences in keystroke durations between usage postures were mainly exhibited with the use of the wide virtual keyboard (BED > DESK > LAP) (Figure 3(b)). No significant changes in average typing accuracy or average IKI were observed across three postures during tablet use.

The design of virtual keyboard was associated with significant differences in all typing performance measurements (typing speed: $p < .001$, Cohen's $f^2 = 0.17$; typing accuracy: $p < .001$, Cohen's $f^2 = 0.07$; keystroke duration: $p < .001$, Cohen's $f^2 = 0.21$; inter-key press interval: $p = .004$, Cohen's $f^2 = 0.13$). Post hoc analyses of the keyboard design main effect suggested that the average typing speed recorded from the split virtual keyboard was faster than those from the standard virtual keyboard ($p = .015$, Cohen's d = 0.36) or wide virtual keyboard ($p < .001$, Cohen's d = 0.67; typing speeds: 26.5 ± 4.6 WPM [SPLIT], 24.8 ± 4.9 WPM [STD], 23.5 ± 4.4WPM [WIDE]). Nevertheless, no significant difference in average typing accuracy was observed between the split keyboard and two other keyboard configurations (STD: 81 ± 15%; WIDE: 85 ± 12%; SPLIT:

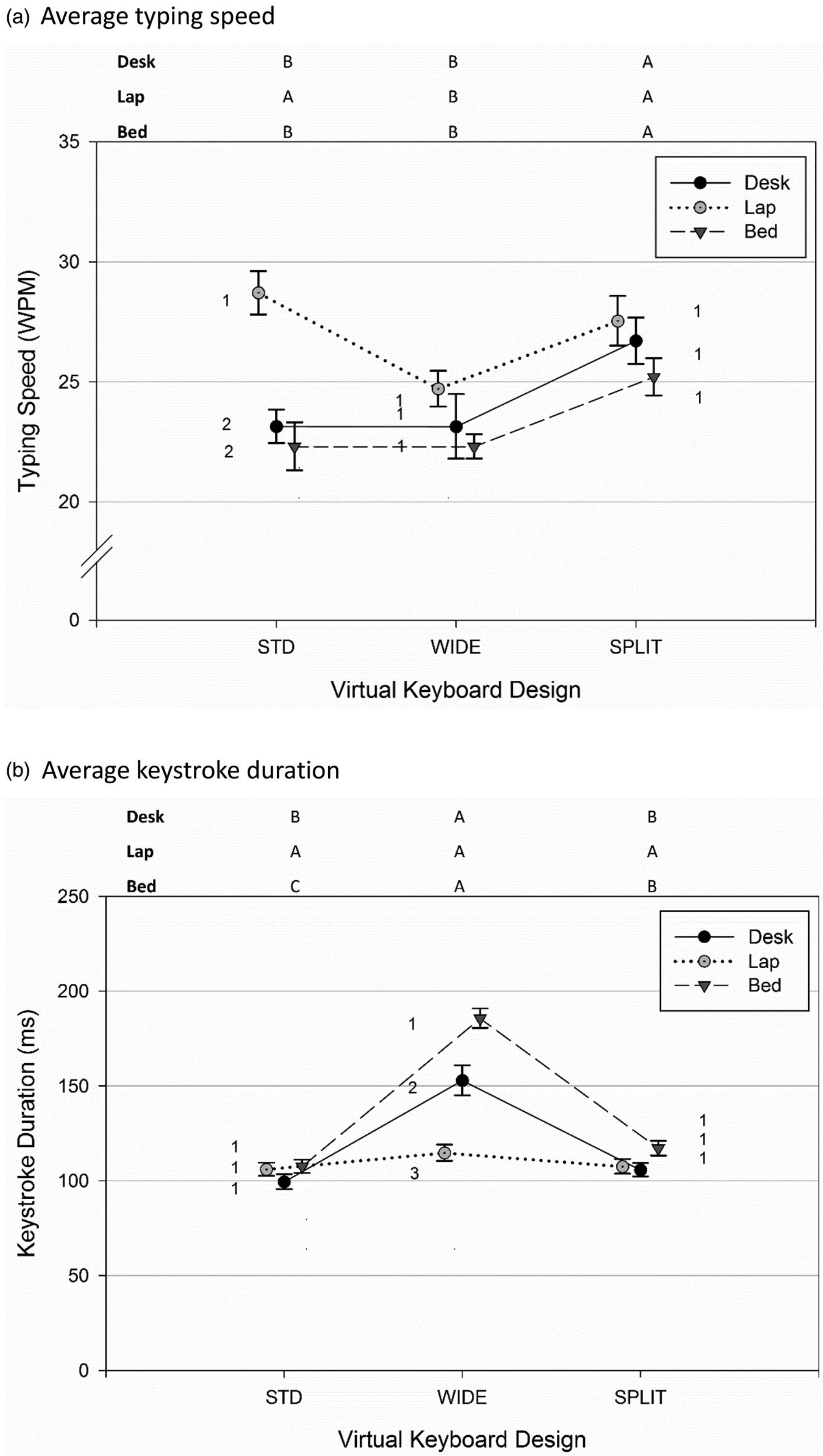

Figure 3. Interaction effects of typing performance across different virtual keyboard designs and usage postures of tablet. Error bars represent the mean ± 1SE. Conditions with the different character (A, B, C) indicates significant for the mean across virtual keyboard designs within the same usage posture based on Tukey's post-hoc comparison from rANOVA. Conditions with the different number (1, 2, 3) indicates significant for the mean across usage postures of tablet within the same virtual keyboard design based on Tukey's post-hoc comparison from rANOVA.

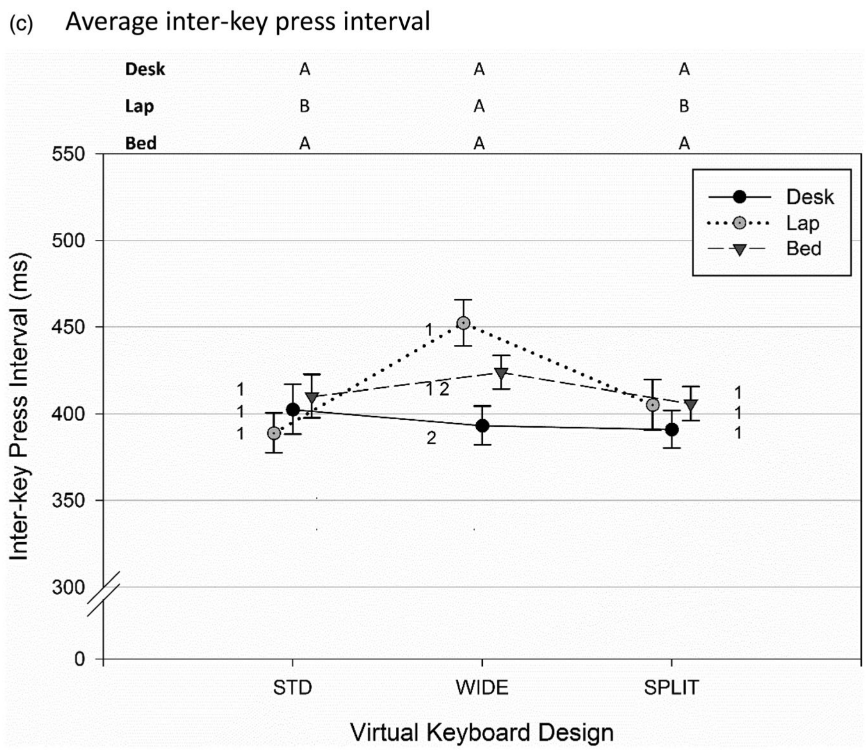

Figure 3. Continued

82 ± 15%). Typing on the wide virtual keyboard led to an increase in average typing accuracy of 5% compared to the standard virtual keyboard ($p < .001$, Cohen's $d = 0.30$). Regarding the measures of keystroke durations and IKI, both the split and standard virtual keyboards were associated with lower average values than those obtained from the wide virtual keyboard (keystroke duration: SPLIT vs WIDE, $p < .001$, Cohen's $d = 1.28$ and STD vs WIDE, $p < .001$, Cohen's $d = 1.48$; IKI: SPLIT vs WIDE, $p = .014$, Cohen's $d = 0.37$ and STD vs WIDE, $p = .008$, Cohen's $d = 0.41$). Participants also exhibited slightly shorter average keystroke durations with the standard virtual keyboard than with the split one ($p = .039$, Cohen's $d_s = 0.32$). Of note, there was a significant posture-keyboard interaction for IKI ($p = .009$, Cohen's $f^2 = 0.14$). As shown in Figure 3(c), significant differences in the average IKI between the wide virtual keyboard and the other virtual keyboards were only found in the lap posture condition, but not in the bed or desk condition.

There were significant differences in average typing speed and average IKI between measurements recorded during the time period of 10–15 min and those from the time period of 55–60 min. Specifically, participants typed slower and extended the time interval between key-pressings during the last 5-minute period compared to the early 5-minute period (typing speeds: 26 ± 4 WPM [10–15 minutes] and 24 ± 4 WPM [55–60 minutes], $p < .001$, Cohen's $f^2 = 0.10$; IKI: 401 ± 6 ms [10–15 minutes] and 415 ± 5 ms [55–60 minutes], $p = .011$, Cohen's $f^2 = 0.05$). Nevertheless, the following post hoc analyses revealed that the aforementioned time effects were negligible and considered statistically insignificant when tablet-typing tasks were performed on the split virtual keyboard (typing speed: $p = .162$; IKI: $p = .358$) or in the lap condition (typing speed: $p = .758$; IKI: $p = .904$). Regarding typing accuracy and keystroke durations, no significant change in the mean values was found between those calculated from the early (10–15 minutes) and late (55–60 minutes) durations. Male and female participants did not exhibit meaningful differences in any typing performance measures obtained from the various posture-keyboard scenarios examined in this study.

Muscle activity

Overall, significant effects of the usage posture were found during tablet typing when muscle activity of the forearms and neck/shoulder regions were examined (Table 1). Specifically, for the EDC (Figure 4(a)) and FDS muscles (Figure 4(b)), the recorded 50th percentile APDF amplitude of the EMG data in the lap condition was significantly higher than those recorded in the desk condition (LAP vs DESK: for left EDC, $p = .039$, Cohen's $d = 1.24$; for right EDC, $p = .009$,

Table 1. Least-square mean (SE) of APDF muscle activity for rANOVA main effects and associated *p*-values for the interactions[a],[b].

	Extensor Digitorum Communis Muscle				Flexor Digitorum Superficialis Muscle				Cervical Erector Spinae Muscle		Upper Trapezius Muscle	
	Left		Right		Left		Right		–		–	
	50th	APDF Range	50th	APDF Range	50th	APDF Range	50th	APDF Range	50th	APDF Range	50th	APDF Range
Posture												
p-value	**.034**	**.021**	**.011**	**.048**	.091	.585	**.004**	**.010**	**.004**	.125	**.021**	**.002**
DESK	8.6(0.9)^{B}	2.1(0.2)^{B}	7.7(0.7)^{B}	2.4(0.3)^{AB}	2.4(0.4)^{A}	1.2(0.3)^{A}	2.4(0.1)^{B}	1.1(0.2)^{B}	9.5(1.1)^{A}	2.0(0.3)^{A}	9.5(2.4)^{A}	4.6(0.5)^{A}
LAP	19.3(3.8)^{A}	5.3(1.1)^{A}	16.2(2.3)^{A}	4.5(0.9)^{A}	3.3(0.4)^{A}	1.5(0.1)^{A}	5.9(0.9)^{A}	3.1(0.5)^{A}	9.7(2.3)^{AB}	2.5(1.1)^{A}	2.3(0.2)^{B}	1.8(0.6)^{B}
BED	8.1(0.6)^{B}	2.6(0.2)^{AB}	9.3(1.5)^{AB}	2.1(0.2)^{B}	2.2(0.3)^{A}	1.4(0.3)^{A}	3.0(0.4)^{B}	1.6(0.2)^{B}	4.8(0.7)^{B}	1.2(0.2)^{A}	3.2(0.7)^{AB}	2.0(0.3)^{B}
Keyboard												
p-value	.399	.173	**.005**	.601	**.013**	**.008**	.214	**.030**	.067	**.010**	.583	.214
STD	12.1(1.3)^{A}	3.3(0.4)^{A}	12.0(1.0)^{A}	3.0(0.3)^{A}	2.7(0.2)^{AB}	1.2(0.1)^{B}	3.4(0.4)^{A}	1.6(0.2)^{B}	7.2(1.0)^{A}	1.6(0.4)^{B}	5.4(0.9)^{A}	2.3(0.4)^{A}
WIDE	12.2(1.3)^{A}	3.1(0.4)^{A}	10.5(1.0)^{B}	2.9(0.3)^{A}	2.4(0.2)^{B}	1.3(0.1)^{B}	4.1(0.4)^{A}	2.1(0.3)^{AB}	8.5(1.0)^{A}	1.9(0.4)^{AB}	4.9(0.9)^{A}	2.9(0.4)^{A}
SPLIT	11.6(1.3)^{A}	3.4(0.4)^{A}	10.6(1.0)^{B}	3.0(0.3)^{A}	2.9(0.2)^{A}	1.6(0.1)^{A}	3.7(0.4)^{A}	2.1(0.2)^{A}	8.3(1.0)^{A}	2.2(0.4)^{A}	4.7(0.9)^{A}	3.2(0.4)^{A}
Time												
p-value	.297	.639	.672	.952	.639	.797	.650	.666	**.042**	.166	.318	.144
10–15 min	12.4(1.4)^{A}	3.4(0.4)^{A}	11.2(1.0)^{A}	3.0(0.3)^{A}	2.6(0.2)^{A}	1.4(0.1)^{A}	3.7(0.4)^{A}	1.9(0.2)^{A}	7.5(0.9)^{B}	1.8(0.4)^{A}	4.7(0.9)^{A}	2.5(0.3)^{A}
55–60 min	11.6(1.4)^{A}	3.2(0.4)^{A}	11.0(1.0)^{A}	3.0(0.3)^{A}	2.7(0.2)^{A}	1.4(0.1)^{A}	3.8(0.4)^{A}	2.0(0.2)^{A}	8.5(0.9)^{A}	2.0(0.4)^{A}	5.3(0.9)^{A}	3.1(0.3)^{A}
Gender												
p-value	.117	.638	.633	.235	**.002**	**< .001**	**< .001**	.682	.968	.835	**< .001**	.464
Female	11.1(1.5)^{A}	3.2(0.5)^{A}	10.8(1.1)^{A}	2.7(0.3)^{A}	3.2(0.3)^{A}	1.9(0.2)^{A}	4.3(0.3)^{A}	2.0(0.2)^{A}	8.0(1.0)^{A}	1.9(0.4)^{A}	6.1(0.9)^{A}	3.0(0.4)^{A}
Male	12.9(1.3)^{A}	3.4(0.4)^{A}	11.4(1.1)^{A}	3.2(0.4)^{A}	2.1(0.3)^{B}	0.9(0.2)^{B}	3.2(0.4)^{B}	1.9(0.2)^{A}	8.0(1.0)^{A}	1.9(0.4)^{A}	3.9(0.9)^{B}	2.6(0.4)^{A}
Interactions												
Posture x Keyboard												
p-value	**.001**	**.044**	.286	.370	.191	**.048**	.173	.231	.097	.199	.173	.988
Posture x Time												
p-value	.988	.592	.423	.411	.834	.127	.974	.572	.287	.648	.824	.270
Keyboard x Time												
p-value	.930	.482	.977	.386	.667	.850	.965	.948	.563	.976	.943	.536
Gender x Time												
p-value	.513	.358	.584	.608	.447	.853	.441	.326	.509	.128	.566	.818

[a]Values are presented as normalised values with respect to the maximum muscle activity recorded during MVC tests for individual muscles (%MVC).

[b]For each main fixed factor, the groupings based on the host hoc analyses are indicated by the superscript and ranked in a descending order such as A > B > C. The same superscript means no significant difference.

Bold values represent *p*-value < 0.05.

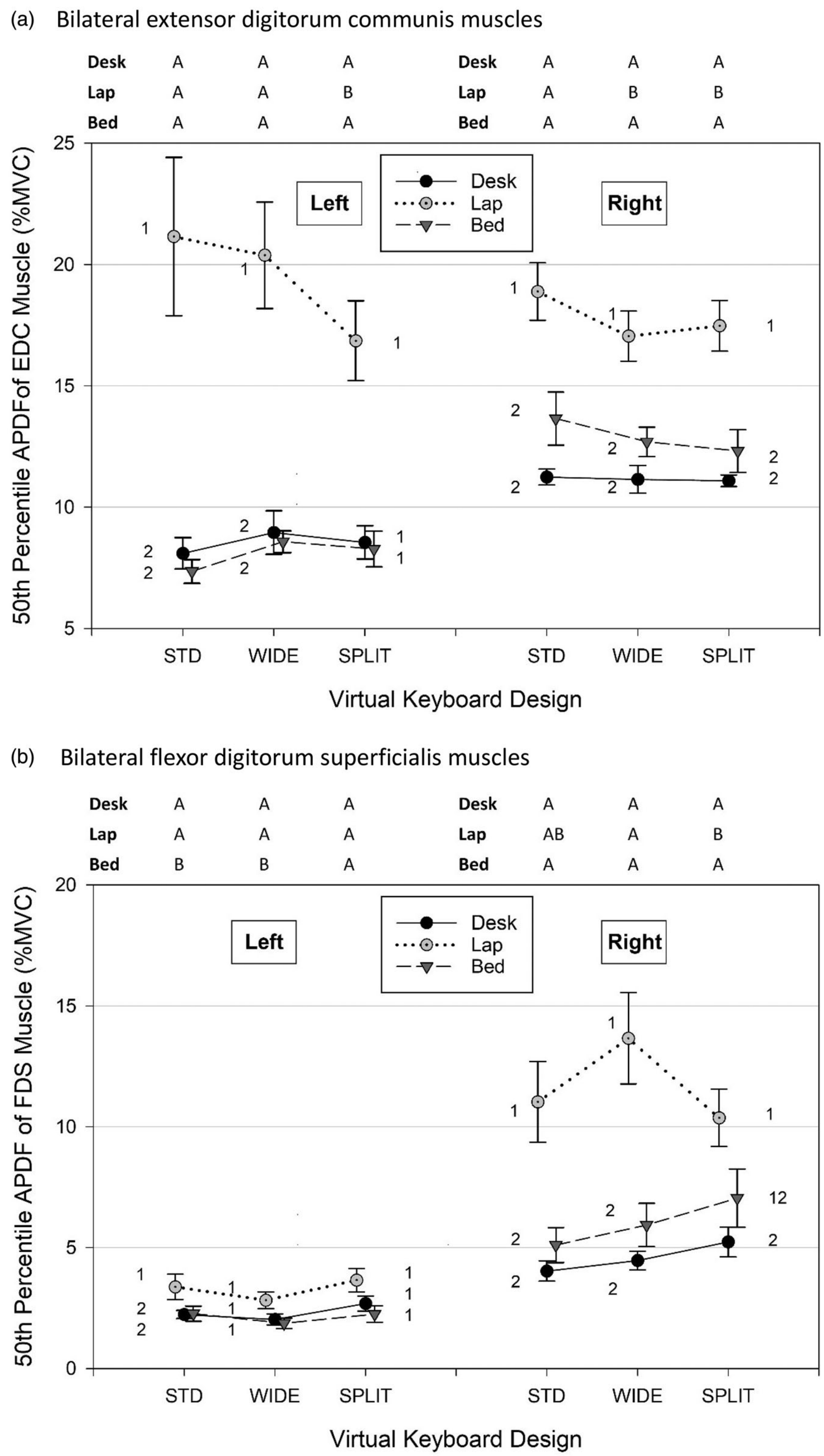

Figure 4. Interaction effects of normalised 50th percentile APDF muscle activity of forearm muscles across different virtual keyboard designs and usage postures of tablet. The conditions observed from the left and the right hand are separated accordingly in each sub figure. Error bars represent the mean ± 1SE. Conditions with the different character (A, B, C) indicates significant for the mean across virtual keyboard designs within the same usage posture based on Tukey's post-hoc comparison from rANOVA. Conditions with the different number (1, 2, 3) indicates significant for the mean across usage postures of tablet within the same virtual keyboard design based on Tukey's post-hoc comparison from rANOVA.

Cohen's d = 1.71; for right FDS, $p = .004$, Cohen's d = 1.22) or in the bed condition (LAP vs BED: for left EDC, $p = .039$, Cohen's d = 1.31; for right FDS, $p = .025$, Cohen's d = 0.87). Moreover, typing in the lap posture also led to an increased APDF range for some examined forearm muscles compared to the other two usage postures (LAP vs DESK: for left EDC, $p = .035$, Cohen's d = 1.21; for right FDS, $p = .008$, Cohen's d = 1.19; LAP vs BED: for right EDC, $p = .043$, Cohen's d = 0.91; for right FDS, $p = .042$, Cohen's d = 0.74). However, the right CES (Figure 5(a)) and UT muscles (Figure 5(b)) exhibited a greater median APDF level of muscle activity in the desk condition than in the bed condition or lap condition (DESK vs BED: for CES, $p = .005$, Cohen's d = 1.34; DESK vs LAP: for UT, $p = .024$, Cohen's d = 1.10).

In terms of virtual keyboard design, compared to the standard design, both the split design and the wide design was associated with lower 50th percentile APDF values for the right EDC muscle (SPLIT vs STD: $p = .021$, Cohen's d = 0.19; WIDE vs STD: $p = .010$, Cohen's d = 0.17). However, the keyboard effect on the left EDC muscle was less consistent and was further affected by the usage posture ($p = .001$, Cohen's $f^2 = 0.04$). When the lap posture was assumed, typing on the split virtual keyboard led to a reduced median APDF amplitude of muscle activity in the left EDC muscle (SPLIT vs STD: $p < .001$, Cohen's d = 0.34; SPLIT vs WIDE: $p = .015$, Cohen's d = 0.38) (Figure 4(a)). Furthermore, the examination of the EMG data recorded from the left FDS muscles revealed a significant difference in the 50th percentile of APDF amplitude across the keyboard designs ($p = .013$, Cohen's $f^2 = 0.06$). Compared to the wide virtual keyboard, a slight elevation in the median APDF EMG value was observed when participants used the split virtual keyboard, particularly when the bed posture was adopted for typing (Figure 4(b)). As shown in Table 1, compared to the standard virtual keyboard, the split virtual keyboard was associated with greater APDF ranges of muscle activity in bilateral FDS (for left DFS, $p = .009$, Cohen's d = 0.53; for right DFS, $p = .042$, Cohen's d = 0.29) and the right CES muscle ($p = .007$, Cohen's d = 0.48).

Regarding the time effect on muscle activity, we found a significant increase in the 50th percentile of the APDF amplitude in the CES muscle during the last 5-minute typing period ($p = .042$, Cohen's $f^2 = 0.05$). No other meaningful changes in EMG measurements between the early and late time periods were found in the other muscles investigated. Finally, during tablet typing, female participants, on average, exhibited greater median APDF EMG values in the bilateral FDS and right UT muscles than their male counterparts (in Table 1, for left FDS, $p = .002$, Cohen's $f^2 = 0.02$; for right FDS, $p < .001$, Cohen's $f^2 = 0.02$; for right UT, $p < .001$, Cohen's $f^2 = 0.02$).

Discussion

The purpose of this study was to evaluate the effects of virtual keyboard design and usage posture on task performances and muscle activity when users performed typing activity on a tablet computer. When the split virtual keyboard was used, participants achieved the fastest average typing speed with average typing accuracy comparable to the standard and wide virtual keyboard. Besides, compared to the standard virtual keyboard, the split design was also associated with reduced muscle activity of bilateral EDC muscles in the lap condition. Typing with a tablet placed on the lap while sitting was associated with faster average typing speed and higher and more dynamic ranges of muscle activity in the bilateral EDC and FDS muscles. Moreover, as time progressed during the experimental sessions, average typing speed decreased with lengthened average IKI and increased CES muscle activity.

Typing performance

Previous studies of physical keyboard designs implied that the split layout of a keyboard may be associated with decreased typing speeds (Marklin and Simoneau 2004; Rempel et al. 2009). Nevertheless, in our study, participants had faster typing speeds with the split virtual keyboard than when using the standard one. The increased typing speed is most likely the result of the more neutral and comfortable posture that tablet users assumed when typing on the virtual keyboard with split geometry (Lin et al. 2015). We speculated that the relatively slow typing speed while typing on a touchscreen may also contribute to the aforementioned discrepancy in the effects of the split design on typing productivity with physical and virtual keyboards (Kim et al. 2014a). Trudeau et al. (2013) examined the influence of the tablet keyboard configuration using thumb typing and revealed greater typing speeds with the standard layout design than with the split layout. However, their findings cannot be directly compared with those of our study in which the two-hand touch-typing method was adopted. Regarding typing accuracy, no significant difference was found between the split and conventional virtual keyboards,

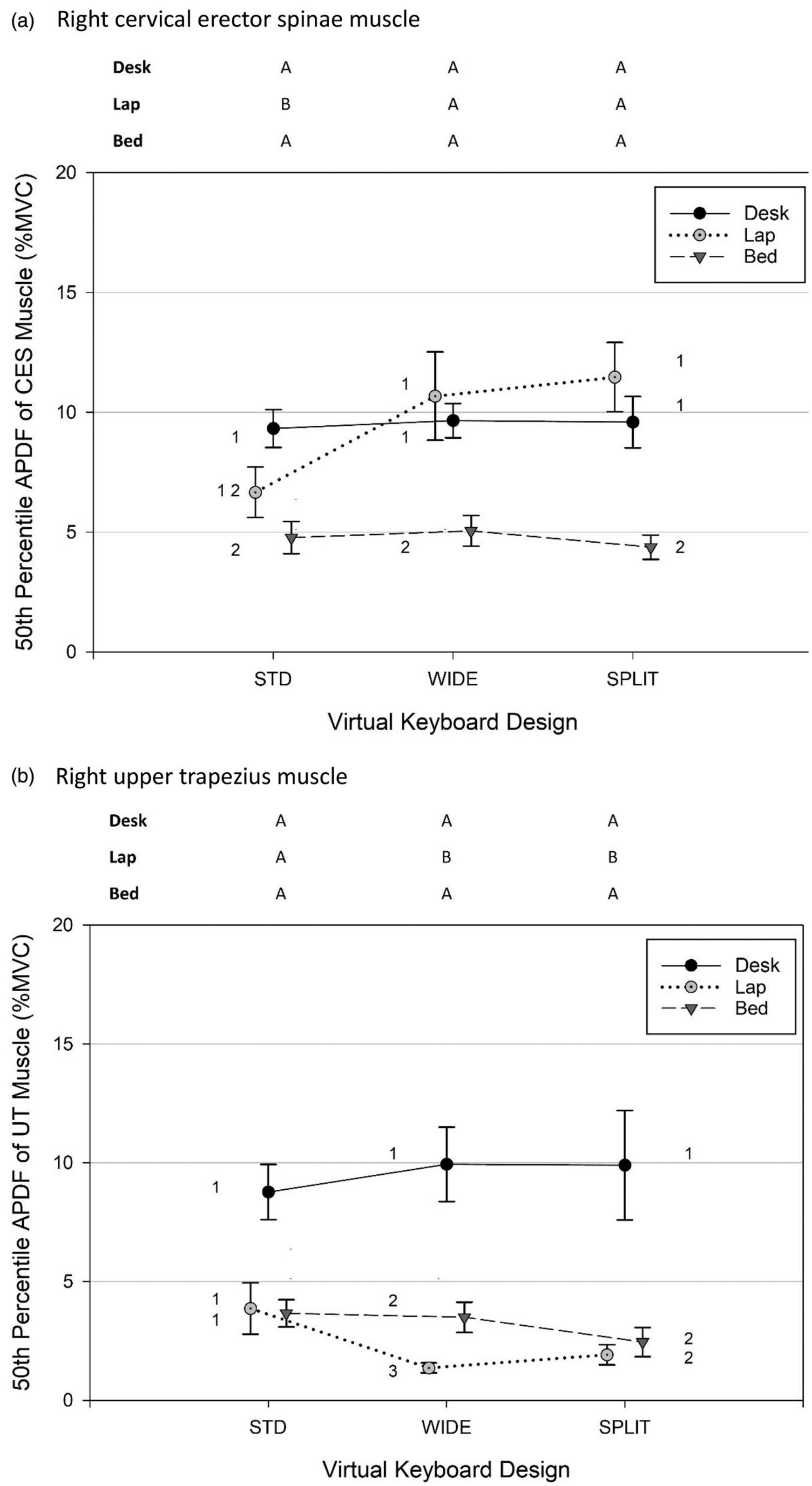

Figure 5. Interaction effects of normalised 50th percentile APDF muscle activity of neck and shoulder muscles across different virtual keyboard designs and usage postures of tablet. Error bars represent the mean ± 1SE. Conditions with the different character (A, B, C) indicates significant for the mean across virtual keyboard designs within the same usage posture based on Tukey's post-hoc comparison from rANOVA. Conditions with the different number (1, 2, 3) indicates significant for the mean across usage postures of tablet within the same virtual keyboard design based on Tukey's post-hoc comparison from rANOVA.

which aligns with the findings of most research of alternative computer keyboards (Marklin and Simoneau 2004).

Pereira et al. (2014) reported that the physical keyboard design with small key spacing (17-mm vertical spacing or 16-mm horizontal spacing) had negative effects on typing speed and accuracy. By increasing the key spacing with reduced key sizes, the wide virtual keyboard tested in the current study showed improved typing accuracy compared with the default layout. This result is also in line with those reported by Kim et al. (2014b), who indicated that improved typing accuracy was associated with a virtual keyboard with 13-mm keys relative to that of keyboards with larger key sizes. However, unlike the findings of Kim et al. (2014b), no significant difference in typing speed under the desk condition was found between the standard and wide virtual keyboards.

Interestingly, typing speeds recorded in the lap condition tended to have the highest average values among three usage postures examined. This result could be at least partly attributed to longer distances between the participants' eyes and the touchscreen of the tablet in the lap posture compared with the desk posture or bed posture. Because of the nature of hand anatomy and finger placement for touch typing, when typing on a virtual keyboard close to the eyes, it is possible that participants may have more difficulty peering through the gaps between fingers (Young et al. 2013). Accordingly, an increase in typing speed was achieved in the lap posture, especially when typing on the standard keyboard layout, which had relatively crowded hand/finger spacing (Figure 3(a)).

When compensating for the negative effects associated with the reduced key size of the wide keyboard layout, participants might purposely press harder to expand the finger pulp to ensure valid key registration, thereby keeping the fingers on the touchscreen longer during those examined conditions (Kohrs et al. 2014). However, this precautionary strategy seems more helpful in situations when the problem of visual obstruction of virtual keys becomes relatively troublesome, such as the desk and bed conditions examined in the current study. This may in part explain why the lengthened average keystroke duration associated with wide virtual keyboard were found in the bed and desk postures, but not in the lap posture (Figure 3(b)). Further research is needed to better elucidate how the speculated conflict between visual access to the information and touchscreen interaction contributes to the observed posture-keyboard interaction effect on typing performance.

Participants in the present study were found to have decreased typing speeds and increased IKI during the last 5-min typing period relative to how they performed during the early 5-min period. The observed decrease in typing productivity over time might be associated with elevated body discomfort as prolonged tablet interaction could increase the discomfort level in both the upper extremities and neck-shoulder regions (Lin et al. 2015). Furthermore, an increase in subjective discomfort perceived during continuous computer work has also been considered as a result of muscle fatigue by some researchers (Zhang, Helander, and Drury 1996; Gerard et al. 2002; Liang, Hwang, and Chang 2008; Jia and Nussbaum 2018). Our findings agree with the results of Gao et al. (1990), who observed decreased typing performance after 50–60 min of text entry work performed on desktop computers. Liang, Hwang, and Chang (2008) also found increased left-hand IKI after 30 minutes of continuous typing even though the typing speed remained relatively unchanged throughout the task period. However, previous studies have shown mixed results regarding the influence of the physiological status and cognitive status on keystroke duration. For example, the study by Chang et al. (2009) demonstrated reduced keystroke duration in the right ring finger after performing fatigue-induced isometric finger exercises. Nevertheless, increased keystroke durations while typing have also been found when the subjects were tired, bored, or experiencing negative emotions (Lee, Tsui, and Hsiao 2015). We did not observe meaningful changes in the keystroke duration during prolonged tablet typing. Given that transcription typing involves a series of cognitive processing and motor control, it is reasonable to assume that many determinants (e.g. localised muscle fatigue, sensory feedback, arousal, central executive function) could affect the keystroke duration during text entry work, leading to inconsistent results across studies.

Muscle activity

Using a virtual keyboard with a split design showed reduced 50th percentile APDF values in the bilateral EDC muscles, particularly when the tablet was placed on the lap (Figure 4(a)). One possible explanation is that due to the long viewing distance with the lap posture, the angled hand placement adopted for the split layout allowed participants to identify the location of virtual keys with less visual interference. Therefore, they might lift their fingers a shorter distance off the touchscreen compared to situations involving the other two keyboard layouts. Besides, it has been shown that users tend to extend their wrists higher while typing on the tablet in the lap posture than in the desk posture (Young et al. 2013; Lin et al. 2015). Altogether, the degree of finger extension required for glancing over virtual keys of the split virtual keyboard might be further compensated. However, given that the EDC muscle activity is affected by both the extent of wrist and finger extension occurred during typing (Lin et al. 2004; Cram and Criswell 2010; Young et al. 2013; Kim et al. 2014a; Werth and Babski-Reeves 2014), the aforementioned speculation cannot be confirmed in the present study as we did not record gaze information and required posture measurements from interphalangeal joints of the hand. It should be noted that we also observed a reduction in muscle activity in the upper trapezius when the split virtual keyboard was used on the lap (Figure 5(b)). These findings are in agreement with those of Strasser, Fleischer, and Keller (2004), who detected a significant decrease in muscle activity of the upper trapezius and, to a lesser extent, of the EDC muscle when using a physical keyboard with a fixed slant angle. Unfortunately, very few tablet studies have been conducted to examine the design aspects of virtual keyboards and their effects on musculoskeletal exposure (Toh et al. 2017). However, the ergonomic concerns of other tablet design features on muscle activity have been investigated in situations wherein tablet interaction was mainly performed by one hand (Pereira et al. 2013; Coppola et al. 2018). For example, the work of Coppola et al. (2018) required participants to hold the tablet with two hands while conducting a series of swiping gestures only with the right thumb. The effects of tablet form factor and swipe gesture design were thus explored with emphasis on physiological loading experienced by forearm muscles (e.g. extensor carpi radialis, extensor pollicis brevis, and flexor carpi ulnari), which were different from those examined in the present study. Therefore, more research is warranted to determine how relevant muscles of the upper extremity respond to different design aspects of virtual keyboards.

Typing on tablets in the lap posture elicited higher and more dynamic muscle activity from both the EDC and FDS muscles compared to the other two postures examined (Table 1). This is probably a consequence of the substantial amount of wrist extension and body discomfort experienced by participants when performing tablet typing on the lap (Lin et al. 2015). Previous research has also shown that exerting force with the wrist extended produced higher EDC muscle activity than it did in the neutral posture (Roman-Liu and Bartuzi 2013). The observed differences in EDC muscle activity between the desk and the lap condition in our study were comparable to early findings regarding keyboarding posture and muscle use (Rose 1991; Keir and Wells 2002). For example, Rose (1991) required participants to alter the finger postures relative to the forearm and found that the activation level of EDC muscle could be up to 22% of MVC (when fingers were held above keys to avoid key activation) from 6% MVC (when fingers rested on keys). Subsequently, the finger needed to be flexed further to strike the virtual keys, thereby causing increased activity in the FDS muscle. Nevertheless, Young et al. (2013) found similar levels of EDC muscle activity under table and lap conditions when tablet users performed an 'email task'. These inconsistent results are possibly related to differences in the experimental design among studies. For example, Young et al. (2013) asked participants to read and then respond to emails with a tablet tilted by its external case on the supported surface. Therefore, the resulting musculoskeletal exposure could be dissimilar to that experienced in our study.

Muscle activity in the neck and shoulder areas differed across usage postures. In comparison to the bed condition, the increased EMG activity of the CES muscle observed in the desk and the lap conditions may have been due to the greater viewing angles between the tablet and participant. Asundi et al. (2012) demonstrated that the use of simple inclines with notebook computers could reduce the viewing angle, thus resulting in decreased neck flexion and forward head tilt. Similarly, mounting the tablet at a high tilt angle was performed to achieve a small viewing angle and caused decreased neck muscle activity (Chiu et al. 2015). Therefore, as expected, the amount of CES muscle activity was decreased in the bed condition when participants had their backs supported and the tablet near eye level. The main effect of usage posture on UT muscle activity was speculated to be associated with the extent of shoulder elevation induced during tablet typing. Consistent with our findings, Young et al. (2013) observed lower UT muscle activity and greater shoulder elevation during tablet use on the lap compared to on a desk. Other research, however, found no significant difference in muscle activity of the sternocleidomastoid and UT muscles when comparing the EMG data obtained while interacting with tablets on a sofa and on a traditional desk (Werth and Babski-Reeves 2014). The discrepancy in study results implies that the distribution of musculoskeletal loadings around the neck-shoulder region during tablet use is complicated and depends on gravitational demand in postures in different scenarios (Vasavada et al. 2015).

We found a slight increase between the later measure of CES and UT muscle activity (55–60 min) and earlier measure (10–15 min), yet the change in the UT did not reach significance. Previous studies have suggested that using tablets in non-traditional workstations could induce more flexing of the neck compared to when sitting at a desk (Young et al. 2013; Werth and Babski-Reeves 2014; Vasavada et al. 2015). Therefore, the observed time effect on the CES muscle could be associated with the physical burden imposed by sustaining the desired cervical and shoulder postures during tablet interaction (Basmajian and Deluca 1985; Merletti and Farina 2016). This speculation is further supported by the evidence that body discomfort perceived during tablet typing increased with time, specifically in the neck-shoulder regions (Lin et al. 2015). Although there are no published data regarding physiological responses after prolonged tablet use, signs of muscle fatigue have been detected in forearm and shoulder muscles after performing typing tasks on either a physical computer keyboard or a smartphone (Lin et al. 2004; Kim et al. 2012). Because the use of virtual keyboard was associated with greater muscle activity and subjective discomfort of the neck and shoulder areas compared to when using a conventional keyboard and mouse (Shin and Zhu 2011), tablet users may experience an increased risk of developing muscle fatigue or other musculoskeletal symptoms in those vulnerable regions over a long period of time. A recent survey of high school students by Shan et al. (2013) revealed that tablet use is significantly correlated with a high prevalence of neck-shoulder pain; however, the effects of specific postures and daily usage time cannot be distinguished from confounding factors due to the limitations of self-reported data. Therefore, the amount of time that users allow spending on tablets per day without imposing undue burden on the musculoskeletal system remains unclear.

Limitations

Several limitations of this study should be considered when interpreting the findings. First, the effects of virtual keyboard design on task performance and musculoskeletal exposure during tablet use were evaluated based on simulated text entry tasks in a laboratory. Typing on the virtual keyboard with one hand or with one or two fingers of each hand might expose the tablet user to physical burdens different from those experienced during our experimental sessions. Second, although three usage postures commonly adopted for tablet activities were investigated, daily use of tablets could involve other postural constraints that significantly deviated from those examined in the present study (e.g. standing, lying, or propped on crossed legs). Because of its portability, users can easily interchange postures from time to time when using a tablet in more naturalistic environments. To the best of our knowledge, this is the first work to show how the continuous use of a tablet for a long period may alter the muscle activity of the neck and upper extremities. However, it is still unclear to what extent this change originates from muscle fatigue or is related to other physiological adaptations to the ergonomic workload imposed. Further work is needed to quantify the changes in the EMG frequency spectrum or local muscle oxygenation over time to provide more insight regarding ergonomic risks associated with tablet use. Last, some of observed differences in muscle activity across virtual keyboard designs were relatively small, albeit significant. More evidence is needed to better understand the long-term benefits of adopting alternative virtual keyboards during tablet typing in real-world environments.

Conclusions

This study demonstrated that the split virtual keyboard allows better task performance with reduced muscle activity of the right EDC muscle than the standard virtual keyboard when performing text entry activities with two hands on a tablet computer. Using tablets on a desk increased muscle activity in the neck and shoulder region, whereas typing with tablets on the lap showed greater and more dynamic EDC and FDS muscle activity and increased typing speed. Regarding the duration of tablet use, the typing performance decreased over time with a significant increase in right CES muscle activity. These findings suggest that the effects of usage postures on the musculoskeletal system were further compounded by the virtual keyboard design. To improve the user experience of using tablets outside a traditional office setting, it is important to gain a better understanding of the relationships between design features of virtual keyboards, task performance, and musculoskeletal outcomes incurred under various usage scenarios.

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