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The Effect of Tablet Computer Configurations and Touchscreen Gestures on Human Biomechanics, Performance, and Subjective Assessment

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ABSTRACT
As the increasing usage scenarios of tablet computers led to more non-neutral postures, optimizing the touchscreen gesture input became imminent to improve system performance and users' well-being. Therefore, we conducted a study to investigate the influence of four tablet configurations and seven touchscreen gestures on electromyography, performance, and subjective assessment. Our results indicated that muscular loads of shoulder decreased under the Stand-Hand configuration while it increased under the Sit-Table during gesture interaction. We also found that Drag-Up and Drag-Left tended to possess higher muscular loads of shoulder while Drag-Down caused greater muscular loads of index finger. Besides, two-touch gestures spent longer duration when performing long-distance movements. Dragging in the inner direction was supposed to be more efficient than that in the outer direction. Our findings could provide a scientific basis for guiding the appropriate selection and the use of touchscreen interaction in the future HCI field.

1. Introduction

With the development and advance of intelligent mobile devices, tablet computers have become ubiquitous due to their high portability and wide usability in many day-to-day activities (Tu et al., 2020). The aggregating studies of global consumer survey research predicted the sale of tablets worldwide in 2023 will be 122.1 million. A lot of previous studies (Gold et al., 2012; Lin et al., 2017; Yu et al., 2018) focused on the evaluation of physiological load in desktop or notebook computers to understand the relationship between physiological load and interactive configuration. So far, there were a few guidelines or recommendations for tablet computer interaction while a series of that related to desktop or notebook computers was established [e.g., ISO-9241, ANSI/HFES 100 (USA), and CSA-Z412-M89 (Canada)]. However, some researchers have compared the influence on upper extremity among the use of different computers and indicated that tablet users exhibited larger neck flexion angles and greater neck muscle activity than standard desktop computer users (Douglas & Gallagher, 2017; Straker, Coleman, et al., 2008; Young et al., 2012). Previous investigations revealed that there was a causal relationship between the mobile device and musculoskeletal symptoms on the neck (68%), upper back (62%), right shoulder (52%), and right hand (46%), which could induce significant biomechanical stress on the upper extremities and possibly lead to musculoskeletal syndrome (Lozano et al., 2011; Shin & Zhu, 2011; Sophia et al., 2011). Therefore, there was an imminent demand for ergonomic evaluation of tablet computer use to clarify the influence of tablet interactive configuration and physiological load, which was crucial for the improvement of tablet usability and system performance, as well as to reduce any potential negative musculoskeletal impact on users (Young et al., 2013).

The usage scenarios of tablet computers were not limited to the daily office environment due to its higher portability. As the third workplaces, such as cafes, waiting lounges, restaurants, or other places evolving into work sites, became more and more popular due to the global advances in communication (Vartiainen, 2007), the tablet technology allowed users to adopt more postural positions, including pilling back the tablet from a desk while in use, holding the device in one's hands, placing it on the lap, using a stand case cover on a tablet to prop device, or bringing elbows close to his body to stabilize arm movement (Eldar & Fisher-Gewirtzman, 2020). Besides, touchscreen devices were used in various public domains, such as airports, train stations, grocery stores, and banks, which required users to interact with tablets in standing or sitting postures (Chourasia et al., 2013). More interactive postures brought higher operation portability to users but might also bring more non-neutral postures and potential risks of musculoskeletal diseases. Previous studies indicated that the poor posture could be further exaggerated by using a tablet computer that is difficult to position efficiently for good posture, which is a likely contributor to altered muscle activation patterns contributing to neck and shoulder pain (Szeto et al., 2005). Eldar

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and Fisher-Gewirtzman (2020) reported that postures were affected by the tablet target location and workplace setting, and there was only half of the time that users' joints tended to remain in the neutral position range during the tablet interaction in third-workplace, which has the potential risk for musculoskeletal diseases. Previous studies mainly evaluated the difference in desktop workstation between sitting and standing (Babski-Reeves & Calhoun, 2016; Lin et al., 2017; Yu et al., 2018) or the difference in tablet settings under sitting postures (Douglas & Gallagher, 2017; Young et al., 2012), which was not enough to cover major daily tablet configurations. Therefore, it was necessary to examine the upper extremity muscle activity under commonly selected tablet configurations including sitting and standing in working and non-working scenes.

As the tablet computer functionally integrated the display and the user input via a touchscreen (Young et al., 2012), gesture interaction was one of the main ways to operate tablets. Gesture interaction was combined by single-touch and multi-touch gestures, the single-touch gestures included clicking (or pressing, tapping), dragging (or scrolling, panning, sliding), whereas the multi-touch gestures included pinching (or zooming-out) and stretching (or zooming-in) (Jeong & Liu, 2017). Users were accustomed to using the index finger to perform the drag gestures and using the thumb and the index finger to complete stretch and pinch (Hinrichs & Carpendale, 2011). Recently, research on gesture input modalities is getting more popular because gesture input modalities are able to provide reduced attentional load or even eyes-free input (Bragdon et al., 2011) and can be committed to muscle memory that helps users focus on their task (Kurtenbach, 1993). Quantifying finger biomechanics in gestures can aid the design of touchscreen interfaces that were both easy to use and reduce strain on the musculoskeletal system (Asakawa, Dennerlein, et al., 2017). Previous studies mainly investigated the gesture differences by performance, subjective assessment, or the joint kinematics (Asakawa, Dennerlein, et al., 2017; Jeong & Liu, 2017; Tapanya et al., 2021), and a few studies analyzed swipe gestures through EMG (Huang, Mao, et al., 2021). It has become very clear that further study is indispensable to explore the differences in muscular activation among common touchscreen gestures, including one-finger and multi-finger, to provide users with appropriate guidance in tablet interaction.

The surface electromyography (sEMG) is the embodiment of neuromuscular electrical activity on the skin surface, which is closely related to muscle activity level. It is considered the most appropriate method to study local muscle fatigue because of its convenience, objectivity, and locality. The Root Mean Square (RMS) is a popular mathematical method to characterize the amplitude change of EMG signal, which calculates the square root of the total value of the average quantity and has become one of the most popular methods to estimate muscle fatigue. The equation to calculate the RMS is shown below, where x_i is the sampled value of EMG signal and N is the length of EMG signal segment.

$$RMS = \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N} x_i^2}$$

In recent years, RMS mathematical methods in EMG have been widely applied to evaluate physiological loads on upper limbs with various HCI modes, such as a desktop computer (Lin et al., 2017), notebook computer (Gold et al., 2012), keyboard (Qin et al., 2013), mouse (Lee et al., 2008), and touch screen (Coppola et al., 2018), which is also applicable to tablet gesture interaction.

The aim of this study was to investigate the influence of common tablet configurations and basic touchscreen gestures on electromyography (EMG), user performance, and subjective assessment comprehensively. The implications of our findings could further clarify the influence of tablet interactive configurations and gestures on physiological load, which was beneficial to reducing any potentially negative musculoskeletal impact on users for repetitive tablet gesture use in various daily scenes.

2. Related work

As this research emphasizes the ergonomic aspects of interactive computing, we collected the research related to tablet computer interaction, which could be divided into three main categories, the impact of configurations when using tablet computers, the impact of touchscreen gesture types during tablet interaction, and the EMG widely use in various HCI fields. Thus, we focused on related works in these areas.

2.1. The effect of configuration in tablet interaction

We started by summarizing the empirical findings on intelligent device interaction under various configurations. These works are mainly concentrated on three aspects. First, previous studies usually evaluated the influence of different placement configurations of tablet computers. For example, Young et al. (2012) indicated that the head-neck posture and viewing angles could be optimized by placing the tablet higher and using the tablet case, respectively. Besides, Kang and Shin (2017) investigated that positioning the display upright and close to the user would help them complete the tap gesture faster with less muscle activity. In addition, Chiu et al. (2015) found that the neck muscle activity was low when the tablet was mounted at a high tilt angle (67.5°) while the shoulder forward flexion activity was low when the tablet computer was mounted at a low tilt angle (22.5°). Albin and McLoone (2014) similarly reported that the neck flexion decreased significantly as the tilt angle increased. Second, some previous studies quantified the difference among sitting configurations during tablet interaction to understand the influence of configurations on biomechanics. For example, Young et al. (2013) reported that the wrist extension of dominant hand was high under the sitting configuration where the tablet was placed on the lap. Besides, Douglas and Gallagher (2017) revealed that reading the tablet in a semi-reclined trunk posture with the tablet in user's lap increased neck flexion angle relative to reading from the standard sitting posture. Third, previous researchers explored how sitting and standing configurations affected physiological loads during the use of desktop workstations and mobile smartphones. For example, some studies pointed out that seated desktop computer workstation resulted in more non-neutral head-neck postures and higher upper trapezius load than standing (Babski-Reeves & Calhoun, 2016; Yu et al., 2018). Similarly, Lin et al. (2017) reported that the sitting computer workstation was associated with more non-neutral shoulder postures and greater shoulder muscle activity, while the standing computer workstation induced greater wrist adduction angle and greater extensor carpi radialis muscle activity. In addition to the desktop workstation, previous studies also revealed that participants maintained significantly larger head flexion and rotation when using the smartphone under sitting posture than standing (Jin et al., 2019; Lee et al., 2015).

2.2. The effect of gesture type in tablet interaction

There is no doubt that gesture operation was the most common way in tablet interactions. In recent years, research works that concentrated on touchscreen gestures can be distributed in three aspects. First, as user experience was considered more important than the traditional technology-centric perspective (Shin et al., 2016), previous studies tended to explore the effect of gesture types on operational performance and subjective assessment. For example, Jeong and Liu (2017) found that one-touch gestures in the horizontal directions were related to higher performance and lower subjective physical demand than those in the vertical and diagonal directions, and the two-touch gestures in the horizontal direction took the shortest time but caused more failures and higher error rates. Besides, Ge et al. (2021) quantified the performance of pointing task on the touchscreen and reported that the gesture movement from outer to center was significantly faster than the movement from center to outer at 45, 90, and 180°. Second, previous studies also explored how gesture types affected the joint kinematics of the upper limb. For example, Asakawa, Dennerlein, et al. (2017) reported that two-finger gestures showed greater joint excursions than single-finger sliding gestures by comparing seven common touchscreen gestures (Tap, Slide Right, Slide Left, Slide Down, Slide Up, Stretch, and Pinch). Asakawa et al. (2022) revealed that swipe left, right, and up involved more shoulder rotation than wrist flexion/extension. Third, there were a few studies evaluating the difference in swipe gestures by EMG. For example, Tapanya et al. (2021) reported that swipe location close to the palm required less forearm muscle activity and also allowed users to swipe with a more neutral posture of thumb and wrist. In addition, Huang, Mao, et al. (2021) reported that performing swipe gestures in the vertical direction tended to possess higher muscular loads than in the horizontal direction on a tablet.

2.3. The EMG was widely used in various human–computer interaction (HCI) fields

The EMG is a biomedical signal, which is acquired by the electrical response generated in muscles throughout its contraction symbolizing neuromuscular activities (contraction/relaxation) (Fattah, 2012). In recent years, EMG has been widely applied to evaluate physiological loads on upper limbs with various HCI modes. First, EMG was commonly used to evaluate the physiological load during various computer interactions. For example, Lin et al. (2017) measured the surface electromyography of shoulder muscle (Anterior Deltoid, Middle Deltoid, Middle Trapezius, and Upper Trapezius) and forearm muscle (Extensor Carpi Radialis) to understand how to assist in developing recommendations for setting up the sit-and-stand desktop workstation. Chiou et al. (2012) measured the EMG of Cervical Erector Spinae and Upper Trapezius to investigate the relationship between the neck discomfort and display tilt angle. The interaction between users and computer accessories was also quantitatively evaluated by EMG, such as a keyboard (Qin et al., 2013) and a mouse (Lee et al., 2008). Second, there also were researchers who studied the mobile device interaction by adopting muscular loads measurement. For example, Coppola et al. (2018) measured the EMG of 6 forearm muscles (Extensor Carpi Ulnaris, Extensor Carpi Radialis, Flexor Carpi Ulnaris, Flexor Carpi Radialis, Abductor Pollicis Longus, and Extensor Pollicis Brevis) to investigate how the forearm muscle activity differ across different tablet forms and touchscreen locations. Syamala et al. (2018) determined whether armrests and back support during mobile phone use affected muscle activity in the neck and shoulder regions by measuring the muscle activity of the Upper Trapezius and Splenius Capitis. Jin et al. (2019) explored the smartwatch as a potential ergonomic intervention by evaluating the muscle load of Upper Trapezius, Splenius Capitis, Semispinalis Cervicis and Semispinalis Capitis. Third, some emerging interactive ways could be evaluated by EMG to explore physiological burdens. For example, Huang, Qi, et al. (2021) applied an assessment system combining EMG indices of five muscles (Biceps Brachii, Triceps Brachii, Flexor Carpi Ulnaris, Extensor Carpi Ulnaris, First Dorsal Interossei) and developed an optimal user-defined Mid-air gesture set. Through sorting out previous studies, we found that EMG was widely used in various human–computer interaction (HCI) fields. We also summarized some upper limb muscles commonly used in human–computer interaction, including the neck muscles (Cervical Erector Spinae and Splenius Capitis), shoulder muscles (Anterior Deltoid and Upper Trapezius), upper arm muscles (Biceps Brachii and Triceps Brachii), forearm muscles (Extensor Carpi Radialis, Flexor Carpi Ulnaris and Extensor Carpi Ulnaris) and finger muscles (Extensor Pollicis Brevis and First Dorsal Interossei), which was able to effectively evaluate the physiological load and muscle fatigue of upper limb in HCI.

3. Methods

3.1. Participants

This experiment was carried out in January 2021 and lasted for 6 months. 32 (17 males and 15 females) participants were recruited for this study. The participants were 24 ($SD = 3$) years old on average and all right-handed without

Table 1. Mean (*SD*) participant anthropometry.

Mean (*SD*) participant anthropometry measures by gender				
	Age (years)	Height (cm)	Weight (kg)	Hand length (mm)
Males ($n = 17$)	24 (4)	176 (7)	66 (10)	190 (7)
Females ($n = 15$)	23 (2)	165 (5)	55 (5)	174 (6)
All ($n = 32$)	24 (3)	171 (8)	61 (9)	183 (10)

musculoskeletal diseases (MSDs). The mean anthropometric measures for participants were shown in Table 1, which were measured in accordance with ISO 7250-1:2008. Volunteers for this study were recruited by advertising the study on noticeboards around the university campus where the study took place and by the online communication, which consisted of social media, university mass email announcements, campus newsletters, and an access link to the survey on the university website. Students and staffs from the university were able to register through an online registration questionnaire to participate in the study. The questionnaire indicated most of the participants engaged in design, computer science, psychology, and financial management and all of them were familiar with tablet computers and had more than two years of experience using them. This study was approved by the university office of research ethics and each participant confirmed the informed consent before beginning the experiment.

3.2. Apparatus and environment

This study was conducted in an ergonomics lab. Two chairs (chair1: a lounge-type chair with a backrest, chair2: a chair without a backrest and armrest) and a sit-stand table were provided for participants in different scenarios. The height of the table and chair can be adjusted to the most suitable position according to the anthropometric data of participants. Participants were requested to stand or sit under four appointed configurations to perform all the gesture tasks to represent typical user situations. The four configurations were chosen based on preliminary unpublished observational research of tablet users at home, office, or other third-workplaces. The light in the lab was indirect and the position of table was arranged to minimize the glare on tablet screens.

3.3. Independent variables

3.3.1. Configuration

Four tablet configurations (Sit-Lap, Sit-Table, Stand-Table, and Stand-Hand) were selected in this study to simulate daily situations where users interacted with a tablet, which consisted of the common postures (sit or stand) and the support conditions (hand-held or in a case). The three-view drawing of four configurations was presented in Figure 1, which was drawn according to the situation of the present experiment by the MagicPoser modeling software.

The Sit-Lap (Figure 1(a)) configuration simulated the scene where people entertained with a tablet on the sofa at home or in the waiting hall. Participants were requested to sit on a lounge-type chair, and the seat pan height and seat-back position were 45 cm and 60° to the horizontal, respectively. During the tasks, participants were asked to hold the tablet on the lap by the non-dominant hand with a self-chosen tilt angle and perform required gestures by the dominant hand which could rest on the lap between gesture trials. The Sit-Table (Figure 1(b)) configuration represented the tablet use in the regular office or some third-workplaces. Participants were asked to sit on the chair without a backrest and put the tablet with a case on the table at a self-selected distance in front of them. The tablet was supported by a case with a tilt angle of 45° to the horizontal according to previous studies that reported 45° was the most preferred angle of inclination (Chiu et al., 2015; Young et al., 2012). The height of the chair and table were adjustable, the highest point of the seat was below the kneecap and the height of the table was adjusted to the participant's third outstretched finger when at a 90° elbow flexion in sitting on the chair (Douglas & Gallagher, 2017; Yu et al., 2018). During the tasks, participants were required to keep their non-dominant hands relaxed on the table and perform the gestures with their dominant hands which could rest on the table between gesture trials. The Stand-Table (Figure 1(c)) configuration simulated the working scenario of sit-stand workstation users or the temporary tablet use in the public domain. Participants were asked to stand by the sit-stand table and put the tablet computer in a case on the table. The height of the table was set to have the top of the desk at elbow height so that participants were able to place their forearms parallel to the ground when they used the table. During the tasks, as same as the Sit-Table configuration, participants were required to keep the non-dominant hand relaxed on the table and interact with the tablet with the dominant hand. The Stand-Hand (Figure 1(d)) configuration was derived from the situation where people have a presentation or instructors teach to students. Participants were instructed to stand naturally and hold the tablet by their non-dominant palm as well as the forearm. During the tasks, participants were asked to keep the device at a fixed height with their non-dominant hands and interact with the tablet with their dominant hands which could wait in the air for a rest between gesture trials.

3.3.2. Gesture task

This study explored seven common touchscreen gestures including one-touch gestures (Tap, Drag-Up, Drag-Right, Drag-Down, and Drag-Left) and two-touch gestures (Stretch and Pinch) (Figure 2). To present different gestures and guide participants to complete tasks, a customized application was programed by Unity software and installed in a 9.7-inch touchscreen device (iPad 3; 9.7 inch, IPS Retina screen; Apple, Cupertino, CA, USA), which could also record the duration of each gesture trial.

For Tap task (Figure 2(A)), participants were asked to click the blue circle of 20px (9 mm) by their right index finger as quickly as possible. If they did the click successfully, the blue circle would turn grey and disappear, which was considered a valid trial. Each participant was required to complete five valid trials during the Tap task. For Drag task (Drag-Up, Drag-Right, Drag-Down, and Drag-Left)

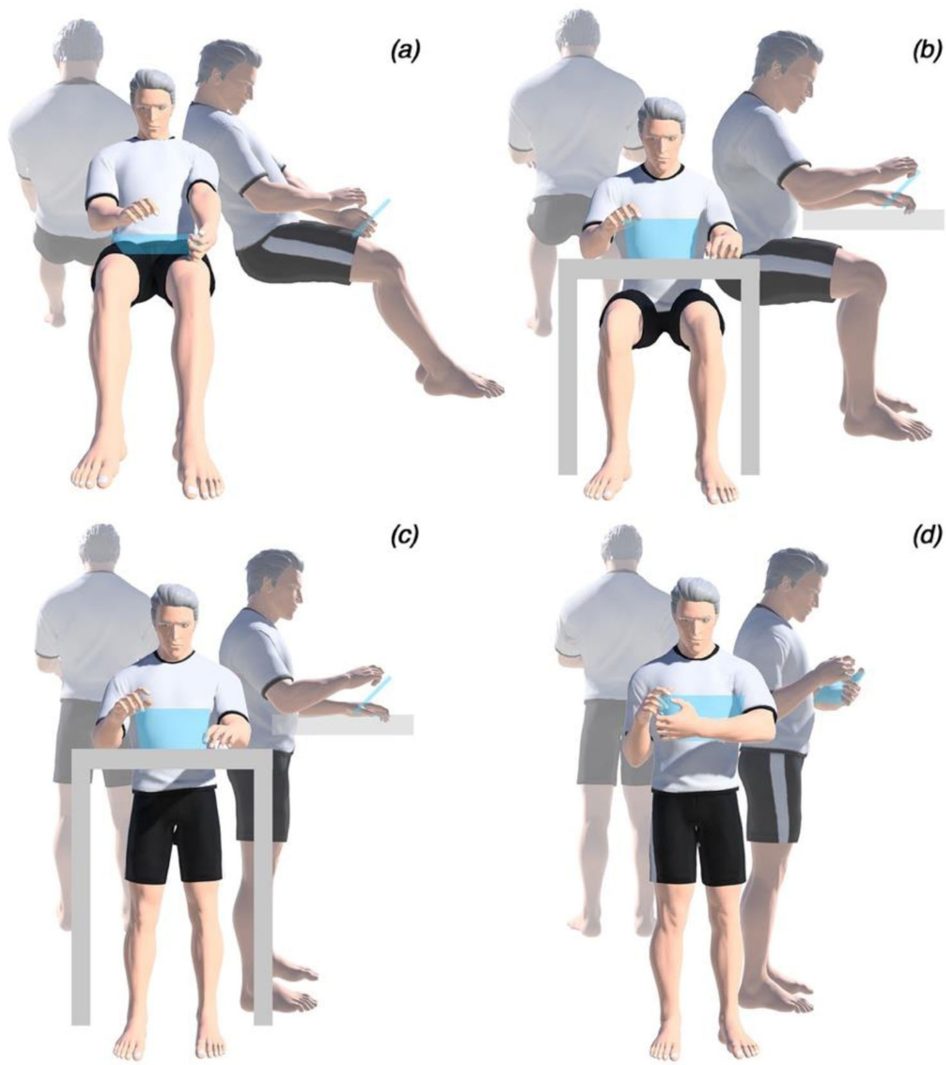

Figure 1. The three-view drawing of four tablet configurations, including Sit-Lap (a), Sit-Table (b), Stand-Table (c), and Stand-Hand (d).

(Figure 2(B)), participants were asked to place their right index finger on a blue circle in the center of the screen and to move their index finger toward each grey circle in four orthogonal directions (top, bottom, left and right). The fixed radius of the two circles was 20px (9 mm) and the distance between two circles was defined as 60 mm according to a pilot test, which was the average dragging distance of ten users frequently dragging on the touchscreen. A success of the Drag task was defined as the situation when the Euclidean distance between the center of the blue circle and grey circle was equal to or <20 pixels. Each participant was asked to complete five valid trials in each orthogonal direction. For Stretch/Pinch task (Figure 2(C)), participants were asked to place their right thumb and index finger on the blue ring and to move the two fingers (thumb and index) to the grey ring along the guided direction on the screen. The direction of guideline inclined 45° from the horizontal according to Jeong and Liu (2017) who reported that this direction produced better operating and subjective performance. The size of the two rings was fixed and the diameter of the outer ring and inner ring were 110 and 30 mm, respectively, which was defined according to an average distance of five users frequently zooming in/out on the screen. A valid trial was defined as the overlapping area of two rings exceeding 90%. Each participant was asked to complete five valid trials for each task.

3.4. Dependent variables

3.4.1. Muscle activity

The muscle activities of upper trapezius (UT), anterior deltoid (AD), flexor carpi ulnaris (FCU), and the first dorsal interosseus (FDI) were recorded by Biopac MP150 (HLT100C high-level transducer module, Biopac system, CA, USA). These muscles included the main motor muscles, respectively controlling the index finger (FDI), wrist (FCU), neck and shoulder (UT and AD) movements. Only the EMG of dominant upper extremity was recorded because a previous study reported that a significant muscle change can be seen on the dominant arm during the use of a tablet (Lozano et al., 2011). EMG signals were digitally sampled at 1000 Hz. Surface electrodes were positioned with the recommendations of Barbero et al. (2012) (Figure 3).

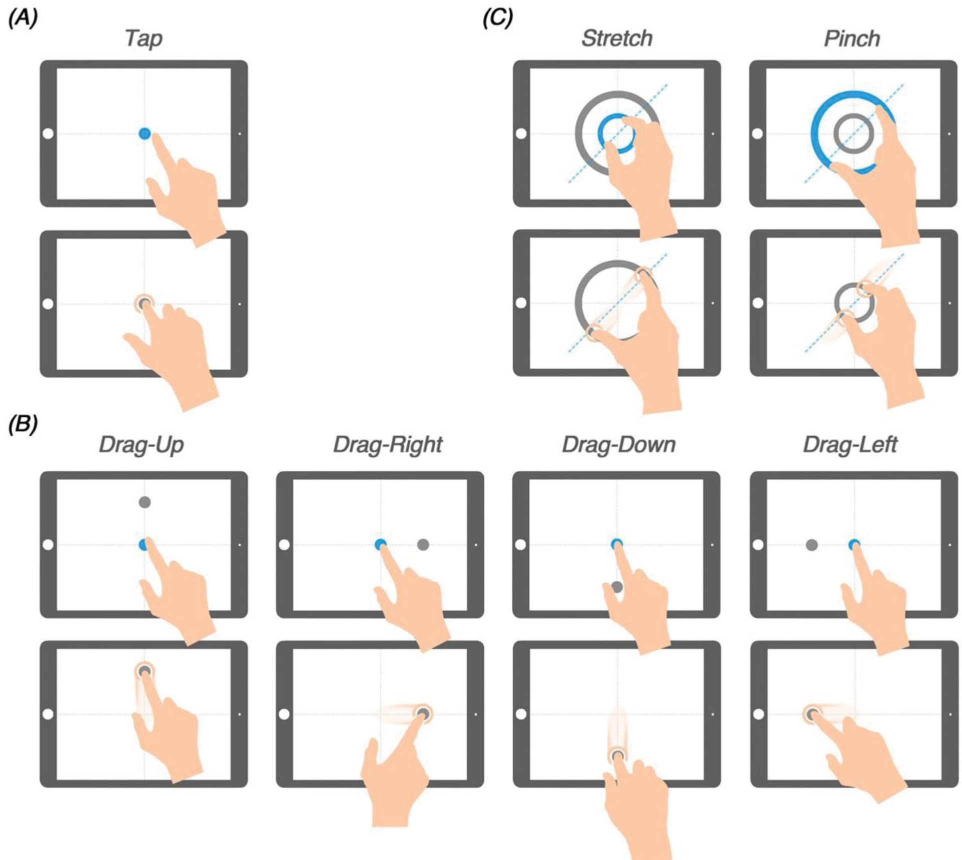

Figure 2. The operation schematic diagram of seven touchscreen gestures, including Tap (A), Drag in four directions (B), Stretch and Pinch (C).

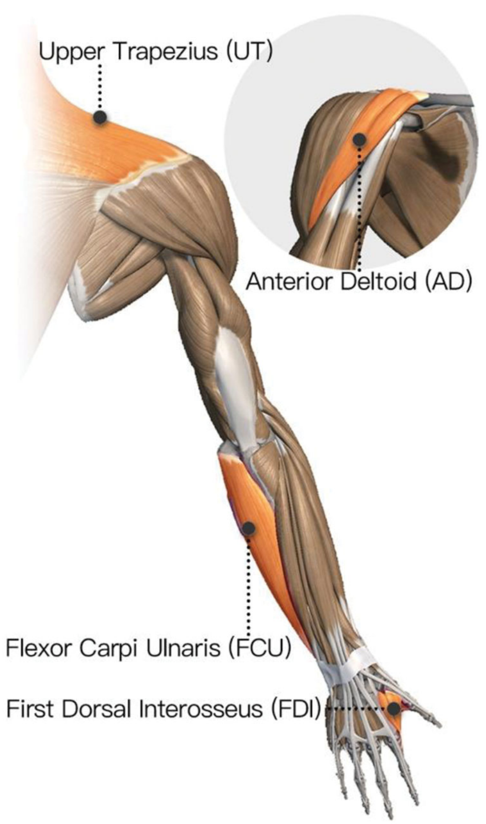

Figure 3. The illustration of four measured muscles of the upper limb.

Participants were asked to perform the muscle-specific maximal voluntary isometric contractions (MVICs) to determine the maximal voluntary excitation (MVE) for tested muscles, which was instructed by Boettcher et al. (2008) and Forman et al. (2019). During the MVIC trial in each muscle, participants were instructed to ramp up to get an MVIC gradually while the experimenter resisted subjects' force exertions using up to their entire strength. Participants were measured by MVIC three times in total and rested for 30 s between exertions (Janssen et al., 2015; Holmes et al., 2015).

The original EMG signal was filtered by the digital band-pass filter (10–500 Hz), and full-wave rectification (30 ms moving window), and then a 2nd order Butterworth low pass filter was applied ($f_c = 3$ Hz) (Alenabi et al., 2019). The maximum voluntary electrical activity (MVE) of each muscle was defined as the maximum voltage value of the processed signal in MVIC trials (Schwartz et al., 2017). The normalization of EMG was calculated as the MVE% of each muscle, which was a way that eliminated differences between participants by ensuring the use of absolute values in the comparative analysis. The mean amplitude level in MVE% was used to evaluate the difference in muscular loads. The first and last gesture movements were discarded because participants might adjust behaviors when "settling in" to a task and then anticipate the end of it (Gustafsson et al., 2018).

Figure 4. The operation schematic diagram of three levels gestures during the measurement of task completion time.

3.4.2. Task completion time

Users can achieve the same goal through different gestures during tablet computer interaction. Therefore, it is necessary to compare the task completion time of different gestures, which is one of the indexes to evaluate the operational performance. Task completion time was a commonly used way in gesture studies. For example, Hoggan et al. (2013) measured the time between the movement onset and the removal of both fingers from the display surface as the pinch/spread gesture duration. Gao and Sun (2015) measured the amount of time that participants spent in completing the task after they clicked the “start” button. Asakawa, Dennerlein, et al. (2017) measured and compared the task completion time of seven different gestures to evaluate the operational performance. Similarly, the task completion time in the present study was recorded by the application program and defined as the time interval between the touch-in and touch-out moments, which was in accordance with Jeong and Liu (2017). For two-finger gestures (Stretch and Pinch), the touch-in moment of the first finger and the touch-out moment of the second finger were recorded and its time gap was regarded as the task completion time. The paths of gesture tasks were able to be recorded by the customed application and the path of Drag and Stretch/Pinch gestures were divided equally into three levels according to the moving distance and their respective task completion time were measured separately (Figure 4).

3.4.3. Subjective assessment

All participants responded to the two survey questions about overall subjective comfort and efficiency. The responses were marked on a 10 cm visual analog scale (VAS) with 0 being the highest level of comfort/efficiency and 10 being the lowest level of it (Coppola et al., 2018). Before the start of the experiment, participants were explained the meaning of Comfort and Efficiency by the experimenter to confirm they have already understood. After each gesture task trial, participants were asked to respond to VAS immediately to record the subjective perception. Tick mark distances from the left side of the 10 cm line were measured and recorded as the ratings of each item.

3.5. Procedure

This experiment was a laboratory study in which all participants performed seven touchscreen gestures in four tablet configuration conditions. The gestures and configurations were randomly presented among participants to avoid the influence of the experiment sequence.

During gesture tasks, participants were instructed to sit or stand at the workspace according to the specific configuration and adjust their posture to the most comfortable state. Then, each participant was assigned an experimental tablet computer with a customized application. Before the formal task trials, there was a 20-s training trial to familiarize participants with the gesture tasks. Each task trial required participants to perform as fast as possible and repeat the required gesture 5 times. Participants were asked to have subjective feedback on the VAS questionnaire about the comfort and efficiency at the end of each gesture task trial. After participants finished all the gesture trials in one configuration, they were allowed to have a rest for 2 min and adjust their posture to the next configuration. The entire experiment took ∼25 min to complete, and participants received the payment after the experiment.

3.6. Statistical analysis

A two-way repeated measure ANOVA (configurations × gestures) was carried out for each of the seven dependent variables, including the EMG of all measured muscles (4, UT, AD, FCU, and FDI), performance (1, task completion time), and subjective assessment (2, comfort and efficiency) by SPSS software (SPSS, V22.0, International Business Machines Corporation, Armonk, NY, USA). Bonferroni post hoc tests were used to identify significant differences among configurations and gestures. The level of

Table 2. The statistic results of muscle activity, user performance, and subjective assessment.

		Muscle activity (MVE%)				User performance			Subjective assessment	
						Task completion time (s)			VAS scores (cm)	
Configuration	Gesture	UT[abc]	AD[abc]	FCU	FDI[ac]	Short-Move[c]	Medium-Move[c]	Long-Move[c]	Comfort[c]	Efficiency[c]
Sit-Lap	Tap	4.36 (3.38)	4.19 (1.77)	3.95 (2.27)	2.40 (1.52)	0.11 (0.01)	0.12 (0.01)	0.10 (0.03)	1.57 (0.52)	0.82 (0.25)
	Drag-Up	4.60 (2.92)	7.02 (2.82)	4.00 (2.13)	2.62 (1.58)	0.29 (0.01)	0.39 (0.03)	0.58 (0.11)	2.96 (1.02)	2.18 (0.62)
	Drag-Right	4.32 (3.05)	4.07 (2.01)	3.70 (2.41)	2.39 (1.43)	0.26 (0.01)	0.39 (0.04)	0.56 (0.13)	2.10 (0.93)	1.82 (0.93)
	Drag-Down	4.38 (2.81)	3.67 (1.29)	4.19 (2.51)	5.77 (3.69)	0.31 (0.04)	0.43 (0.05)	0.59 (0.08)	2.44 (1.69)	2.22 (0.71)
	Drag-Left	3.65 (2.47)	5.42 (2.25)	4.48 (2.70)	2.60 (1.49)	0.25 (0.02)	0.42 (0.07)	0.54 (0.08)	3.10 (1.44)	2.13 (0.47)
	Stretch	3.36 (2.10)	3.93 (1.54)	4.06 (2.35)	2.16 (1.50)	0.31 (0.02)	0.44 (0.05)	1.07 (0.24)	2.37 (1.76)	3.30 (0.43)
	Pinch	3.57 (2.23)	3.91 (1.69)	4.13 (2.26)	1.88 (1.43)	0.28 (0.02)	0.43 (0.02)	1.12 (0.23)	2.54 (1.71)	3.15 (0.39)
Sit-Table	Tap	7.56 (3.00)	9.25 (3.40)	4.13 (2.26)	2.64 (2.06)	0.11 (0.01)	0.12 (0.01)	0.10 (0.03)	1.56 (0.67)	1.05 (0.40)
	Drag-Up	9.03 (3.20)	11.13 (4.03)	3.74 (2.09)	2.73 (2.01)	0.30 (0.03)	0.43 (0.01)	0.55 (0.08)	3.09 (1.45)	3.12 (0.88)
	Drag-Right	7.95 (2.90)	8.89 (2.98)	3.70 (2.20)	2.64 (2.07)	0.29 (0.04)	0.40 (0.03)	0.57 (0.12)	1.39 (0.71)	1.70 (0.66)
	Drag-Down	7.39 (2.72)	7.97 (2.77)	4.29 (2.92)	4.66 (3.26)	0.29 (0.03)	0.40 (0.04)	0.56 (0.08)	2.40 (1.78)	2.38 (0.92)
	Drag-Left	8.08 (3.09)	9.56 (3.32)	4.64 (3.20)	2.89 (2.07)	0.28 (0.02)	0.44 (0.01)	0.54 (0.08)	2.09 (1.10)	3.15 (0.59)
	Stretch	8.19 (3.49)	8.66 (2.86)	4.12 (2.46)	2.72 (2.23)	0.28 (0.02)	0.44 (0.02)	1.08 (0.22)	2.77 (1.49)	3.55 (0.50)
	Pinch	8.22 (3.27)	8.55 (2.92)	4.19 (2.96)	2.55 (2.14)	0.29 (0.02)	0.44 (0.06)	1.11 (0.26)	2.30 (0.79)	3.33 (0.51)
Stand-Table	Tap	3.44 (2.07)	4.99 (2.09)	3.75 (2.12)	2.64 (1.60)	0.11 (0.02)	0.11 (0.01)	0.11 (0.05)	1.23 (0.97)	0.83 (0.45)
	Drag-Up	4.59 (2.15)	7.15 (2.72)	3.67 (1.95)	2.60 (1.45)	0.29 (0.05)	0.41 (0.02)	0.55 (0.08)	3.90 (2.03)	2.30 (0.81)
	Drag-Right	3.84 (1.77)	5.04 (2.16)	3.51 (1.81)	2.77 (1.77)	0.30 (0.03)	0.43 (0.01)	0.53 (0.07)	2.39 (1.56)	1.73 (0.48)
	Drag-Down	3.71 (1.70)	4.68 (1.79)	4.19 (2.30)	4.87 (3.49)	0.29 (0.02)	0.45 (0.02)	0.57 (0.09)	2.21 (1.05)	1.90 (0.69)
	Drag-Left	3.35 (1.80)	5.63 (2.48)	4.36 (2.51)	2.92 (1.59)	0.28 (0.03)	0.43 (0.02)	0.58 (0.19)	2.94 (2.18)	2.56 (0.73)
	Stretch	3.50 (1.96)	5.38 (2.11)	4.18 (2.23)	2.31 (1.54)	0.30 (0.03)	0.42 (0.03)	1.09 (0.27)	2.59 (1.39)	3.47 (0.49)
	Pinch	3.47 (2.19)	5.07 (2.21)	3.78 (2.90)	2.33 (1.67)	0.29 (0.01)	0.45 (0.08)	1.16 (0.28)	2.57 (1.10)	3.25 (0.38)
Stand-Hand	Tap	2.79 (1.86)	2.79 (1.77)	4.34 (2.41)	2.75 (1.38)	0.10 (0.01)	0.10 (0.01)	0.08 (0.02)	1.76 (0.72)	3.25 (0.38)
	Drag-Up	3.54 (1.89)	4.24 (2.19)	4.31 (2.42)	2.71 (1.31)	0.30 (0.03)	0.41 (0.03)	0.54 (0.11)	2.77 (1.07)	1.58 (0.59)
	Drag-Right	3.32 (2.58)	2.32 (1.41)	4.03 (2.10)	2.99 (1.67)	0.29 (0.04)	0.43 (0.04)	0.55 (0.06)	2.09 (0.58)	1.62 (0.40)
	Drag-Down	3.25 (2.34)	2.32 (1.54)	4.39 (2.46)	5.98 (3.69)	0.29 (0.03)	0.41 (0.02)	0.56 (0.07)	2.09 (1.09)	1.65 (0.20)
	Drag-Left	2.97 (2.08)	2.69 (1.63)	4.74 (2.74)	3.22 (2.02)	0.28 (0.02)	0.43 (0.02)	0.54 (0.08)	2.37 (1.12)	1.70 (0.82)
	Stretch	3.10 (1.81)	2.08 (1.26)	4.46 (2.39)	1.90 (1.33)	0.30 (0.03)	0.42 (0.02)	1.11 (0.31)	2.53 (1.38)	3.37 (0.85)
	Pinch	2.87 (1.70)	2.10 (1.14)	4.54 (2.44)	1.76 (1.55)	0.31 (0.02)	0.41 (0.03)	1.08 (0.23)	1.67 (0.95)	2.92 (0.74)

[a]There was a statistically significant interaction between configuration and gesture.
[b]There was a significant main effect for configuration.
[c]There was a significant main effect for gesture.

statistical significance for all of these analyzes was set at 0.05.

4. Results

The repeated measures results for the effect of configurations and gestures on muscle activity, user performance, and subjective assessment were summarized in Table 2.

4.1. Muscle activity

For the upper trapezius (UT), the result showed statistically significant main effects for the configuration [$F(2, 67) = 60.988$, $p < 0.000$] and gesture [$F(3, 85) = 10.283$, $p < 0.000$]. Additionally, the interaction between configuration and gesture was significant for UT [$F(7, 217) = 5.176$, $p < 0.000$] (Figure 5). When comparing the muscular loads of UT among configurations, the significantly higher muscle activity occurred under the Sit-Table configuration than in the other three configurations during all of the gestures ($p < 0.000$). Significantly less muscle activity was generated under the Stand-Hand configuration than in the other three configurations during the Drag-Up gesture ($p < 0.05$). When comparing the muscular loads of UT among gesture types, performing the Drag-Up gesture generated significantly higher muscular loads than that of other gestures under the Sit-Table and Stand-Table configurations ($p < 0.000$). Besides, performing Drag-Up gesture generated greater muscular loads than Drag-Left, Stretch, and Pinch gestures under the Sit-Lap ($p < 0.05$), while performing Drag-Up gesture generated greater muscular loads than Tap, Drag-Left, Stretch, and Pinch gestures under the Stand-Hand configuration ($p < 0.05$).

For the anterior deltoid (AD), significant main effects of the configuration [$F(2, 68) = 86.555$, $p < 0.000$] and gesture [$F(3, 78) = 52.546$, $p < 0.000$] were found in muscle activity. And the interaction between configuration and gesture also reached significance [$F(7, 201) = 5.503$, $p < 0.000$] (Figure 6). When comparing the muscular loads of AD among configurations, the result showed that using tablets under the Sit-Table configuration generated significantly greater muscle activity than that under the other three configurations ($p < 0.000$). Besides, significantly less muscle activation occurred under the Stand-Hand configuration than in others no matter what the gesture tasks were completed ($p < 0.000$). When comparing the muscular loads of AD among gestures, there was significantly higher muscle activation when the Drag-Up gesture was performed, which was greater than other gestures under all configurations ($p < 0.000$). In addition, performing the Drag-Left gesture generated significantly higher muscular loads than the Tap, Drag-Right, Drag-Down, Stretch, Pinch gestures under the Sit-Table and Sit-Lap configurations ($p < 0.05$).

For the flexor carpi ulnaris (FCU), there were no significant main effects and the interaction in muscle activity.

For the first dorsal interosseus (FDI), the result showed a significant main effect for the gesture task [$F(2, 58) = 36.404$,

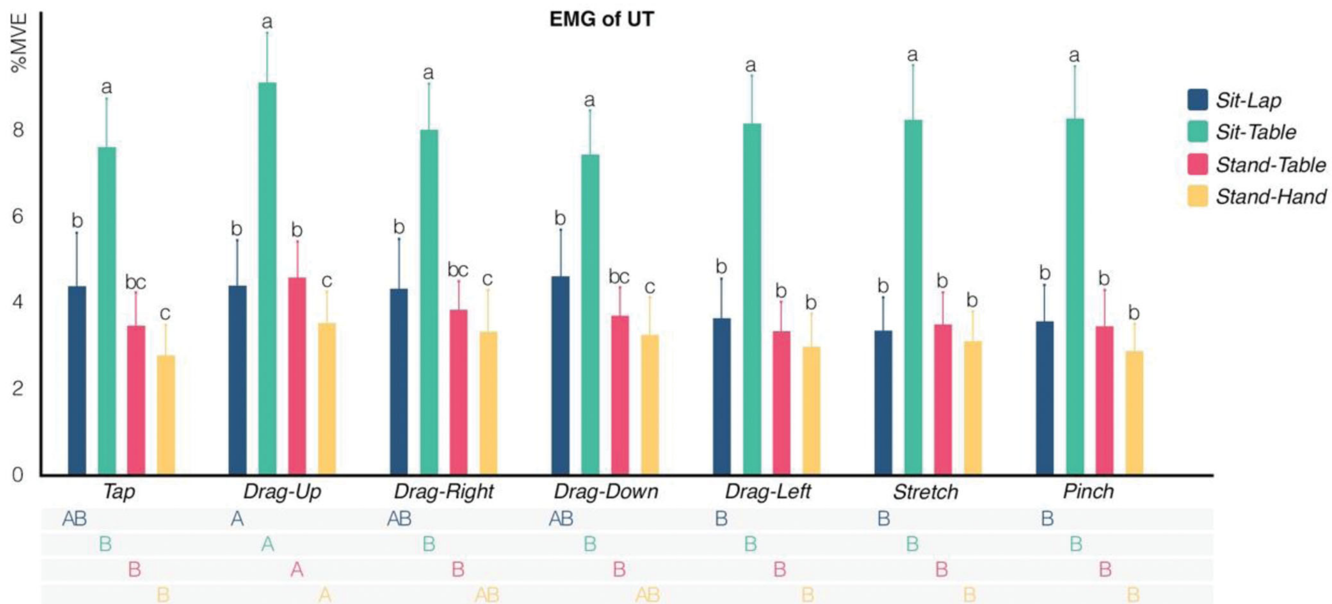

Figure 5. Mean EMG amplitudes of the upper trapezius (UT). Means with different lowercase letters indicated significant differences among configurations. Means with different capital letters indicated significant differences among gesture types.

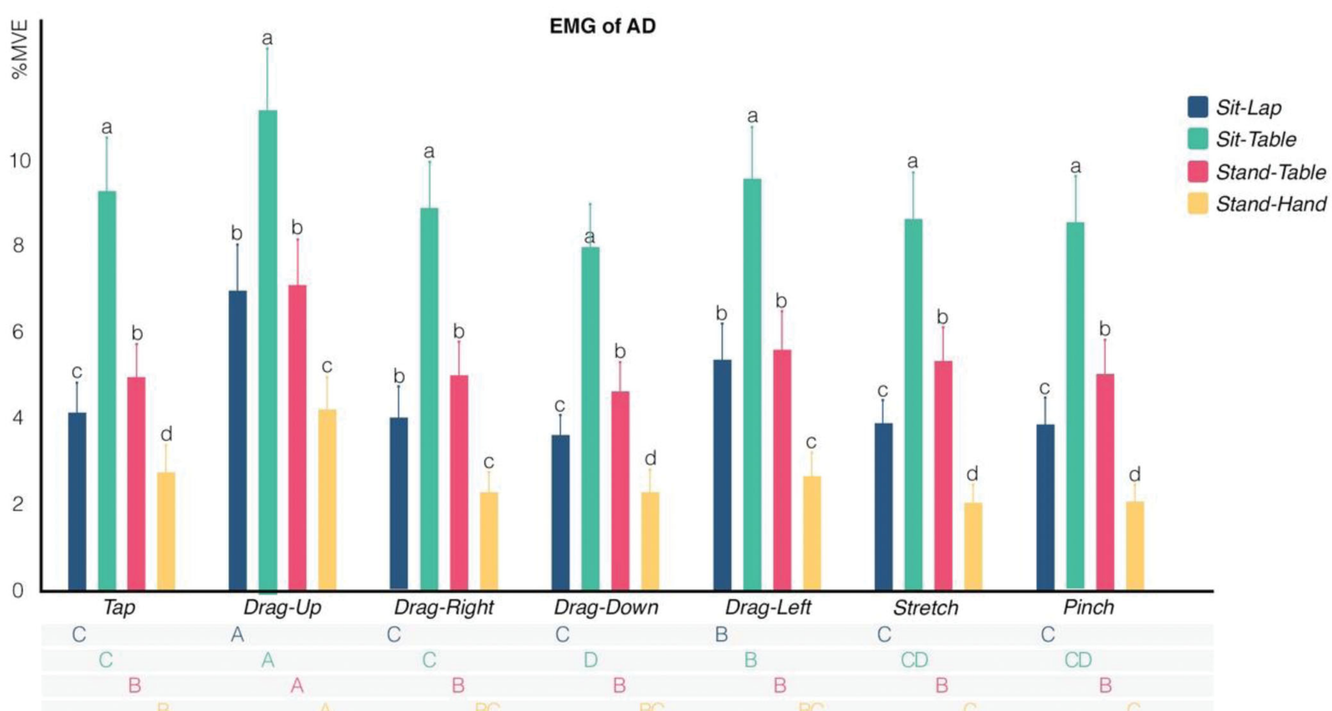

Figure 6. Mean EMG amplitudes of the anterior deltoid (AD). Means with different lowercase letters indicated significant differences among configurations. Means with different capital letters indicated significant differences among gesture types.

$p < 0.000$]. Interaction between configuration and gesture was significant [$F(5, 165) = 5.912$, $p < 0.000$] (Figure 7). When comparing the muscular loads of FDI among configurations, there was significantly greater muscle activity under the Stand-Hand configuration than Sit-Table when the Drag-Down gesture was completed ($p < 0.05$). And the significantly lower muscle activation occurred under the Stand-Hand configuration as compared to the Sit-Table when the Stretch and Pinch gestures were performed ($p < 0.05$). When comparing the muscular loads of FDI among gesture types, performing the Drag-Down gesture generated significantly greater muscular loads than any other gestures regardless of configurations ($p < 0.000$). And also, there were significantly fewer FDI muscular loads during the Pinch gesture compared to Drag-Up, Drag-Right, Drag-Down, and Drag-Left gestures under the Sit-Lap and Stand-Hand configurations ($p < 0.05$).

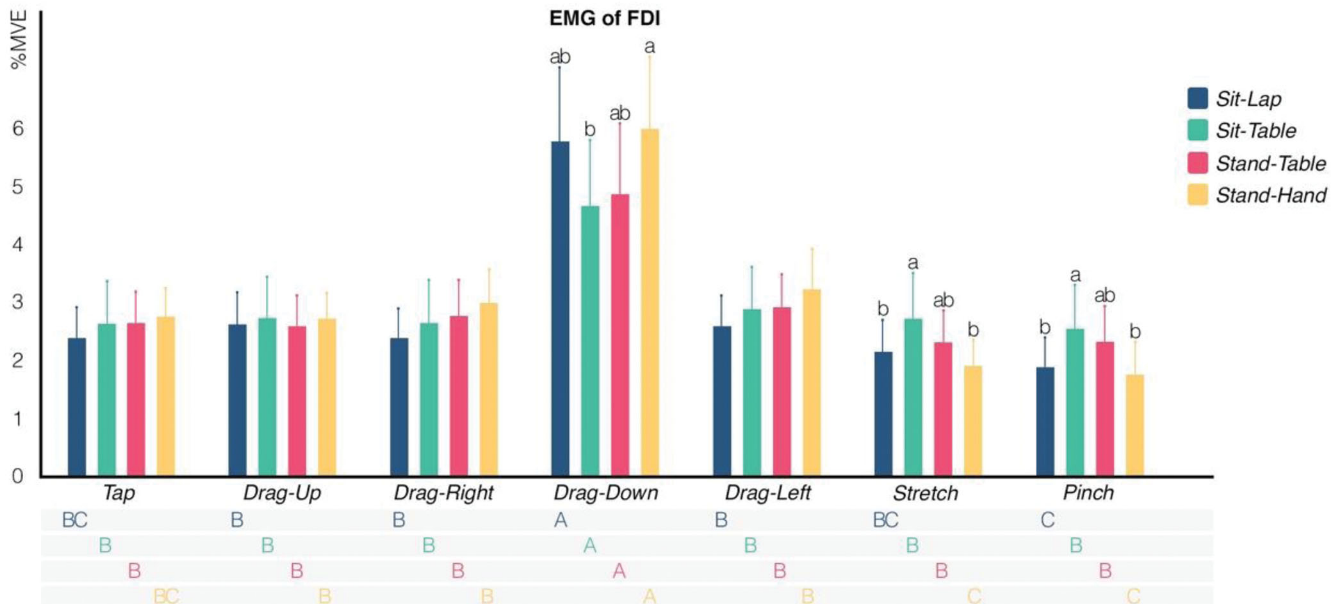

Figure 7. Mean EMG amplitudes of the first dorsal interosseus (FDI). Means with different lowercase letters indicated significant differences among configurations. Means with different capital letters indicated significant differences among gesture types.

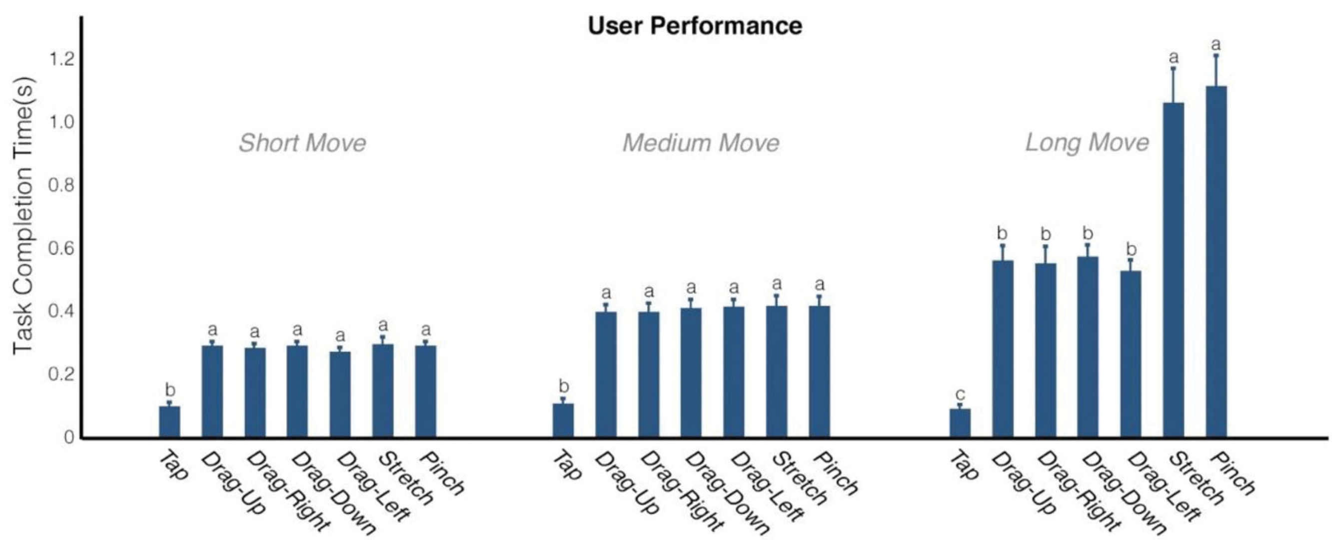

Figure 8. Mean task completion time. Means with different lowercase letters indicated significant differences among gesture types.

4.2. Performance

For the result of the task completion time, the main effect of gesture task can be found in the short-move level [$F(2, 14) = 238.212$, $p < 0.000$], medium-move level [$F(2, 13) = 442.054$, $p < 0.000$] and long-move level [$F(2, 34) = 253.989$, $p < 0.000$] (Figure 8). In all the three moving levels, the result showed that less duration time occurred during the Tap gesture, which was significantly less than other gestures ($p < 0.000$). In addition, the Stretch and Pinch gestures produced a significantly longer task completion time than Tap and Drag gestures in the long-move level ($p < 0.000$). However, the task completion time among Drag gestures in four directions had not reached significance in all three moving levels.

4.3. Subjective assessment

For the level of Comfort, a significant main effect for gestures was found [$F(2, 72) = 9.084$, $p < 0.000$] (Figure 9). The result showed that the Tap and Drag-Up were the most comfortable and uncomfortable gestures, respectively, which was significantly different from others ($p < 0.05$). The result also showed that the Drag-Left gesture was more uncomfortable than Drag-Right gesture significantly ($p < 0.05$). The result of the self-reported efficiency showed a significant main effect for gestures [$F(2, 21) = 61.247$, $p < 0.000$] (Figure 10). The Tap gesture was significantly more efficient than others ($p < 0.000$). The Stretch and Pinch gestures were less efficient than all one-touch gestures ($p < 0.05$). For the Drag gestures in four directions, the result showed that

Drag-Down and Drag-Right were more efficient than Drag-Up and Drag-Left significantly ($p < 0.05$).

5. Discussion

5.1. Muscle activity

5.1.1. EMG of the upper trapezius (UT)

The upper trapezius (UT) acted to extend, rotate, and side-bend the neck and elevate the scapula (Netter, 2010). On the aspect of the configuration (Figure 4), we found that there was a higher upper trapezius muscle activity under the Sit-Table configuration than that under Stand-Table and Stand-Hand during all of the gestures. This result was similar to previous studies that the sitting computer workstation was associated with greater UT muscle activity as compared to standing (Babski-Reeves & Calhoun, 2016; Lin et al., 2017). One key reason for this result was that there was more neck flexion and flexor moment in the sitting position (Gold et al., 2012), which was attributed to the sitting posture characteristics that sitting posture required more neck flexion to counterbalance the body (Bendix, 1984; Bridger et al., 1989; O'Sullivan et al., 2012; Vaucher et al., 2015). In addition, through comparing the two kinds of sitting configurations, the result showed that using the tablet under Sit-Table configuration occurred greater UT muscle activity than that under Sit-Lap no matter what the gesture tasks were completed. Our result could be supported by Douglas and Gallagher (2017) that the semi-reclined sitting position required less neck muscle activity than sitting with a table because the semi-reclined sitting position had the potential to decrease the neck muscle activity by reducing the gravitational moment. We also found that there was less muscle activity under the Stand-Hand than in other configurations when performing the Drag-Up gesture. In our experiment, as participants held the tablet near to their body by their forearm under the Stand-Hand configuration, they were able to keep their upper arm almost vertically to the ground to perform Drag-Up gesture instead of raising their arm higher and further, which might generate less UT muscle activation because Kang and Shin (2017) reported that lower EMG amplitude of the UT muscle was produced by less arm elevation and moment when interacted with near tablet targets.

On the aspect of the gesture (Figure 4), we found that greater UT muscle activation was generated during the Drag-Up gesture under the Sit-Table and Stand-Table configurations. Previous studies reported that the position of the touchscreen target relative to the user could affect the muscle activity (Schüldt et al., 1987; Sporrong et al., 1998). Kang and Shin (2017) also illustrated that greater muscle activity of UT was generated by interacting with the higher position of a tablet screen. In our study, this kind of top-area interaction that participants were asked to move the target point from the center of the screen to the top area during the Drag-Up gesture might require more elevation of scapula and greater muscle activity. In addition, performing the Drag-Up gesture generated greater UT muscular loads than Drag-Left, Stretch, and Pinch under the Sit-Lap, while it also generated greater muscular loads than Tap, Drag-Left, Stretch, and Pinch under the Stand-Hand. It was obvious that although performing Drag-Up gesture generated the highest UT activation under the two configurations supported by the non-dominant hand, there was no significant difference between Drag-Up and Drag-Left, Drag-Down. We supposed the reason might be that participants had to keep a very small shoulder flexion angle when they performed the Drag-Down and Drag-Right gestures under the two hand-support conditions. This kind of tablet interaction might lead to greater UT loads because Tapanya et al. (2021)

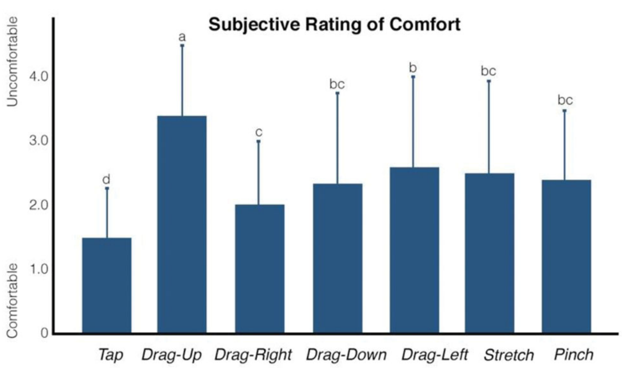

Figure 9. Mean subjective comfort rating (VAS scores). Means with different lowercase letters indicated significant differences among gesture types.

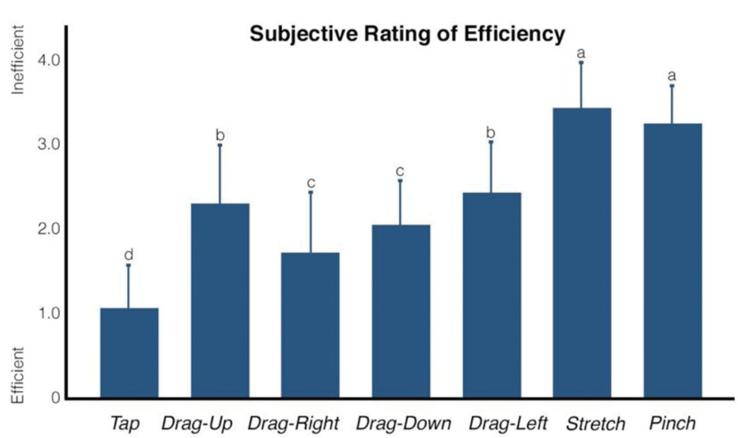

Figure 10. Mean subjective efficiency rating (VAS scores). Means with different lowercase letters indicated significant differences among gesture types.

reported that the greater UT activation was generated when participants kept a minuscule shoulder flexion angle to use mobile devices.

5.1.2. EMG of the anterior deltoid (AD)

The anterior deltoid (AD) mainly stabilized the shoulder complex and was the primary active portion for the movement of arm flexion (Gonçalves et al., 2017). On the aspect of the configuration (Figure 5), we found that there was greater AD muscle activity under Sit-Table configuration than in the two standing configurations during all of the gesture tasks, which was similar to the previous study that sitting position increased muscle activity of AD than standing under the computer workstation due to the larger mean upper arm elevation produced in sitting (Barbieri et al., 2019). Besides, through comparing the two sitting configurations, we found that greater muscle activity occurred under Sit-Table configuration than that under Sit-Lap during all of the gestures, either. It was partly supported by a previous study that sitting without a backrest and putting the device on the table generated greater AD muscular loads than sitting with an inclined backrest and putting the tablet on the lap during the tablet email tasks (Young et al., 2013). In addition, we also found that less muscle activity of AD occurred under the Stand-Hand configuration compared to other configurations regardless of gesture tasks. This result might be related to the fact that the tablet under Stand-hand configuration possessed the highest vertical height and the shortest interaction distance among those under all the configurations, which have been confirmed by previous studies that less neck flexion and shoulder movement were associated with a higher vertical height of the screen and the closer distance between device and sternum (Lin et al., 2017; Straker, Pollock, et al., 2008; Villanueva et al., 1997).

On the aspect of the gesture (Figure 5), we found that greater muscular loads of AD were generated during the Drag-Up gesture than others no matter the configurations, which was partly supported by Lozano et al. (2011) that panning up produced the relatively higher muscle activation of dominant deltoid. As ANSI/HFES (2007) indicated that greater arm elevation was generated by designing the target area higher, this result might be related to the fact that participants had to touch a higher position of the touchscreen to complete the Drag-Up gesture by elevating their arms, which caused greater muscular loads of AD. Besides, we found that performing the Drag-Left gesture produced greater muscle activity than other gestures except Drag-Up under the two sitting configurations. Our result was similar to Kang and Shin (2017) that there were greater shoulder muscular loads when right-handed people interacted with the left area of the screen under the sitting configuration.

5.1.3. EMG of flexor carpi ulnaris (FCU)

The flexor carpi ulnaris (FCU) mainly controlled wrist rotation during the execution of gestures. There were neither main effects in gestures and configurations nor interaction. Previous studies revealed that the use of a virtual keyboard resulted in lower muscle activity in the wrist muscle and higher muscle activity in the shoulder than did the use of a conventional keyboard, and it might be the evidence that during tablet use, the major stress was on the shoulder muscles than on the wrist (Chiu et al., 2015; Kim et al., 2012). These might be part of the reason why there was no significant difference in the EMG result of FCU.

5.1.4. EMG of first dorsal interosseus (FDI)

The first dorsal interosseus (FDI) provided forces for the first metacarpal bone and it mainly acted on and stabilized the index finger (Putz & Pabst, 2006). On the aspect of the configuration (Figure 6), we found that there were greater FDI loads under the Stand-Hand configuration than Sit-Table during the Drag-Down gesture, while there were fewer FDI loads under the Stand-Hand configuration than Sit-table during the Stretch and Pinch gestures. As previous studies pointed out that the short distance between the device and sternum could lead to shoulder elevation and more shoulder abduction (Kotani et al., 2007; Young et al., 2013), there might be more shoulder abduction under the Stand-Hand configuration, which might need more adduction or abduction of index finger and wrist to compensate when performing gesture tasks. When performing the Drag-Down gestures under the Stand-Hand configuration, participants might use the abduction of the index finger to compensate for the shoulder abduction, which could lead to greater FDI loads. However, when performing Stretch and Pinch gestures under Stand-Hand configuration, participants bent their wrists to make their thumb and index finger touched the screen. The compensation for shoulder abduction might occur to the wrist instead of the index finger, which might lead to less FDI activation during the Stretch and Pinch under the Stand-Hand. This conjecture was supported by our EMG result but also needed to be proved by quantifying upper limb biomechanics during gesturing to more completely understand the relationship between force generation and configuration in future work.

Through comparing different gesture tasks (Figure 6), we found that performing the Drag-Down gesture generated greater muscle activity of FDI regardless of the configurations, which was partly supported by Huang, Mao, et al. (2021) that swipe down generated greater FDI muscular loads than swipe left and swipe right. Besides, we also found that completing Pinch gesture generated lower FDI muscular loads than performing Drag-Down, Drag-Left, Drag-Up, and Drag-Right under the Sit-Lap and Stand-Hand configurations. As Lee et al. (2009) pointed out that the fewer finger muscular loads were related to the smaller finger activation force, our result could be indirectly supported by Asakawa, Crocker, et al. (2017) that the mean shear force of finger during the Pinch gesture was smaller than that during Drag in four directions. However, the difference between Pinch and Drag in FDI muscular loads was only significant under the Sit-Lap and Stand-Hand configuration. One of the possible inducements was the non-dominant hand support during gesture interaction under these two configurations because previous studies reported that the device support of the non-dominant hand could affect the magnitude of forces applied (Gold et al., 2012; Jonsson et al., 2011; Kietrys et al., 2015), which could further influence the muscular loads (Lee et al., 2009).

5.2. Performance

The task completion time could be used to estimate biomechanics and in turn exposure during touchscreen gesturing (Asakawa, Crocker, et al., 2017). In all three moving distance levels, the significant main effect of gesture types could be found in task completion time (Figure 7) and the task completion time of Tap was shorter than others, this result was consistent with Asakawa, Dennerlein, et al. (2017) that participants needed to move a distance on the touchscreen during the Drag, Stretch and Pinch gestures, which could increase task completion time. In addition, we also found that longer task completion time occurred during the Stretch and Pinch gestures than others when performing the long-distance movement. As the task completion time may be affected by the distance traveled by the fingertip during touchscreen gestures (Jeong & Liu, 2017; Kim & Song, 2014), our result might be explained that the longer moving distance of Pinch and Stretch gestures induced longer task completion time than Drag and Tap gestures when performing the long-distance movement. We perceived that the distance of gesture tasks might cause differences in operation performance. This research was mainly focused on exploring the performance differences among gesture types. And it was valuable to use the selected gestures for a common calibrated task with more distance levels to explore the relationship between gesture length and user performance in our future work.

5.3. Subjective assessment

In the present study, the subjective assessment (comfort and efficiency) was collected by a 10-cm visual analog scale (VAS) with 0 cm being the best rating of the corresponding item and 10 cm being the worst (Coppola et al., 2018). We found the main effect of gestures in subjective comfort ratings (Figure 8). The result showed that performing the Tap gesture was more comfortable than others. As a previous study pointed out moving on the touchscreen with the finger involved high contact friction and led to fatigue (Huang, Mao, et al., 2021), our result might be explained that performing Tap gesture with low friction on the touchscreen generated more comfortable sense than others. We also found that performing the Drag-Up gesture caused less comfort sense than other gestures, which was partly supported by Huang, Mao, et al. (2021) that swipe up gesture produced higher discomfort compared to swipe down, swipe left, and swipe right. This result was also in accordance with our result of muscle activity that greater muscular loads of UT and AD were generated during the Drag-Up gesture. Besides, we found that performing the Drag-Left gesture was less comfortable than Drag-Right. L. As Straker and Mekhora (2000) reported that users may have a trend of discomfort when there was a greater muscular load, this result was able to be supported by our muscular result of AD that there were greater muscular loads during Drag-Left than Drag-Right.

There was a main effect of gestures in subjective efficiency ratings (Figure 9). Our result showed that Tap gesture was more efficient than others, which was similar to Asakawa, Dennerlein, et al. (2017) that using tap gesture could increase interface performance relative to using sliding gestures, pinch or stretch. Besides, there was less efficiency during the Drag-Up and Drag-Left gestures than Drag-Down and Drag-Right, which was partly supported by Huang, Mao, et al. (2021) that swipe up was less efficient than swipe down and swipe right. In addition, our result showed that Pinch and Stretch gestures were more inefficient than others. The reason for this result might be that two-touch gestures needed longer finger moving distance and spent more task completion time than one-touch gestures, which led to less efficiency.

There was no main effect of configurations in subjective ratings, which was similar to Lin et al. (2017) that there was no subjective difference among configurations in a short time during the interaction of computer workstation. In addition, our result was also supported by Chiu et al. (2015) that the short duration of tablet interaction might not be sufficient to have an effect on subjective assessment in configuration settings.

5.4. Implication for applications

The gesture interaction with tablet computers under common configurations was studied in this experiment. There were two aspects in meaning and application of the experimental result.

On the one hand, it was able to help tablet users choose the appropriate configurations and gestures during the tablet use. The result revealed that there was relatively greater muscle activity of AD and UT under the Sit-Table configuration while the less occurred under the Stand-Hand. Therefore, for some tablet users with pain in the shoulder or neck, it was recommended to avoid sitting with a table to use a tablet for a long time to reduce the muscular loads of neck and shoulder. In addition, users with shoulder and neck discomfort were suggested to avoid sliding to the top of the screen frequently because the greater muscular loads of AD and UT were found when the Drag-Up gesture was completed. Specifically, it was recommended that users with MSDs of neck and shoulder use Tap gestures as an alternative gesture to complete high-frequency operations, such as trying to click the Turn-page button to complete page turns instead of swiping up the screen frequently. Although the precise relationship between MSDs risks and non-neutral postures remains unknown (Lin et al., 2017), the increases in non-neutral posture and muscle activation over time may still pose a risk for developing MSDs (Cooper & Straker, 1998; Aaras et al., 1997; Kleine et al., 1999).

On the other hand, our study was able to guide tablet software developers to design operational gestures more reasonably. In our study, Tap was the most efficient gesture both in operating duration and self-reported efficiency. Therefore, Tap was recommended to adopt to complete some high-frequency operations to improve interface performance. When long-distance movements were required to be performed on the screen (e.g., Dragging the progress bar of the video or continuous zooming in on the image), tap or drag was recommended as an alternative to two-finger gestures because the task completion time results indicated that the Pinch and Stretch spent longer when performing long-distance movements. Besides, for the Drag gestures, Drag-Up and Drag-Left showed the lower self-reported sense of efficiency and comfort and also generated higher muscle activity in the neck and shoulder than Drag-Down and Drag-Right. It was suggested to reduce the priority of design in Drag-Up and Drag-Left gestures to optimize the ease of use. Moreover, some application software with specific usage scenarios could be optimized according to our study. For example, when optimizing the applications developed for waiters, teachers, or others who needed to use the tablet in a standing posture for a long time, Drag-Down gesture was recommended to be replaced to reduce the musculoskeletal burden on the index finger because our result showed that muscular loads of FDI were greater under the Stand-Hand configuration, especially performing the Drag-Down gesture. It is essential to optimize interaction gestures from the physiological load aspect and to guide software interaction design because a previous study reported that a computer task requiring low but sustained exertion and repeated daily in long durations could cause muscle fatigue and contribute to the occurrence of musculoskeletal discomforts (Blatter & Bongers, 2002).

5.5. Research limitations and future work

The present study also needed to be interpreted within some limitations. Initially, the interaction behavior of participants might have altered from daily use imperceptibly because our study was a laboratory study that simulated tablet use. Participants were likely to feel discomfort due to the instrumentations attached to participants and the carefully arranged configurations. Moreover, the activity of the upper extremity was evaluated only with EMG data, which was a lack of quantifying upper limb kinematics during gestures. In the future work of our study, we will adopt more interactive gestures, such as rotate and scroll. Besides, we will fit the physiological data into the fatigue model and further demonstrate the relationship between gestures and fatigue to predict and the potential MSDs and put forward more comprehensive conclusions.

6. Conclusion

In this study, we conducted a comparison experiment to evaluate the influence of four self-selected tablet configurations and seven common touchscreen gestures in EMG, user performance, and subjective assessment. The following main conclusions were made:

- Our experimental parameters could be effectively used to determine the differences in tablet configurations in the musculoskeletal load of upper limbs. We found that the shoulder muscle activation decreased under the Stand-Hand configuration while it increased under the Sit-Table configuration during the tablet interaction regardless of the gesture types. Our result indicated that the Stand-Hand configuration might be the preferable choice for avoiding the potential risk of shoulder musculoskeletal disorders.
- We clarified the differences between tablet gestures in electromyography, user performance, and subjective assessment. On the side of muscle activation, performing Drag-Up, Drag-Left gestures tended to possess higher muscular loads of the shoulder while performing Drag-Down gestures led to greater muscular loads of the index finger during all four configurations. On the side of user performance, two-touch gestures (Pinch and Stretch) spent a longer duration when performing long-distance movements. On the side of subjective assessment, Tap gesture brought more comfort and efficiency for users and Our experimental parameters could be effectively used to determine the differences in tablet configurations in the musculoskeletal load of upper limbs. Drag gesture in the inner direction (Drag-Left, Drag-Down) was more efficient than that in the outer direction (Drag-Right, Drag-Down).

This is the first study that focused on investigating the impact of tablet computer configurations and touchscreen gestures on EMG, user performance, and subjective assessment. Our findings could provide a scientific basis for guiding the appropriate selection and the use of touchscreen interaction in the future HCI field. The implications of our findings could be beneficial to avoid the risk of musculoskeletal disorder for repetitive touchscreen gesture use.

Disclosure statement

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