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Wrist and shoulder posture and muscle activity during touch-screen tablet use: Effects of usage configuration, tablet type, and interacting hand

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Abstract.
BACKGROUND: Due to its rapid growth in popularity, there is an imminent need for ergonomic evaluation of the touch-screen tablet computing form-factor.
OBJECTIVE: The aim of this study was to assess postures of the shoulders and wrists and their associated muscle activity during touch-screen tablet use.
METHODS: Fifteen experienced adult tablet users completed a set of simulated software tasks on two media tablets in a total of seven user configurations. Configurations consisted of a combination of a support condition (held with one hand, two hands or in a case), a location (on the lap or table surface), and a software task (web browsing, email, and game). Shoulder postures were measured by using an infra-red LED marker based motion analysis system, wrist postures by electro-goniometry, and shoulder (upper trapezius and anterior deltoid) and forearm (flexor carpi radialis, flexor carp ulnaris, and extensor radialis) muscle activity by surface electromyography.
RESULTS: Postures and muscle activity for the wrist significantly varied across configurations and between hands, but not across the two tablets tested. Wrist extension was high for all configurations and particularly for the dominant hand when a tablet was placed on the lap (mean = 38°). Software tasks involving the virtual keyboard (e-mailing) corresponded to higher wrist extensor muscle activity (50^{th} percentile = 9.5% MVC) and wrist flexion/extension acceleration (mean = $322°/s^2$). High levels of wrist radial deviation were observed for the non-dominant hand when it was used to tilt and hold the tablet (mean = 13°). Observed differences in posture and muscle activity of the shoulder were driven by tablet location.
CONCLUSION: Touch-screen tablet users are exposed to extreme wrist postures that are less neutral than other computing technologies and may be at greater risk of developing musculoskeletal symptoms. Tablets should be placed in cases or stands that adjust the tilt of the screen rather than supporting and tilting the tablet with only one hand.

Keywords: Slate computing, media tablets, mobile computing

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Table 1
Mean (± SD) participant anthropometry

	Age (yrs)	Height (cm)	Weight (kg)	Hand length (mm)
Males ($n = 7$)	29 ± 4	177 ± 9	83.5 ± 7.3	193 ± 11
Females ($n = 8$)	30 ± 6	170 ± 6	65.3 ± 5.9	176 ± 8
All ($n = 15$)	29 ± 5	174 ± 8	73.5 ± 11.3	184 ± 13

1. Introduction

Since the introduction of the Apple iPad® in 2010, "slate", "tablet", or "media tablet" computers have become a viable consumer alternative to traditional notebook (laptop) and desktop computing modes. Over 60 million media tablets were sold in 2011, and it is projected that over 360 million tablets will be sold in 2016 with over a third of all sales in the enterprise market [1]. Due to its rapid growth in popularity, there is an imminent need for ergonomic evaluation of the tablet computing form-factor in order to build a set of specific guidelines or recommendations similar to those developed for current desktop and notebook computers (e.g. ISO-9241 and ANSI/HFES 100 (USA)). The development of ergonomic recommendations is crucial for improvement of tablet usability and system performance, as well as to reduce any potentially negative musculoskeletal impact on users.

The tablet's integration of the display and user input interface into a stand-alone touch-screen device provides both ergonomic potential and challenges. First, these self-contained and inherently portable devices offer many potential usage locations and positions (rather than being constrained to level surfaces such as desks, tables, or laps). Previous studies have shown that the placement of input devices and displays has significant effects on posture and muscle activity of desktop [2–4] and notebook [5,6] computer users. Tablet users may place the devices in positions unlike traditional computing situations, which may either promote more neutral, comfortable postures, or potentially awkward postures not observed in previous studies of other computing devices.

Second, tablets generally do not have rigid supports or stands, so there is not a standard position or tilt angle at which the touch-screen surface is set. Consequently, neck, upper arm, and wrist postures may be affected by the particular configuration, case design, and surface tilt chosen by the user. Some previous studies have shown that increasing the tilt of keyboards increases wrist extension postures during typing [4,7]. This suggests that tablet users may be exposed to higher wrist extensions when interacting with a tablet touch screen that is not laid flat. Furthermore, supporting and tilting an input device with one hand while simultaneously interacting with the other hand has not been required for standard computing situations and results in various user grip approaches [8].

Third, while touch-screen input may allow for more natural user interfaces utilizing gestures (including single or multiple finger and thumb interactions), software functions currently optimized for the traditional keyboard or mouse are still required. Because the screen and input devices cannot be adjusted independently of each other like with notebook or desktop computers, a conflict between visual access to information and touch interaction may arise. Users may adopt floating forearm and finger postures so they do not inadvertently activate the touchscreen and users may have to move their hands out of the way to locate onscreen key locations since there is reduced tactile feedback. It is unknown whether visual access is optimized at the expense of upper extremity posture or comfort, or vice versa.

The aim of this study was to assess postures of the shoulders and wrists and their associated muscle activities for various usage configurations commonly observed during typical tablet computer use and how they vary between different software tasks, and tablet computer or case designs. This will provide the first ergonomics evaluation of users of popular media tablets and deliver initial kinematic data that can be used to establish guidelines for use. The results will also allow for new hypotheses to be generated about multi-touch touchscreen interactions and the design of new devices.

2. Methods

Fifteen adult experienced tablet computer users (Table 1) completed a set of simulated tasks on two media tablet computers in seven configurations while postures and muscle activity were measured. Configurations were chosen based on preliminary unpublished observational studies of tablet users at their homes and workplaces. Our previous paper [9] presented results of the experiment in regard to the neck and head, while this paper will present new data and findings for the shoulder and wrist. As reported there, all ex-

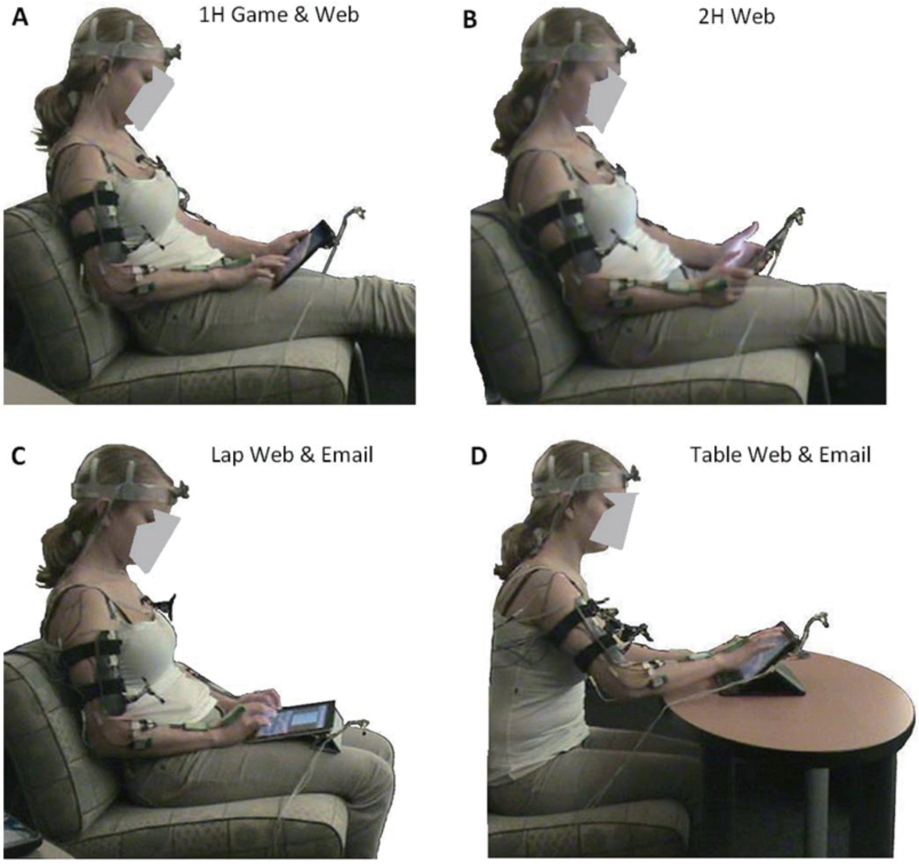

Fig. 1. (a) Tablet 2 on the lap without its case is held and tilted by the participant's non-dominant hand while the dominant hand interacts (b) Tablet 1 on the lap without its case is held and tilted by both hands while both thumbs interact (c) Tablet 1 on the lap held and tilted by its case while both hands are free to interact (d) Tablet 2 on the table held and tilted by its case while both hands are free to interact. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/WOR-131604)

periment participants either owned or had experience working with a tablet computer and reported no current or previous history of head, neck, back or upper extremity musculoskeletal disorders (MSDs). Each participant gave informed consent prior to beginning the study. The Harvard School of Public Health Office of Human Research Administrationapproved all protocols and consent forms.

Participants performed all the tasks while seated in a lounge-type chair with a seat pan height of 440 mm, a slightly reclined backrest, and no armrests (Fig. 1). In addition, a 400 mm tall ottoman-style footrest was provided as an optional accessory and participants were free to use it if desired, except for conditions when the tablet was on the table. All nearby light sources in the laboratory were indirect lighting and the chair was positioned to minimize any glare on the tablet screens.

2.1. Independent variables: Tablet, configuration, and hand

2.1.1. Tablet

The two media tablet computers tested were Tablet 1, an iPad2 (Apple, Cupertino, CA, USA) with dimensions of 241.2 × 185.7 × 8.8 mm and mass 601 g, and Tablet 2, a Xoom (Motorola Mobility, Libertyville, IL, USA) with dimensions of 249.1 × 167.8 × 12.9 mm and mass 708 g. Tablet 1 ran on the iOS 4.3 operating system (Apple, Cupertino, CA, USA) and Tablet 2 ran on the Android 3.0 operating system (Google, Mountain View, CA, USA). Each device was tested only in the landscape orientation. Each tablet also had a proprietary case that could be fitted to the device and adjusted in order to prop up or tilt the tablet computer (Figs 1c and 1d). Only a few different tilt angles were possible with each case and each case's tilt angles were different from the other: Case 1, the Smart Cover (Apple,

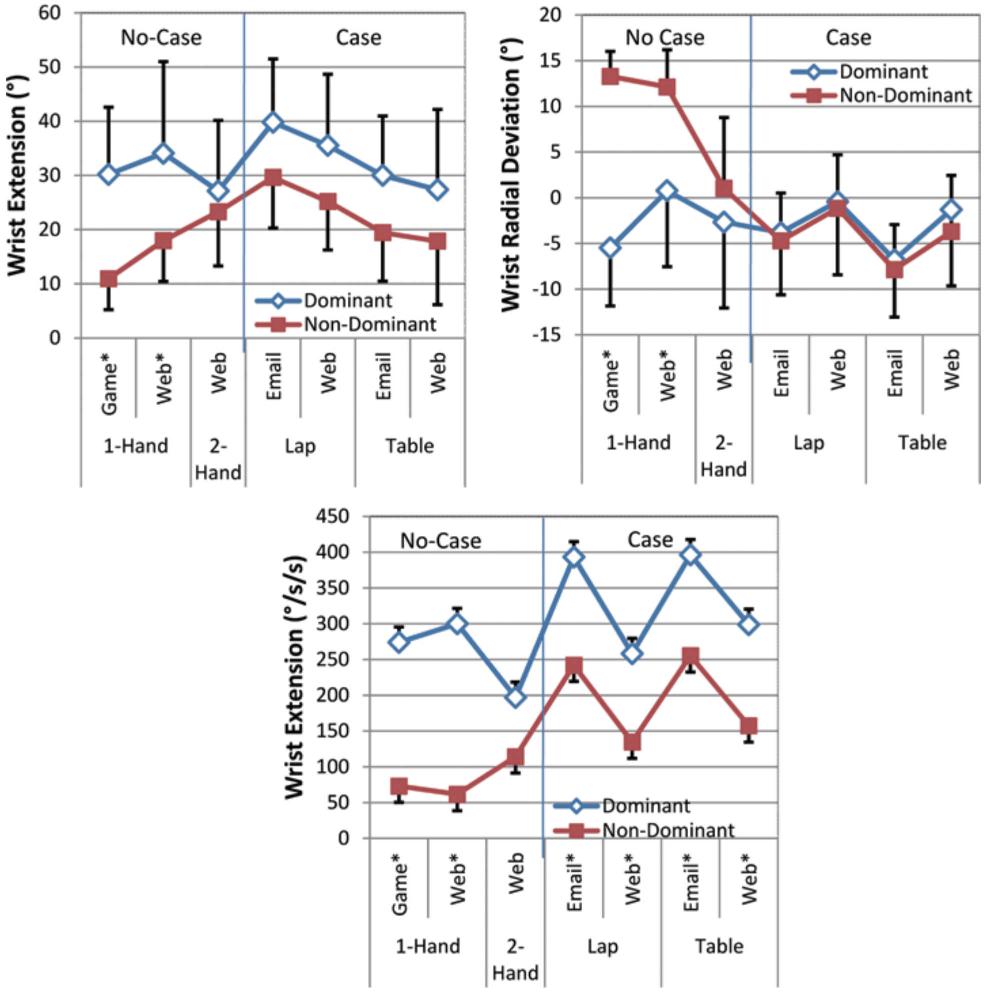

Fig. 2. Mean wrist postures and acceleration for the dominant (14 right, 1 left) and non-dominant (14 left, 1 right) arms averaged across participants. The error bars represent the averaged across participant standard deviation of the wrist posture during the task – only one direction is show for clarity. * indicates significant differences for both the mean and the standard deviation between the hands based on Tukey's post-hoc comparison from the Hand x Configuration ANOVA interaction term. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/WOR-131604)

Cupertino, CA, USA) allows for tilt angles (from horizontal) of 15° and 73°, and Case 2, the Portfolio Case (Motorola Mobility, Libertyville, IL, USA) allows for tilt angles of 45° and 63° (Fig. 2). The order of testing the tablets was randomized and balanced across subjects.

2.1.2. Hand

Hand dominance was determined prior to the start of the study by asking the participant "Are you right- or left-handed?" If the participant reported that they were ambidextrous, then hand dominance was determined by observing which hand the participant used to write with. Hand dominance was of interest due to the varied role of the dominant or non-dominant hand for each of the tested configurations.

2.1.3. Configuration

Seven user configurations, which consisted generally of a support condition (held with one hand, two hands or in a case), location (on the user's lap or table surface) and a software task (web, email, and game), were tested (Fig. 1). The seven configurations (denoted by the name "support/location-software task") were chosen based on unpublished observations of adult media tablet computer users in their own homes and in usability studies. The order of the configurations were randomized and balanced within each tablet. There was a short break (approximately two minutes) between configurations.

For hand-held configurations (Figs 1a and 1b), the tablet was supported by placing it on the user's lap (i.e. top of the thighs) while one or two handsheld and adjusted the tablet tilt. For the one-handed configurations ("1H-"), the non-dominant handheld and adjusted the tablet's tilt while the dominant hand interacted with the screen. For the two-handed configuration ("2H-"), both hands held and adjusted the tablet's tilt while only the thumbs of both hands interacted with the screen. No cases were used with the tablets for these hand-held conditions. The specific position on the lap and the tilt angle were chosen by the participants; they were instructed only to place and hold the tablet in a comfortable position.

For case-supported configurations (Figs 1c and 1d), the tablets were inserted into their respective cases, where the tablet was at a stable case-defined tilt angle (15° for Tablet 1 and 45° for Tablet 2) while placed on either the lap or a table. For the "Lap" configurations, participants placed the tablets in their cases on their laps in a position similar to the hand-held configurations. For the "Table-" configurations, participants set the tablets in their cases on a 667 mm high table. Participants were instructed to position the tablet directly in front of them and at a comfortable distance in both case-supported configurations.

The three simulated computer tasks, representative of typical tablet usage, that were developed for this study were Internet browsing and reading ("-Web"), game playing ("-Game"), and e-mail reading and responding ("-Email"). The five-minute web task consisted of entering URL addresses, navigating through four pages, and reading an online newspaper article. The three-minute game task consisted of playing the common solitaire card game available on most computers. The three-minute email task consisted of using the tablet-based email client to read and respond to short email messages in an email account set up by the experimenters. Subjects read messages and responded with short replies answering the simple question in the read message (e.g. "What is your favorite food and why?"). While the two tablets differed in their operating system software, tasks were selected and designed to have similar interface requirements for each tablet.

2.2. Dependent variables and instrumentation: Posture and muscle activity

2.2.1. Posture

Postural angles for the shoulder were calculated from 3-dimensional kinematics of the upper arms and trunk measured using an infrared three-dimensional motion analysis system (OptotrakCertus, Northern Digital, Waterloo, Canada). Three clusters of three infrared light emitting diodes (IREDs) fixed to a rigid surface were secured to each upper arm and the trunk [10]. An additional cluster of four IREDs was attached to the upper right corner of the tablet computer. The 3-D position of these IREDs were tracked at 100 Hz and recorded to a personal computer and then digitally filtered through a low-pass, fourth-order Butterworth filter with a 5 Hz cutoff frequency. Using the system's digitizing probe, the locations of the left and right acromion and the left and right medial and lateral epicondyle boney landmarks and the four corners of the tablet (tablet cluster) were digitized relative to their associated IRED cluster. For the duration of the measurements, the 3-D position and orientation of these landmarks were calculated based on the position and orientation of their associated IRED cluster [11]. Angles were then derived from these segment and landmark positions and orientations: shoulder flexion and abduction were defined with respect to the vertical, and elevation was defined as the vertical translation of the upper arm relative to a reference posture in which the participant was seated upright, looking straight forward, with arms at side and hands resting comfortably on lap.

Postural angles for the wrist were measured using bi-axial goniometers (SG65 Biometrics Ltd, London, UK) and sampled at 25 Hz with a wireless data-logging system (V-Link, Microstrain, Boston, Ma). Goniometers were calibrated prior to the experiment [12]. Flexion and deviation angles were defined with respect to a reference posture, in which the experimenter positioned each participant's wrists so that they were straight (0°) while the elbows were bent to approximately 90° and the forearms pronated. Wrist accelerations were calculated by differentiating angular position data twice [13–15].

The mean and standard deviation of continuous measures of the three shoulder postures, the two wrist postures and two wrist accelerations were calculated for each trial for dominant and non-dominant arms. These were the outcome metrics used for statistical analysis.

2.2.2. Muscle activity

Electromyographic (EMG) activity of two shoulder muscles (anterior deltoid (AD) and upper trapezius (UT)) and three muscle groups of the forearm (extensor carpi radialis/extensor digitorum (ECU/ED), flexor

Table 2
Wrist Posture and Kinematics: Least squares means (SE) for ANOVA main effects Tablet, Configuration, and Hand and p-values for interactions[1,2]

	Wrist extension			Wrist radial deviation		
	Mean (°)	St Dev (°)	Acc (°/s^2)	Mean (°)	St Dev (°)	Acc (°/s^2)
Configuration						
ANOVA	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0019}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
1H-game	21 (2)^{C}	9 (1)^{C}	174 (19)^{C}	4 (2)^{A}	5 (1)^{D}	101 (13)^{B}
1H-Web	26 (2)^{B,C}	12 (1)^{A,B}	181 (19)^{B,C}	6 (2)^{A}	6 (1)^{B,C}	116 (13)^{B}
2H-Web	25 (2)^{B,C}	12 (1)^{A,B,C}	156 (19)^{C}	−1 (2)^{B}	9 (1)^{A}	110 (13)^{B}
Lap-Email	35 (2)^{A}	11 (1)^{A,B,C}	318 (19)^{A}	−4 (2)^{B,C}	6 (1)^{B,C,D}	179 (13)^{A}
Lap-Web	30 (2)^{A,B}	11 (1)^{A,B,C}	196 (19)^{B,C}	−1 (2)^{B}	7 (1)^{B,C}	132 (13)^{A,B}
Table-Email	25 (2)^{B,C}	10 (1)^{B,C}	326 (19)^{A}	−7 (2)^{C}	6 (1)^{C,D}	163 (13)^{A}
Table-Web	23 (2)^{C}	13 (1)^{A}	228 (19)^{B}	−3 (2)^{B}	7 (1)^{A,B}	129 (13)^{A,B}
Hand						
ANOVA	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
Dominant	32 (1)^{A}	13 (1)^{A}	302 (16)^{A}	−3 (1)^{B}	8 (1)^{A}	169 (10)^{A}
Non-Dominant	20 (2)^{B}	9 (1)^{B}	148 (16)^{B}	1 (1)^{A}	5 (1)^{B}	94 (10)^{B}
Tablet						
ANOVA	$p = 0.6274$	$p = 0.7390$	$p = 0.2477$	$p = 0.3587$	$p = 0.0903$	$p = 0.7412$
Tablet 1	26 (2)	11 (1)	231 (16)	0 (1)	6 (1)	130 (10)
Tablet 2	27 (2)	11 (1)	220 (16)	−1 (1)	7 (1)	133 (10)
Interactions						
Hand x Config[3]	$p = 0.0502$	$\boldsymbol{p = 0.0036}$	$\boldsymbol{p = 0.0003}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0342}$	$p = 0.4492$
Tablet x Config	$p = 0.3798$	$p = 0.5846$	$p = 0.1792$	$p = 0.5407$	$p = 0.8149$	$p = 0.0509$
Tablet x Hand	$p = 0.7788$	$p = 0.6583$	$p = 0.7382$	$p = 0.6391$	$p = 0.7382$	$p = 0.8203$

[1]Repeated Measures ANOVA with Participant as a random variable and Hand, Configuration, and Tablet as fixed effects (bold indicates significant effect $p < 0.05$).
[2]For each dependent variable, values with the same superscript letters indicate no significant difference and post hoc groupings are ranked such that A>B>C>D.
[3]Values are presented in Fig. 2.

carpi radialis (FCR), and flexor carpi ulnaris/palmarislongus (FCU/PL)) were measured using surface electrodes (DE 2.1 Single Differential Electrode, Delsys, Boston, MA, USA) for both left and right sides of the body. Electrodes were placed over muscle bellies [16]. Specifically, the electrodes of the ECU/ED and FCR were placed two-thirds of the distance from the styloid process of the radius to the medial epicondyle of the humerus on the ventral and dorsal aspects of the forearm, respectively. Electrodes for the FCU/PL were placed three-quarters of the distance from the sulcus carpi to the medial epicondyle of the humerus. The electrode for the trapezius was placed at approximately 50 mm vertical distance from the midpoint between the neck and acromion. The electrode for the anterior deltoid was placed on the ventral side of the shoulder approximately 50 mm from the acromion. Placement of the electrode on the muscles was validated through palpation and signal response to targeted muscle contractions.

After amplification, EMG signals were recorded at a frequency of 1000 Hz. To normalize results across participants, three 3-second maximum voluntary contractions (MVC) were collected three times for each muscle using standard manual muscle testing procedures [14]. Participants rested for two minutes between muscle contractions and the maximum value obtained during the contractions was used as the MVC value. The 10^{th}, 50^{th}, and 90^{th} percentile of the continuous measures of the five muscle activities were calculated for each trial for dominant and non-dominant arms [15]. These were the outcome metrics used for statistical analysis.

2.3. Statistics

To test the hypothesis that postures and muscle activities varied across tablets, dominant and non-dominant hands, and user configurations, we employed a 2×2×7 repeated measures analysis of variance (RM-ANOVA) for each posture and muscle activity outcome metric. Independent variables Configuration (2H-Web/1H-Web/1H-Email/Lap-Email/Lap-Web/Table-Email/Table-Web), Hand (Dominant/Non-dominant), and Tablet (Tablet 1/Tablet 2) were set as fixed effects and participant as a random effect. All interaction terms for the fixed effects were included in the model. When significance was observed for an effect ($p < 0.05$), a post-hoc Tukey's HSD test was used to determine if differences in the metrics existed between effect levels. All

Table 3
Forearm Muscle Activity: Normalized EMG amplitudes' least squares means (SE) for ANOVA main effects Tablet, Configuration, and Hand and p-values for interactions[1,2]

	FCR (%MVC)			FCU (%MVC)			ED/ECR (%MVC)		
	10^{th}	50^{th}	90^{th}	10^{th}	50^{th}	90^{th}	10^{th}	50^{th}	90^{th}
Configuration									
ANOVA	$\boldsymbol{p = 0.0060}$	$\boldsymbol{p = 0.0144}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0349}$	$\boldsymbol{p = 0.0037}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
1H-game	0.9 (0.1)^{A}	1.3 (0.2)^{A}	2.1 (0.3)^{C}	1.3 (0.2)^{A}	1.8 (0.2)^{A,B}	2.6 (0.4)^{C}	2.0 (0.4)^{B}	3.7 (0.6)^{B}	6.0 (1.2)^{C,D}
1H-Web	0.8 (0.1)^{A,B}	1.2 (0.2)^{A,B}	2.3 (0.3)^{B,C}	1.2 (0.2) ^{A,B}	1.7 (0.2)^{A,B}	3.0 (0.4)^{C}	1.4 (0.4)^{B,C}	3.3 (0.6)^{B}	7.2 (1.2)^{D}
2H-Web	0.6 (0.1)^{A,B}	1.3 (0.2)^{A,B}	3.0 (0.3)^{A,B,C}	1.0 (0.2)^{A,B}	1.5 (0.2)^{B}	3.1 (0.4)^{B,C}	0.9 (0.4)^{C}	1.5 (0.6)^{C}	4.4 (1.2)^{D}
Lap-Email	0.6 (0.1)^{A,B}	1.1 (0.2)^{A,B}	3.2 (0.3)^{A,B}	1.1 (0.2)^{A,B}	1.6 (0.2)^{A,B}	3.7 (0.4)^{A,B}	5.6 (0.4)^{A}	9.9 (0.6)^{A}	16.8 (1.2)^{A}
Lap-Web	0.6 (0.1)^{A,B}	0.8 (0.2)^{A,B}	1.9 (0.3)^{A,B}	1.1 (0.2)^{A,B}	1.4 (0.2)^{B}	2.5 (0.4)^{B,C}	1.8 (0.4)^{B,C}	4.9 (0.6)^{B}	11.9 (1.2)^{B}
Table-Email	0.5 (0.1)^{A,B}	1.2 (0.2)^{A,B}	3.4 (0.3)^{A}	1.2 (0.2)^{A,B}	2.1 (0.2)^{A}	4.6 (0.4)^{A}	5.1 (0.4)^{A}	9.0 (1)^{A}	15.1 (1.2)^{A}
Table-Web	0.4 (0.1)^{B}	0.7 (0.2)^{B}	2.0 (0.3)^{C}	0.9 (0.2)^{B}	1.4 (0.2)^{B}	2.8 (0.4)^{B,C}	1.3 (0.4)^{B,C}	3.4 (0.6)^{B}	10.0 (1.2)^{B}
Hand									
ANOVA	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.1925}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0010}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
Dominant	0.7 (0.1)^{B}	0.6 (0.2)^{B}	2.5 (0.2)	1.4 (0.2)^{A}	1.9 (0.2)^{A}	3.7 (0.4)^{A}	2.9 (0.3)^{A}	5.9 (0.6)^{A}	11.2 (1.1)^{A}
Non-Dominant	1.1 (0.1)^{A}	1.5 (0.2)^{A}	2.8 (0.2)	0.9 (0.2)^{B}	1.4 (0.2)^{B}	2.7 (0.4)^{B}	2.3 (0.3)^{B}	4.4 (0.6)^{B}	9.2 (1.1)^{B}
Tablet									
ANOVA	$\boldsymbol{p = 0.0768}$	$\boldsymbol{p = 0.1992}$	$\boldsymbol{p = 0.4169}$	$\boldsymbol{p = 0.0014}$	$\boldsymbol{p = 0.0406}$	$\boldsymbol{p = 0.2304}$	$\boldsymbol{p = 0.7317}$	$\boldsymbol{p = 0.1908}$	$\boldsymbol{p = 0.0997}$
Tablet 1	0.7 (0.1)	1.1 (0.2)	2.7 (0.2)	1.2 (0.2)^{A}	1.8 (0.2)^{A}	3.2 (0.4)	2.6 (0.3)	5.0 (0.6)	9.9 (1.1)
Tablet 2	0.6 (0.1)	1.0 (0.2)	2.6 (0.2)	1.0 (0.2)^{B}	1.6 (0.2)^{B}	3.1 (0.4)	2.6 (0.3)	5.3 (0.6)	10.6 (1.1)
Interactions									
Hand x Config[3]	$\boldsymbol{p = 0.0013}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0260}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0006}$	$p = 0.1968$	$p = 0.0798$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
Tablet x Config	$p = 0.8160$	$p = 0.5934$	$p = 0.4075$	$p = 0.9585$	$p = 0.8218$	$p = 0.8541$	$p = 0.8594$	$p = 0.9133$	$p = 0.8956$
Tablet x Hand	$\boldsymbol{p = 0.0385}$	$\boldsymbol{p = 0.0269}$	$p = 0.0800$	$p = 0.9202$	$p = 0.4627$	$p = 0.5748$	$p = 0.4982$	$p = 0.1648$	$p = 0.0774$

[1]Repeated Measures ANOVA with Participant as a random variable, Hand, Configuration and Tablet as fixed effects (bold indicates significant effect $p < 0.05$).
[2]For each dependent variables, values with the same superscript letters indicate no significant difference and groupings are ranked such that A>B>C>D.
[3]Values for the 50^{th} percentile are presented in Fig. 3.

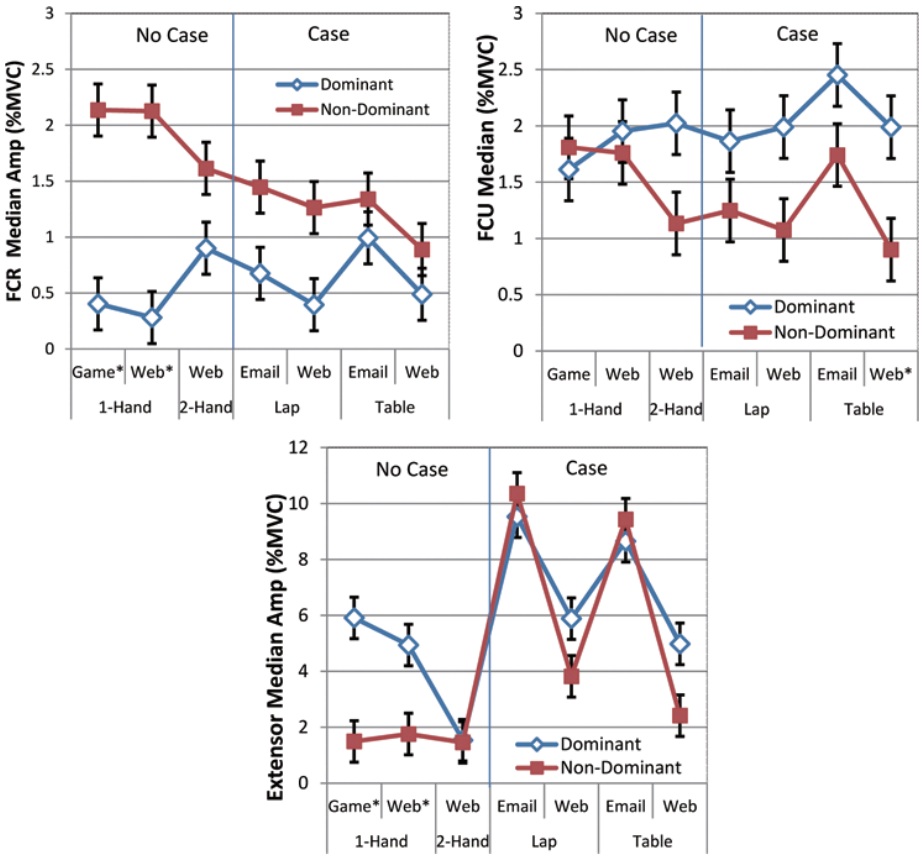

Fig. 3. Forearm muscle median EMG amplitude values for the dominant (14 right, 1 left) and non-dominant (14 left, 1 right) arms averaged across participants. The error bars represent standard error for the across participant average. * indicates significant differences between the hands based on Tukey's post-hoc comparison from the Hand x Configuration ANOVA interaction term. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/WOR-131604)

analyses were run using JMP Software (SAS Institute, Cary, NC).

3. Results

3.1. *Wrist postures and forearm muscle activity*

All mean wrist postures, variability in wrist postures, wrist angle accelerations and forearm muscle activities varied significantly across main effects Configuration and Hand, but not across Tablet, except for the FCU muscle (Tables 2 and 3). For Hand, wrist extension posture, variability and acceleration were on average greater for the dominant hand than the non-dominant hand except in the two-handed configuration. The one-handed configurations lead to the largest differences between the hands, stemming from large radial deviation and small variability of the non-dominant hand in those configurations (Fig. 2). For Configuration, wrist extension posture was greatest when participants used the tablets on their lap while it was in its case, and accelerations were greatest during typing. Wrists were significantly more ulnar deviated when typing email than for other configurations.

Extensor muscle activity in the forearm was the highest for conditions that involved typing (e-mail), and were, on average, higher for the dominant hand. The differences in the activity between the hands were driven by differences during the one-handed configurations (Fig. 3). Flexor muscle activity was low (90^{th} percentile values below 5% MVC) for all conditions.

3.2. *Shoulder posture and muscle activity*

All shoulder postures and the variability in shoulder postures varied significantly by Configuration, with

Table 4
Shoulder Posture: Least squares means (SE) for ANOVA main effects Tablet, Configuration, and Hand and p-values for interactions[1,2]

Shoulder	Flexion		Abduction		Elevation	
	Mean (°)	St Dev (°)	Mean (°)	St Dev (°)	Mean (cm)	St Dev (cm)
Configuration						
ANOVA	$\boldsymbol{p = 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
1H-game	23 (2)^{A}	2 (0)^{B}	8 (1)^{A,B,C}	1 (0)^{B}	0 (2)^{B}	2 (0)^{C,D}
1H-Web	21 (2)^{A,B}	3 (0)^{B}	9 (1)^{A,B,C}	2 (0)^{B}	−1 (2)^{B}	3 (0)^{B,C}
2H-Web	20 (2)^{A,B}	2 (0)^{B}	8 (1)^{B,C}	2 (0)^{B}	−1 (2)^{B}	3 (0)^{B}
Lap-Email	18 (2)^{B}	2 (0)^{B}	12 (1)^{A}	1 (0)^{B}	−2 (2)^{B}	2 (0)^{D}
Lap-Web	17 (2)^{B}	3 (0)^{B}	11 (2)^{A,B}	2 (0)^{B}	−0 (2)^{B}	3 (0)^{B,C}
Table-Email	24 (2)^{A}	3 (0)^{B}	7 (1)^{C}	2 (0)^{B}	6 (2)^{A}	2 (0)^{B,C,D}
Table-Web	19 (2)^{A,B}	5 (0)^{A}	7 (1)^{C}	3 (0)^{A}	6 (2)^{A}	4 (0)^{A}
Hand						
ANOVA	$p = 0.9247$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0178}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0124}$
Dominant	20 (2)	3 (0)^{A}	10 (1)^{A}	2 (0)^{A}	3 (1)^{A}	3 (0)^{A}
Non-Dominant	20 (2)	2 (0)^{B}	8 (1)^{B}	1 (0)^{B}	0 (1)^{B}	2 (0)^{B}
Tablet						
ANOVA	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p = 0.0048}$	$p = 0.3855$	$p = 0.3223$	$p = 0.0030$	$p = 0.3732$
Tablet 1	17 (2)^{B}	3 (0)^{B}	9 (1)	2 (0)	0 (1)^{B}	2 (0)
Tablet 2	23 (2)^{A}	3 (0)^{A}	9 (1)	2 (0)	2 (1)^{A}	3 (0)
Interactions[3]						
Hand x Config	$p = 0.6017$	$\boldsymbol{p < 0.0001}$	$p = 0.7170$	$\boldsymbol{p = 0.0002}$	$p = 0.4835$	$p = 0.3826$
Tablet x Config	$\boldsymbol{p = 0.0002}$	$p = 0.4758$	$p = 0.1992$	$p = 0.2424$	$p = 0.6609$	$p = 0.6534$
Tablet x Hand	$p = 0.4536$	$p = 0.7138$	$p = 0.9126$	$p = 0.9218$	$p = 0.4036$	$p = 0.5225$

[1]Repeated Measures ANOVA with Participant as a random variable and Hand, Configuration, and Tablet as fixed effects (bold indicates significant effect $p < 0.05$).
[2]For each dependent variables, values with the same superscript letters indicate no significant difference and groupings are ranked such that A>B>C>D.
[3]Values for some significant interactions are presented in Fig. 4.

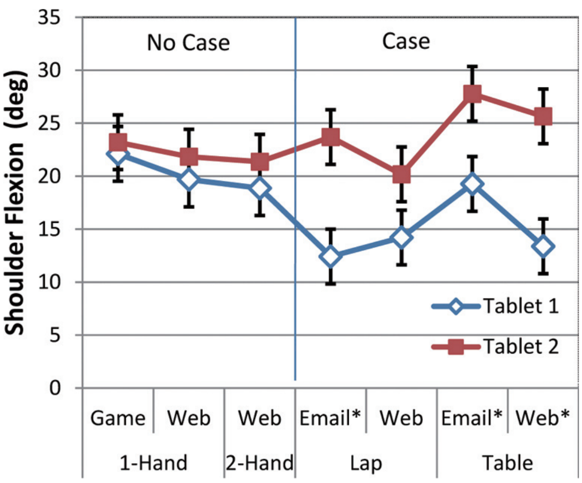

Fig. 4. Mean values for shoulder flexion angle for the two tablets averaged across participants. The error bars represent standard error for the across participant average * indicates significant differences between the tables based on Tukey's post-hoc comparison from the Tablet x Configuration ANOVA interaction term. Differences between the tables occur mainly when the devices are in their cases, which have different tilt angles. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/WOR-131604)

the greatest flexion, least abduction, greatest elevation, and the greatest variability of all postures occurring when using the tablet on the table (Table 4). The dominant arm demonstrated greater angles and elevations, as well as greater variability, compared to the non-dominant arm. Greater shoulder flexion and elevation were also observed for Tablet 2 compared to Tablet 1, which appears to be influenced mainly by the conditions where the devices were in their cases (Fig. 4).

All shoulder muscle activities varied across Conditions with the largest values also occurring when operating the tablets on tables (Table 5). For the dominant shoulder, there was more variability in the anterior deltoid and larger EMG values for the upper trapezius compared to the non-dominant side (Fig. 5). Only the 90th percentile of the anterior deltoid showed a larger value for Tablet 2 compared to Tablet 1.

4. Discussion

The aim of this study was to assess posture and muscle activity for the wrists and shoulders during touch-screen tablet computer use with the intention of making recommendations for healthy usage practices. The results show that user configuration significantly affected all dependent variables; however, the

Table 5

Shoulder Muscle Activity: Normalized EMG amplitudes' least square's means (SE) for the ANOVA main effects for Tablet, Configuration, and Hand and p-values for interactions[1,2]

	Anterior Deltoid (%MVC)			Upper Trapezius (%MVC)		
	10th	50th	90th	10th	50th	90th
Configuration						
ANOVA	$\boldsymbol{p = 0.0002}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0349}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
1H-game	2.0 (0.4)^{A,B}	3.0 (0.4)^{B}	4.9 (0.6)^{B,C}	0.6 (0.3)^{B,C}	1.2 (0.4)^{B,C}	2.0 (0.7)^{B}
1H-Web	1.7 (0.4)^{B}	2.1 (0.4)^{C}	4.2 (0.6)^{B,C}	0.5 (0.3)^{B,C}	1.2 (0.4)^{B,C}	2.5 (0.7)^{B}
2H-Web	1.6 (0.4)^{B}	1.8 (0.4)^{C}	2.5 (0.6)^{D}	0.2 (0.3)^{C}	0.7 (0.4)^{C}	1.8 (0.7)^{B}
Lap-Email	1.9 (0.4)^{A,B}	2.5 (0.4)^{B,C}	3.9 (0.6)^{C,D}	0.7 (0.3)^{B,C}	1.4 (0.4)^{B,C}	2.6 (0.7)^{B}
Lap-Web	2.2 (0.4)^{A,B}	2.6 (0.4)^{B,C}	4.4 (0.6)^{B,C}	0.6 (0.3)^{B,C}	1.2 (0.4)^{B,C}	2.6 (0.4)^{B}
Table-Email	2.6 (0.4)^{A}	4.2 (0.4)^{A}	7.5 (0.6)^{A}	1.7 (0.3)^{A}	3.0 (0.4)^{A}	4.8 (0.7)^{A}
Table-Web	1.8 (0.4)^{B}	2.3 (0.4)^{B,C}	5.7 (0.6)^{B}	0.8 (0.3)^{B}	1.8 (0.4)^{B}	3.9 (0.7)^{A}
Hand						
ANOVA	$\boldsymbol{p < 0.0001}$	$p = 0.2687$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$	$\boldsymbol{p < 0.0001}$
Dominant	1.7 (0.3)^{B}	2.5 (0.4)	5.3 (0.5)^{A}	0.9 (0.2)^{A}	1.9 (0.4)^{A}	3.8 (0.7)^{A}
Non-Dominant	2.2 (0.3)^{A}	2.7 (0.4)	4.1 (0.5)^{B}	0.5 (0.2)^{B}	1.0 (0.4)^{B}	2.0 (0.7)^{B}
Tablet						
ANOVA	$p = 0.8062$	$p = 0.2458$	$\boldsymbol{p < 0.0001}$	$p = 0.1082$	$p = 0.2943$	$p = 0.3416$
Tablet 1	2.0 (0.3)	2.5 (0.4)	4.1 (0.5)^{B}	0.6 (0.2)	1.4 (0.4)	2.8 (0.7)
Tablet 2	2.0 (0.3)	2.7 (0.4)	5.4 (0.5)^{A}	0.8 (0.2)	1.6 (0.4)	3.0 (0.7)
Interactions						
Hand x Config[3]	$p = 0.8809$	$\boldsymbol{p = 0.0024}$	$\boldsymbol{p < 0.0001}$	$p = 0.1066$	$p = 0.0824$	$\boldsymbol{p = 0.0218}$
Tablet x Config	$p = 0.7206$	$p = 0.5324$	$\boldsymbol{p = 0.0080}$	$p = 0.9057$	$p = 0.7913$	$p = 0.5857$
Tablet x Hand	$p = 0.6304$	$p = 0.8531$	$p = 0.2452$	$p = 0.3840$	$p = 0.9534$	$p = 0.4135$

[1]Repeated Measures ANOVA with Participant as a random variable, Hand, Configuration and Tablet as fixed effects (bold indicates significant effect $p < 0.05$).

[2]For each dependent variable, values with the same superscript letters indicate no significant difference and groupings are ranked such that A>B>C>D.

[3]Values for the 50th percentile are presented in Fig. 5.

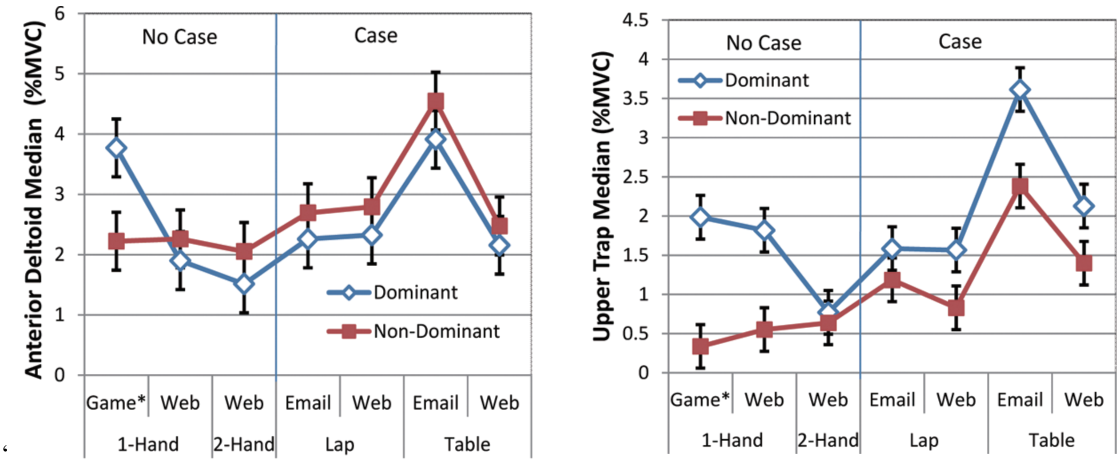

Fig. 5. Shoulder muscle median EMG amplitude values for the dominant (14 = right, 1 Left) and non-dominant (14 left, 1 right) arms averaged across participants. The error bars represent standard error for the across participant average. * indicates significant between the hands based on Tukey's post-hoc comparison from the Hand x Configuration ANOVA interaction term. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/WOR-131604)

specific type of tablet and its respective case design did not significantly affect most dependent variables. There were significant differences between dominant and non-dominant hands for nearly all outcomes and significant interactions between Hand and Configuration. This suggests that how the tablet is supported (i.e. with a single hand or with a case) and specific interaction mode with software tasks performed influences differences in observed wrist postures and forearm muscle activities; while the location of the tablet (on the lap or on a table) influences differences in observed shoulder postures.

These data suggest that during tablet use, especially during tasks requiring use of the virtual keyboard, wrist postures may be an issue when compared to other computing form factors. Mean wrist extension for nearly all usage configurations, especially for the dominant hand, were at the high end of the spectrum of values observed in previous studies of desktop keyboard and mouse users [2,3,10,17]. Mean or median wrist extension values greater than 30° have been reported by few studies previously: only for users of notebook computers placed on the lap with no palm support surfaces, or on risers that introduce significant keyboard slope [18–20], or when typing on standard keyboards with extreme slopes beyond >45° [21,22]. Mean wrist extension was greater than 27° for the dominant hand in all configurations and was greatest in the configurations where the tablets were in their cases on the participant's lap. This highlights the influence of the location of the tablet surface in relation to the elbow; wrist extension has been shown to increase for input devices below elbow level [4]. In addition, these high extension postures were associated with large amount of forearm extensor muscle activity and wrist accelerations during the keyboarding tasks, adding to the risks of high pressures in the carpal tunnel during these conditions [21, 23].

Unexpectedly, we observed no effect of the tablet tilt angle on wrist posture; which is contrary to results from most studies of standard keyboard tilts and practice guidelines. Based on these previous studies [4, 7,21,22], we expected that wrist extension would be higher for Tablet 2 than Tablet 1 due to the difference in case-defined tilt angle when typing, but this effect was not observed. Therefore the extreme wrist extension postures observed are not likely due to tablet tilt angle alone and may be related to inherent aspects of an integrated touchscreen display and virtual keyboard. These may elicit floating finger postures to avoid unintentional activation and cause users to move the hand out of the field of view to visually locate the onscreen keys or icons [19]. These effects could be reduced with use of a peripheral or external keyboard.

The results also indicate that supporting the device with a single hand increases levels of wrist radial deviation and corresponding muscle activity for the supporting hand (Fig. 2). A high degree of radial deviation is required in order for the non-dominant hand to tilt the tablet up from horizontal and provide a suitable viewing angle for the user, which can increase carpal tunnel pressure [21]. Tilting the tablet to this angle requires a constant and stable effort, which is reflected in the low variability of postures and muscle activities for the three configurations (Table 2), and may quickly lead to fatigue. Radial deviation is reduced significantly for conditions where the device is supported and tilted by its case.

There was a significant difference between hands even for configurations where the tablets were in their cases and both hands were free to interact. Differences between the dominant and non-dominant hands during these case-supported conditions are typical of differences observed during desktop and notebook computing as the dominant hand takes on tasks associated with the pointing device [14,15]. Tablets require simple point and touch tasks similar to the point and click of the mouse; however both hands may interact as point and touch inputs rather than a single hand for a traditional mouse. The dominant hand had approximately 10° greater mean wrist extension posture and $139°/s^2$ greater mean flexion/extension acceleration than the non-dominant hand for both email and web tasks in case-supported configurations (Fig. 2), which suggests a dominant-hand interaction preference exists even for a centrally-located touch screen. These results may also suggest that the dominant hand must be moved out of the way of the screen more often than a more-idle non-dominant hand in order to access visual information. Further research is needed to elucidate how users' dominant and non-dominant hands are utilized and affected differently for various touchscreen functions and onscreen locations.

Mean shoulder flexion and abduction were generally lower than shoulder elevation, similar to previous studies of notebook computer use and mousing in various desktop locations [2,5,18]. Differences in shoulder outcomes were most likely due to differences in location of the device, as suggested by these previous studies. When placed on the table, shoulder abduction decreased and elevation increased compared to placement on the lap (Table 4). Significantly greater shoulder muscle activations were observed for the Table-Email configuration compared to the Table-Web, suggesting that more shoulder effort is required to stabilize the arm when typing in this flexed position.

Unlike for the wrist and lower arm, the main effect of Tablet did significantly affect some shoulder postural outcomes. Mean shoulder flexion angle and elevation was higher for Tablet 2 than Tablet 1. This was likely due to the case-specified tilt angle that changes the relative height of the center of the screen, rather than differences in the tablet's design or operating system. Tablet 2 had higher case-specified screen tilt than Tablet 1 (Fig. 1).

These results have implications for practice supporting the use of a case to allow for hands-free operation and the use of an external keyboard to reduce the high wrist extension during extended keyboarding. Based on our previous publication, the case needs to provide for a range of moderate tilt angles that allow for more neutral head and neck postures [9]. An external keyboard accommodates separation of the input and display components, allowing for more neutral wrist postures [6,24]. Many off-the-shelf products that combine cases and external keyboards for tablet devices are now available for consumers. Overall, the factors identified as concerns here are based on tablet interaction over longer durations; whereas, for short durations, the mobility of the tablet computer can add to postural variability and may mitigate musculoskeletal health concerns. Therefore, the intended frequency and duration of use should be considered when choosing an appropriate computing form factor and peripherals (virtual or physical).

These results need to be considered within the context of the limitations of the study. This is a laboratory study with simulated tasks and a large amount of instrumentation attached to the users. As a result users may have altered their behavior from how they otherwise naturally interact with tablets. In addition, our measurements for each experimental condition were collected for only a short period of time, which may allow users to adopt a posture that they would not have been able to maintain for a longer period of time or limit the opportunity for the participants to shift into typical long-duration usage postures. Future studies should monitor tablet usage behaviors over longer periods and in several settings.

5. Conclusions

These data suggest that use of touch-screen media tablet users can produce extreme non-neutral wrist postures along with high forearm extensor muscle activities in some user-adopted configurations. These data suggest that tablets should be placed in cases or stands rather than using the hands to hold, support, and/or tilt the tablet. External input devices may reduce the extreme postures; however, this relationship needs further investigation to develop the evidence as this study did not examine other input devices.

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Conflict of interest

At the time this study was conducted, authors Kim Marinelli and Dan Odell were employees of Microsoft, a partial funding source for this study. Dr. Odell and Mrs. Marinelli took part in the experimental and study design, including the selection of specific usage configurations; however, they did not participate in data collection or analysis and interpretation of the results. There is no other potential conflict of interest or the appearance of a conflict of interest with regards to the study.

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