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Anna Pereira [a], Tevis Miller [a], Yi-Min Huang [a], Dan Odell [a] & David Rempel [a]

[a] School of Public Health & Department of Bioengineering, University of California Berkeley, Berkeley, CA, USA

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Anna Pereira, Tevis Miller, Yi-Min Huang, Dan Odell and David Rempel*

School of Public Health & Department of Bioengineering, University of California Berkeley, Berkeley, CA, USA

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The purpose of this study was to evaluate tablet size (weight), orientation, grip shape, texture and stylus shape on productivity, biomechanics and subjective usability and fatigue when the tablet was held with just the left hand. A total of 15 male and 15 female subjects, ages 16–64 years, tested eight tablets and three styluses. Overall, the usability, fatigue and biomechanical evaluation of tablet design features supported the use of smaller to medium-sized tablets, with a ledge or handle shape on the back and surfaced with a rubberised texture. Larger, heavier tablets had significantly worse usability and biomechanics and their use with one hand should be limited. The stylus with a tapered grip (7.5–9.5 mm) or larger grip (7.6 mm) had better usability and biomechanics than one with a smaller grip (5 mm). There were no significant differences in productivity between design features. These design parameters may be important when designing tablets.

Practitioner Summary: Different tablet and stylus design features were evaluated for usability and biomechanical properties. On the basis of short-term tasks, emulating functional tablets, usability was improved with the smaller and medium-sized tablets, portrait (vs. landscape) orientation, a back ledge grip and rubberised texture. There were no differences in productivity between design features.

Keywords: mobile computing; hand-held; fatigue; productivity; design

1. Introduction

The use of tablet computers and smartphones is increasing in applications such as retail, books, auto navigation, home controls and health care (Jana 2011). The trend is likely to increase as studies demonstrate an improved productivity with the hand-held tablet compared to a conventional computer (Horng et al. 2012). As computer technology moves towards higher mobility through the use of hand-held tablets and smartphones, there is a need for empirical evidence of tablet and smartphone design features that increase usability and improve biomechanics. Concern that early desktop computer designs were associated with discomfort and musculoskeletal problems was one of the factors that prompted the creation of design guidelines for desktop computer workstations such as the ISO 9241 and ANSI/HFES 100-2007. No such national or international guidelines exist for mobile devices. In 1995, the United States Department of Defense released guidelines for palm top computers (PDAs) and tablets for use in military settings (Department of Defense 1995). They recommended that hand-held equipment should not weigh more than 2.3 kg; should be capable of being held and operated with a single hand; and should be smaller than 100-mm high × 255-mm long × 125-mm wide.

Only a handful of studies have evaluated the musculoskeletal risks associated with mobile devices. Some case studies have noted an increased risk for musculoskeletal disorders with increasing use of cell phones (Ming, Pietikainen, and Hänninen 2006; Storr, de Vere Beavis, and Stringer 2007). Among university students and faculty, increasing hours of use of hand-held mobile devices was associated with increased neck, shoulder and thumb pain (Berolo, Richard, and Benjamin 2011). Interestingly, the studies of mobile devices that evaluated exposure to musculoskeletal risks use have found an asymmetrical risk to the upper extremities. The non-dominant hand (e.g. usually left) holds the device, while the dominant hand performs data entry. While holding a tablet, the non-dominant arm experiences increased shoulder flexion, shoulder load, sustained pinch grip and muscle activity, as evaluated by electromyography (EMG), compared to the dominant arm (Lozano, Jindrich, and Kahol 2011; Young et al. 2012). The increased posture deviation from neutral and sustained muscle activity poses an increased risk for musculoskeletal disorders, fatigue and discomfort in the non-dominant arm compared to the dominant arm (Werner et al. 2005; Fischer, Wells, and Dickerson 2009). In addition, mobile device use is associated with greater head and neck flexion when compared to desktop computer use (Heasman, Brooks, and Stewart 2000; Young et al. 2012). One of the few studies of tablet use evaluated seated children using tablets placed on a table compared to use of desktop computer (Straker et al. 2008). Tablet use was associated with more neck and trunk flexion, more flexed and

*Corresponding author. Email: david.rempel@ucsf.edu

elevated shoulders, and greater muscle activity around the neck. However, there was a greater variation of both posture and muscle activity with the tablet, which, the authors noted, may offset the non-neutral postures and higher muscle activity.

In a search of the literature, no study was found that evaluated the effects of specific tablet design features, such as size, weight, orientation, grip shape and texture on biomechanics, usability or musculoskeletal health. However, the design features of other hand-held tools, such as weight, texture and grip size can influence posture, applied force, muscle activity and comfort (Kodak 2004). Texture can influence the perception of control and the grip force applied to hand-held objects (Augurelle et al. 2003). A tool with a large finger contact area in comparison to a small contact area is perceived as lighter (Flanagan and Bandomir 2000). Different grip sizes influence the grip force that can be developed. A power grip, in which the force is applied between the palm and the thumb and fingers, provides the greatest amount of available force and is typically used when the grip is 3 cm or larger. In contrast, a pinch grip is typically applied when the grip is less than 3 cm. The pinch grip does not involve the palm, instead, the force is delivered between the thumb and one or more fingers. A pinch grip typically delivers 25% of the strength of a power grip and is associated with an increased risk of musculoskeletal disorders for the same applied force (Silverstein, Fine, and Armstrong 1986). An increased applied grip force, whether pinch or power grip, is associated with increased risk of musculoskeletal disorders (Harris et al. 2011).

Use of a stylus with a tablet can provide greater accuracy and precision than input with the finger (Greenstein 1997). The additional precision may be beneficial to those with limited mobility, especially the older user. Smartphones with a stylus are widely used (Cheng 2012) but few studies have evaluated the effect of stylus design, such as diameter, on performance, usability and biomechanics. A study of styluses with four different diameters (5.5, 8, 11 and 15 mm) and three lengths (80, 110 and 140 mm) found a productivity and preference advantage for the 8-mm-diameter stylus (Wu and Lou 2005). At least, a length of 100-mm was recommended so that the stylus extended beyond the side of the hand. However, the study did not evaluate hand muscle activity. A study of ballpoint pens with a diameter of 8 mm compared to a concave grip diameter of 12 mm found a significant reduction of user pain and right thumb muscle activity with the 12-mm-diameter pen (Udo et al. 2000). A pilot study of five adults compared the use of a tablet and stylus to the use of a desktop computer with a mouse and found decreased muscle activity of the shoulder and forearm muscles and better performance with the tablet and stylus (Kotani and Horri 2003). However, the tablet was not hand-held, it was supported on a table.

It is desirable to be able to hold mobile devices with one hand. This is necessary to enable stylus input or pointing with the finger, using the dominant hand, over the full screen of the device. In addition, allowing the tablet to be held in a single hand allows the other hand to be used for non-tablet tasks common to mobile activities. Finally, people simply prefer to hold mobile devices with a single hand. A study on cell phone usage found that people overwhelmingly preferred one-handed instead of two-handed use across 18 different tasks (Karlson, Bederson, and Contreras-Vidal 2007). The same paper reported observing higher frequencies of one-handed cell phone use versus two-handed use in an airport field study. To enable this type of usage, mobile devices must be designed so that they can be held securely and comfortably with a single hand.

The purpose of the present study was to evaluate the tablet design features of size (weight), orientation, grip shape and texture when the tablet is gripped with the non-dominant hand and entry is done with the dominant hand by users with small hands. The outcome measures were preference; productivity; subjective usability and fatigue; muscle activity; wrist, forearm, gaze angle and torso posture; shoulder moment; and tablet tilt and distance from eyes. Due to resource limitations, an unbalanced study design was used and not all possible combined features or interactions were tested. This study evaluated subjects with smaller fingers because these are likely to be the users at highest risk of using hand-held devices compared to users with large fingers and hands. Because styluses are frequently used in conjunction with tablets, stylus design was also examined. The null hypotheses are that the design features do not cause (1) a decrease in usability or subjective fatigue or (2) an increase in left arm muscle activity, awkward wrist postures or shoulder moments. The answers to these questions will provide tablet designers with empirical evidence for tablet design features that may decrease the risk of dropping the tablet, decrease musculoskeletal disorder risk and improve comfort, usability and productivity.

2. Methods

In this laboratory study, 30 subjects with small hands held a tablet with the left hand and performed data entry tasks with the right hand using eight different tablet and three different stylus test conditions. The independent variables were tablet size (weight), orientation, grip shape, surface texture and the shape of styluses. Dependent variables were typing speed, subjective ratings of usability and fatigue, upper extremity and neck posture, forearm muscle activity and preference. The study was approved by the University Institutional Review Board and subjects signed a consent form.

2.1. Subjects

Following were the eligibility criteria: (1) age between 18 and 65 years, (2) own or regularly use a touch screen tablet or smartphone, (3) right handed and (4) a middle finger length (from palmer proximal metacarpophalangeal crease to tip of finger) of less than 1.93 cm or proximal interphalangeal joint breadth (at proximal interphalangeal joint) of less than 7.71 cm for females or 2.24 cm and 8.37 cm, respectively, for males. The finger length and breadth thresholds were the 50th percentile based on hand anthropometry from the US military (Greiner 1991). Subjects were excluded if they reported current upper extremity musculoskeletal disorders. Subjects were recruited with flyers placed on the university campus, in the community and from among participants of prior studies.

Left hand grip strength was recorded as the average grip dynamometer reading from three maximum grip exertions (Baseline 200lb Hand Dynameter, White Plains, New York). Eyesight was tested at 4 m (LVRC Distance Visual Acuity Test, Bailey-Love Design, LVRC Numbers #1, Hong Kong, China). Each eye was tested individually and the smallest line for each eye seen correctly was recorded as 20/x.

A total of 15 females and 15 males participated in the study. Subject age, height, weight, hand anthropometry, grip strength and visual acuity are summarised in Table 1.

2.2. Tablet test conditions

Non-functional tablet models were created in three different sizes (and weights) approximating the size of the iPad2 (241 mm × 186 mm × 9 mm; 613 g), Kindle Fire (189 mm × 120 mm × 11 mm; 400 g) and Samsung Galaxy Note (147 mm × 83 mm × 10 mm; 178 g). Functional iPad2, Kindle and Note tablets would confound results, as different tablet models have different touch sensitivity and response. The aspect ratio, 1.6:1, was the same for all devices, which was slightly different from the commercial tablets (Table 2; Figure 1). The different test conditions and test sets are summarised in Table 2. The first test set (A) was tablet size (weight) with three levels: large, medium and small, all with a flat grip shape. The second (B) was tablet size (weight) with two levels: large and small, both with a ledge grip shape. The third (C) was orientation with two levels: landscape and portrait, both large tablets with a ledge grip shape. The fourth (D) was grip shape with three levels: flat, ledge and handle grip, all on large tablets. The fifth (E) was grip shape with two levels: flat and ledge, both on small tablets. The sixth (F) was texture with two levels: smooth and rubberised/rough, both on large tablets with flat grip. All tablets were 10-mm thick with 4.75-mm radius back edges and 0.32-mm radius front edges. Interaction between size and ledge was examined, e.g. large, large ledge, small and small ledge.

The ledge grip (large ledge, large portrait ledge and small ledge) was cut into the back of the tablet, reducing the thickness at the grip location and the large handle tablet grip protruded from the back left side of the tablet, the side that is gripped with the left hand. The ledge grip was a 3-mm step on the back of the tablet that was 40 mm and parallel to the entire left side. The ledge corner had a radius of 0.32 mm. The 8.5-mm thick handle grip protruded from the back left edge of the tablet at a 27°- angle for 40 mm and had corner radius of 4.25 mm. The smooth surface texture was flexible urethane paint

Table 1. Summary of subject left-hand measurements and grip strength, visual acuity, age, weight and height ($N = 30$).

Measurement	Mean (SD)	Range
Proximal finger width (mm)	18.4 (2.4)	14.0–22.2
Distal finger width (mm)[a]	16.0 (2.2)	12.4–19.9
Middle finger length (mm)	75.8 (6.5)	55.7–87.4
Hand length (mm)[b]	180.3 (13.1)	145.1–205.0
Hand width (mm)[c]	81.5 (7.7)	70.0–97.5
Thumb width (mm)[d]	19.8 (3.3)	13.4–24.6
Thumb length (mm)[e]	60.9 (5.9)	47.6–76.0
Eyesight – left (20/x)	27.4 (13.2)	16–63
Eyesight – right (20/x)	26.7 (12.6)	16–63
Age (years)	30.0 (11.0)	16–64
Weight (kg)	70.0 (17.4)	43.5–120.9
Height (cm)	166.3 (12.1)	130–185
Grip strength (kg)	30.2 (11.3)	10–55

[a] Middle finger distal interphalangeal joint breadth.
[b] Palmer distal wrist crease to end of middle finger.
[c] Metacarpale II to metacarpale V landmarks.
[d] Maximum breadth measured perpendicular to long axis.
[e] Tip to base.

Table 2. Descriptive parameters and test sets for eight tablet configurations.

	Design features				Test sets[a]			
Tablet	Size (mm)	Weight (g)	Grip shape	Texture	Size	Orientation	Grip	Texture
Large	233 × 147	694	Flat	Smooth	A		D	F
Large rubberised	233 × 147	694	Flat	Rough		C		F
Large ledge	233 × 147	601	Ledge	Smooth	B	C	D	
Large portrait ledge	147 × 233	599	Ledge	Smooth				
Large handle	233 × 147	620	Handle	Smooth			D	
Medium	190 × 120	446	Flat	Smooth	A			
Small	147 × 93	241	Flat	Smooth	A		E	
Small ledge	147 × 93	218	Ledge	Smooth	B		E	

Note: All tablets except one were used in landscape orientation.
[a] Test sets have a common letter and identify conditions compared within a design feature.

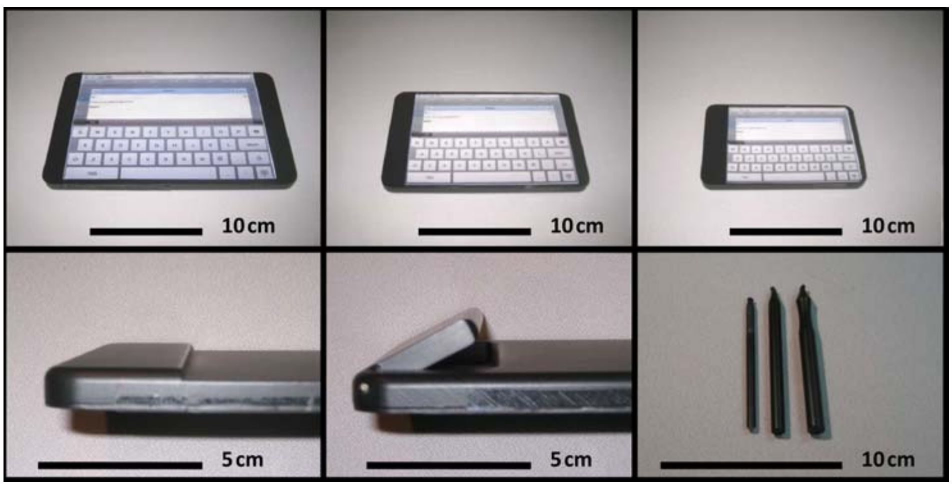

Figure 1. From top left-hand corner moving clockwise: large tablet, medium tablet, small tablet, styluses (small, large and tapered), large handle tablet and large ledge tablet. The ledge and handle grip are on the side of the tablet that is held with the left hand.

(Color Coat, Satin Black, SEM Products INC, Rock Hill, SC) and the large rubberised tablet rough surface texture was a rubber coating (Plasti-Dip, Black, Rubber Coating, Blaine, MN).

The prototype screens were not functional. Therefore, a scaled paper screenshot of an empty email form from an iPad was inserted beneath a clear plastic sheet on the front of each of tablet (Figure 1). The email form included a QWERTY keyboard, which was approximately half the size of the screen.

2.3. Stylus test conditions

Three different stylus designs were evaluated (Figure 1): a small diameter (5.0 mm; 6.62 g), large diameter (7.6 mm; 6.78 g) and a tapered diameter (7.5–9.5 mm; 6.90 g). The tip of the stylus was a felt marker.

2.4. Tablet task

Subjects held the tablet with the left hand and performed a simulated typing task with the right hand. Subjects were required to hold the tablet with the left hand with the thumb along the front vertical left edge of the tablet. A specific grip was required to prevent confounding by grip type. The other fingers of the left hand could be placed against the back of the tablet as they chose. Subjects were instructed to stand upright on both feet and support the tablet only with the left hand and were verbally reminded as needed. They sat during the three-minute breaks between tasks. A computer-based random number generator was used to assign the test order of tablets.

For four minutes, pangrams were read to each subject while they typed the pangrams with their right hand. Pangrams were not repeated and were randomly ordered to tablets. Dictation speed was matched to the subject's typing speed.

After each tablet, the total number of words completed in four minutes was recorded and reported as words per minute (WPM). WPM was calculated from gross typing speed of total letters divided by typing duration by the standard word length of five letters. Because this was a simulated entry task, on a non-functional tablet without screen or audio feedback, the validity of the productivity measurements relative to a functional tablet may be low.

2.5. Stylus task

For four minutes, subjects wrote numbers and then spelled the numbers with the stylus starting from the number 1 and increasing by one digit. Spelling was written longhand. Subjects were instructed to use a majority of the screen area for writing. The medium-sized tablet (190 mm × 120 mm) was used for the task. Productivity was estimated using the number that the subject reached at the end of each four-minute session. The task was repeated for each stylus and the order was randomised.

2.6. Usability and fatigue ratings

After each tablet or stylus was used, usability and fatigue were assessed with a modified ISO questionnaire (ISO9241-410:2008). The tablet survey questions were as follows: posture required for tablet use, overall usability, overall productivity, security from dropping the tablet, fatigue in left hand or wrist, fatigue in left forearm, fatigue in left shoulder, fatigue in neck and how many additional minutes could you hold the tablet in this posture. The stylus survey questions were as follows: posture required for stylus use, overall usability, overall productivity, security from dropping the stylus, fatigue in right hand or wrist, fatigue in right forearm and fatigue in right shoulder. Fatigue was rated on a seven-point numeric scale with verbal anchors (1 = very high and 7 = very low). At the end of testing all tablets, the tablets were rank ordered from least to most preferred. The same was done at the end of the stylus testing.

2.7. Forearm electromyography

Muscle activity was recorded from five left forearm and shoulder muscles during the tablet tasks: extensor digitorum communis (EDC) flexes the wrist and fingers; flexor carpi radialis (FCR) stabilises the wrist; flexor digitorum superficialis (FDS) is used for gripping; upper trapezius (UT) supports the head and elevates the shoulder; and extensor carpi radialis (ECR) extends the wrist. The muscles sampled are involved in gripping and stabilising the tablet. During the stylus task, muscle activity was recorded from the right ECR and flexor pollicis brevis (FPB). The stylus was always gripped with the right hand. Self-adhesive silver-to-silver chloride snap electrodes (active diameter of 10 mm and a centre-to-centre distance of 20 mm) were placed on cleaned, shaved skin using anatomical landmarks (Perotto 2005). Surface EMG activity was sampled at 1500 Hz (TeleMyo 2400T, Noraxon USA Inc, Scottsdale, AZ). The data were normalised to the maximum voluntary electrical exertion obtained by having the subject perform three 3-second maximum voluntary contractions (MVC) for each muscle (Shergill et al. 2009). The MVC values were calculated from the highest value of an averaging 1000 ms moving window across the three maximum exertions. The amplitude probability density function (APDF) 50% (Shergill et al. 2009) was calculated for each muscle across the four-minute test for each tablet and stylus test, representing the 50th percentile muscle exertion over the course of the task.

2.8. Posture measurement

Subjects wore tank tops to expose their arms and shoulders. To record the posture of the left wrist, left elbow and torso and the angle of the tablet, small lightweight plastic plates were mounted to the dorsum of the left wrist, left forearm, left upper arm, sternum and tablet. Each plate contained three infrared emitting diodes (IREDs). To record the head posture, a plastic plate with two IREDs was secured next to the tragus and a single IRED was secured next to the left side of the left eye. Two IREDs on the stylus recorded stylus tilt.

The three dimensional coordinates of each IRED marker were recorded continuously at 10 Hz using two camera sensor banks (Optotrack 3020, Northern Digital, Ontario, Canada). A reference posture was collected with subjects standing upright, head straight, looking at a spot on the wall at eye level, shoulder relaxed at 0° flexion/abduction, elbow at 90° flexion, forearm at 0° pronation and wrist at 0° of flexion and deviation. Calibration of marker placement to joint centres was recorded in reference posture according to placement to anatomical landmarks (Meskers et al. 1998; Wu et al. 2006). Torso, gaze, tablet and stylus angles were calculated as vectors from the triad of IREDS compared to the reference posture for torso and gaze or the $x-y$ plane for tablet and stylus angles which was parallel to the floor (Serina, Tal, and Rempel 1999). Tablet angle was calculated as the vector created along the top of the tablet to the $x-y$ plane. Left wrist extension/flexion and ulnar/radial deviation were calculated comparing the two planes on the dorsal surface of the hand and forearm to neutral posture using Euler angles. Left shoulder flexion moment was calculated by summing the forces about the shoulder joint from the centre of mass of the upper arm, lower arm, hand and tablet. Mean joint postures were calculated across the four-minute tasks for each tablet and stylus configuration.

2.9. Statistical analysis

The outcome measures are summarised in tables as mean and standard deviation for each feature set. Differences in muscle activity, posture and actual productivity measures between levels within a design feature set (A, B, C, D, E and F; Table 2) were evaluated by repeated-measures analysis of variance (RMANOVA) ($p < 0.05$) (SAS Institute, Cary, NC). *Post hoc* analyses were performed with the Tukey test. EMG APDF was logarithmically transformed for RMANOVA for normal distribution. Interaction, when testable, was examined using RMANOVA and for comparison of main effects and interaction. Differences in subjective usability and fatigue ratings were evaluated using Friedman's matched group analysis of variance test with Nemenyi multiple comparison test. Tablet and stylus preference was analysed using the χ^2 test followed up with partitioned χ^2 tests. Correlation coefficients between outcome measures were calculated and reported for variables with high correlation. The data were initially examined separately for each gender but because there were few important differences, the data were combined to increase power.

3. Results

The results are presented by design feature set, e.g. tablet size, orientation, grip shape, surface texture and stylus design.

3.1. Tablet size

Differences in usability ratings and biomechanical measures by tablet size are summarised in Table 3, first for three tablets with a flat grip and then for two tablets with a ledge grip. Higher usability numbers represent better ratings. For the comparison of three different-sized tablets with a flat grip, the subjective *overall usability* and *productivity* ratings for the medium tablet were significantly better than those of the large tablet. However, there were no significant differences in measured productivity. *Security from dropping* was rated better for the medium and small tablets compared to the large tablet. Generally, *fatigue* across the different body regions was rated better for the medium and small tablet compared to the large tablet. The smaller tablets were estimated to be held comfortably for more time than the large tablet. Significant differences in the biomechanical measures also favoured the smaller tablets. Generally, left-sided muscle activity was less for the medium and small tablets compared to the large tablet. Left wrist extension was less for the small tablet compared to the medium and large tablets. Left shoulder moment was less for the small tablet compared to the medium and large tablets, and was less for the medium tablet compared to the large tablet.

For the small and large tables with the ledge grip, the overall findings were similar (Table 3). All usability ratings were significantly better for the lighter, small ledge tablet than the large ledge tablet, except for the ratings for *overall usability* and *overall productivity*. Left FDS and FCR muscle activity were less for the small ledge tablet compared to the large ledge tablet. Left wrist extension was less for the small ledge tablet compared to the large ledge tablet.

3.2. Tablet orientation

There were no significant differences in muscle activity between use of the tablet in portrait and landscape orientations (Table 4). Wrist extension was significantly less in the portrait orientation compared to landscape orientation. Subjects reported less *fatigue in the left forearm* and *left shoulder* when using the tablet in the portrait orientation. The portrait orientation was estimated to be held comfortably for more time than landscape orientation. There were no significant differences in measured productivity.

3.3. Tablet grip shape

The differences between the grip shapes, for both large and small tablets, are summarised in Table 5. For the large tablets, all usability and fatigue ratings were rated significantly better for the ledge or handle grip compared to the conventional, flat grip. Shoulder moment was less for the ledge and handle grip compared to the flat grip. There were no significant differences in muscle activity between grip shapes and no significant differences in measured productivity.

The effects of grip shape (ledge vs. flat) for the small tablet were much less than the effects for the large tablet (Table 5). The only usability rating difference was an increased *security from dropping the tablet* with the ledge shape

Table 3. Tablets of different sizes with common orientation (landscape) and texture (smooth) ($N = 30$).

	Large versus medium versus small tablets (flat grip)				Large versus small tablet (ledge grip)		
	Large (694 g, 233 mm × 147 mm)	Medium (446 g, 190 mm × 120 mm)	Small (241 g, 147 mm × 93 mm)	p	Large ledge (601 g, 233 mm × 147 mm)	Small ledge (218 g, 147 mm × 93 mm)	p
Writing speed (WPM)	31.8 (7.6)	31.8 (7.0)	32.7 (9.2)	0.66	32.3 (8.0)	31.6 (7.2)	0.518
Overall usability[1]	3.7 (1.3)[a]	4.8 (1.3)[a]	4.7 (1.4)	0.008	4.2 (1.3)	4.7 (1.2)	0.084
Overall productivity[1]	3.9 (1.3)[a]	4.9 (1.3)[a]	4.6 (1.3)	0.004	4.3 (1.2)	4.5 (1.4)	0.545
Security from dropping the tablet[1]	3.1 (1.6)[a,b]	4.8 (1.3)[a]	5.4 (1.6)[b]	$p < 0.001$	3.9 (1.6)	5.9 (1.1)	$p < 0.001$
Posture required for tablet use[1]	3.6 (1.4)[a]	4.4 (1.4)	4.5 (1.5)[a]	0.003	4.0 (1.3)	4.8 (1.6)	0.005
Fatigue in left hand or wrist[1]	2.7 (1.7)[a,b]	4.1 (1.6)[a]	5.2 (1.5)[b]	$p < 0.001$	3.0 (1.3)	5.4 (1.5)	$p < 0.001$
Fatigue in the left forearm[1]	3.0 (1.5)[a,b]	4.6 (1.5)[a,c]	5.3 (1.4)[b,c]	$p < 0.001$	3.3 (1.4)	5.5 (1.4)	$p < 0.001$
Fatigue in left shoulder[1]	3.7 (1.6)[a,b]	5.1 (1.2)[a]	5.2 (1.9)[b]	$p < 0.001$	3.8 (1.4)	5.6 (1.5)	$p < 0.001$
Fatigue in neck[1]	4.0 (1.5)[a,b]	5.1 (1.4)[a]	5.0 (1.8)[b]	0.007	4.1 (1.2)	5.1 (1.7)	0.002
Comfortable holding time (min)[1]	14.7 (10.0)[a,b]	26.3 (21.1)[a]	35.5 (30.3)[b]	$p < 0.001$	16.5 (11.4)	40.4 (40.4)	$p < 0.001$
Left FDS[2]	16.9 (15.5)[a,b]	12.8 (12.4) [a]	10.6 (10.4)[b]	0.005	14.7 (13.5)	10.5 (11.6)	$p < 0.001$
Left EDC[2]	7.9 (9.5)	6.1 (6.8)	9.3 (12.0)	0.14	7.3 (11.1)	9.9 (12.6)	0.28
Left FCR[2]	15.9 (13.8)[a,b]	11.7 (12.8)[a,c]	7.9 (9.5)[b,c]	$p < 0.001$	14.6 (13.3)	8.6 (12.8)	$p < 0.001$
Left UT[2]	6.2 (5.3)[a]	5.0 (5.4)	4.8 (5.1)[a]	0.005	6.1 (7.9)	5.3 (5.1)	0.93
Left ECR[2]	12.2 (14.2)	9.8 (10.5)	11.6 (10.0)	0.095	10.7 (10.7)	11.2 (10.6)	0.35
Wrist ulnar deviation (°)	17.0 (28.9)	27.2 (36.0)	28.7 (35.1)	0.090	22.1 (29.8)	28.6 (27.4)	0.12
Wrist extension (°)	21.6 (29.2)[a]	19.3 (30.4)[b]	12.7 (29.5)[a,b]	0.002	19.6 (32.8)	12.2 (30.5)	0.006
Forearm supination (°)	15.6 (31.7)	17.4 (32.5)	17.3 (31.2)	0.46	14.9 (30.9)	15.7 (29.4)	0.64
Relative elbow height (cm)	− 3.1 (4.1)	− 2.8 (3.7)	− 2.8 (3.7)	0.16	− 2.9 (3.9)	− 3.0 (3.9)	0.60
Shoulder moment ($N \cdot m$)	35.0 (16.6)[a,b]	30.0(13.9)[a,c]	25.7(11.2)[b,c]	$p < 0.001$	33.3 (15.4)	24.5 (11.7)	$p < 0.001$
Right corner lower than left (°)	9.6 (12.1)	9.3 (12.4)	11.1 (13.9)	0.14	10.2 (13.7)	11.5 (14.2)	0.26
Distance from tablet to eyes (cm)	32.6 (5.1)	33.8 (5.3)	33.2 (5.0)	0.053	32.5 (5.8)	33.3 (5.0)	0.14
Gaze angle down (°)	24.4 (17.3)	21.9 (15.2)	23.3 (17.1)	0.43	22.5 (14.8)	21.9 (15.2)	0.27
Torso angle forward (°)	0.8 (5.5)	1.4 (4.9)	2.3 (5.1)	0.069	1.8 (4.7)	1.5 (4.7)	0.60

Note: One set all have a flat grip and one set all have a ledge grip. Significant differences between pairs within a set-row are indicated by a common superscript letters.
[1] Average subjective ratings, 1–7. Higher value is an improvement.
[2] Percentage of MVC – 50% APDF. Log transformation was used for RMANOVA analysis.

Table 4. Tablets of different orientation ($N = 30$).

	Landscape versus portrait orientation		
	Large ledge (601 g, landscape)	Large portrait ledge (599 g, portrait)	*p*
Writing speed (WMP)	32.3 (8.0)	33.3 (7.1)	0.39
Overall usability[a]	4.2 (1.3)	4.4 (1.3)	0.39
Overall productivity[a]	4.3 (1.2)	4.1 (1.4)	0.49
Security from dropping the tablet[a]	3.9 (1.6)	4.5 (1.5)	0.11
Posture required for tablet use[a]	4.0 (1.3)	4.3 (1.3)	0.16
Fatigue in left hand or wrist[a]	3.0 (1.3)	3.4 (1.4)	0.13
Fatigue in the left forearm[a]	3.3 (1.4)	3.8 (1.5)	0.05
Fatigue in left shoulder[a]	3.8 (1.4)	4.3 (1.7)	0.06
Fatigue in neck[a]	4.1 (1.2)	4.3 (1.4)	0.45
Comfortable holding time (min)[a]	16.5 (11.4)	20.3 (13.6)	0.04
Left FDS[b]	14.7 (13.5)	15.8 (16.2)	0.51
Left EDC[b]	7.3 (11.1)	6.9 (7.8)	0.60
Left FCR[b]	14.6 (13.3)	14.2 (13.1)	0.81
Left UT[b]	6.1 (7.9)	6.5 (7.6)	0.17
Left ECR[b]	10.7 (10.7)	11.9 (13.2)	0.79
Wrist ulnar deviation (°)	22.1 (29.8)	20.6 (27.7)	0.71
Wrist extension (°)	19.6 (32.8)	13.4 (25.7)	0.006
Forearm supination (°)	14.9 (30.9)	13.2 (27.3)	0.26
Relative elbow height (cm)	− 2.9 (3.9)	− 3.0 (4.0)	0.63
Shoulder moment (N · m)	33.2 (15.4)	33.4 (15.5)	0.77
Right corner lower than left (°)	10.2 (13.7)	10.9 (12.7)	0.59
Distance from tablet to eyes (cm)	32.5 (5.8)	32.9 (5.0)	0.45
Gaze angle down (°)	22.5 (14.8)	22.6 (16.4)	0.97
Torso angle forward (°)	1.8 (4.7)	1.6 (4.1)	0.72

[a] Average subjective ratings, 1–7. Higher value is an improvement.
[b] Percentage of MVC – 50% APDF. Log transformation was used for RMANOVA analysis.

grip. There were no biomechanical differences between grip shapes for the small tablet. There were no significant interactions between ledge and size for large, large ledge, small and small ledge.

3.4. *Tablet surface texture*

Differences between the conventional smooth tablet surface and a rubberised, rough tablet surface for the large tablet size are summarised in Table 6. The only significant difference in usability was that subjects rated the rough surface significantly better for *security from dropping the tablet*. There were no significant differences in fatigue ratings or biomechanical measures.

3.5. *Preference across all tablets design features*

After using all the tablets, subjects ranked all in order from their *least favourite* to *most favourite*; the percentages of subjects who rated each tablet as their most favourite are summarised in Table 7. Table 7 also includes the average preference rankings. The only significant difference within a design feature was on size; subjects preferred the small tablet to the large tablet, with or without a ledge.

3.6. *Post hoc correlations between outcomes*

A *post hoc* analysis evaluated the correlations between outcome measures across all tablet design features. There was a correlation between left hand/wrist, forearm, shoulder and neck fatigue to security from dropping ($r = 0.66$, 0.61, 0.57 and 0.45, respectively). Downward gaze angle increased as subjects leaned their torso forward ($r = 0.74$) and decreased with increasing elbow height ($r = 0.67$). Shoulder moment and gaze angle were also correlated ($r = 0.54$).

3.7. *Stylus design*

The effects of stylus design are summarised in Table 8. *Security from dropping the stylus* was rated better for the large diameter stylus than the small diameter one. *Fatigue in the right hand or wrist* was less for tapered stylus compared to small

Table 5. Tablets with different grip shapes but common orientation (landscape) and texture (smooth) ($N = 30$).

	Flat v ledge versus handle grip (large tablets)				Flat versus ledge grip (small tablets)		
	Large (694 g, flat)	Large ledge (601 g, ledge)	Large handle (620 g, handle)	*p*	Small (241 g, flat)	Small ledge (218 g, ledge)	*p*
Writing speed (WPM)	31.8 (7.6)	32.3 (8.0)	31.5 (7.5)	0.73	32.7 (9.2)	31.6 (7.2)	0.41
Overall usability[1]	3.7 (1.3)^{a,b}	4.2 (1.3)^{a}	3.8 (1.2)^{b}	<0.001	4.7 (1.4)	4.7 (1.2)	0.99
Overall productivity[1]	3.9 (1.3)^{a,b}	4.3 (1.2)^{a}	4.2 (1.2)^{b}	<0.001	4.6 (1.3)	4.5 (1.4)	0.78
Security from dropping the tablet[1]	3.1 (1.6)^{a,b}	3.9 (1.6)^{a}	4.1 (1.7)^{b}	<0.001	5.4 (1.6)	5.9 (1.1)	0.01
Posture required for tablet use[1]	3.6 (1.4)^{a,b}	4.0 (1.3)^{a}	3.9 (1.1)^{b}	<0.001	4.5 (1.5)	4.8 (1.6)	0.07
Fatigue in left hand or wrist[1]	2.7 (1.7)^{a,b}	3.0 (1.3)^{a}	3.0 (1.5)^{b}	<0.001	5.2 (1.5)	5.4 (1.5)	0.32
Fatigue in the left forearm[1]	3.0 (1.5)^{a,b}	3.3 (1.4)^{a}	3.3 (1.4)^{b}	<0.001	5.3 (1.4)	5.5 (1.4)	0.46
Fatigue in left shoulder[1]	3.7 (1.6)^{a,b}	3.8 (1.4)^{a}	3.9 (1.4)^{b}	<0.001	5.2 (1.9)	5.6 (1.5)	0.27
Fatigue in neck[1]	4.0 (1.5)^{a,b}	4.1 (1.2)^{a}	4.5 (1.4)^{b}	<0.001	5.0 (1.8)	5.1 (1.7)	0.72
Comfortable holding time (min)[1]	14.7 (10.0)	16.5 (11.4)	17.5 (16.5)	0.28	35.5 (30.3)	40.4 (40.4)	0.26
Left FDS[2]	16.9 (15.5)	14.7 (13.5)	16.6 (14.6)	0.27	10.6 (10.4)	10.5 (11.6)	0.19
Left EDC[2]	7.9 (9.5)	7.3 (11.1)	7.2 (6.8)	0.03	9.3 (12.0)	9.9 (12.6)	0.86
Left FCR[2]	15.9 (13.8)	14.6 (13.3)	15.9 (14.4)	0.12	7.9 (9.5)	8.6 (12.8)	0.40
Left UT[2]	6.2 (5.3)	6.1 (7.9)	6.0 (5.8)	0.27	4.8 (5.1)	5.3 (5.1)	0.05
Left ECR[2]	12.2 (14.2)	10.7 (10.7)	11.9 (13.5)	0.42	11.6 (10.0)	11.2 (10.6)	0.53
Wrist ulnar deviation (°)	17.0 (28.9)	22.1 (29.8)	22.6 (43.8)	0.56	28.7 (35.1)	28.6 (27.4)	0.99
Wrist extension (°)	21.6 (29.2)	19.6 (32.8)	19.5 (33.2)	0.53	12.7 (29.5)	12.2 (30.5)	0.88
Forearm supination (°)	15.6 (31.7)	14.9 (30.9)	16.7 (36.5)	0.68	17.3 (31.2)	15.7 (29.4)	0.31
Relative elbow height (cm)	− 3.0 (4.1)	− 2.9 (3.9)	− 2.9 (3.9)	0.34	− 2.8 (3.7)	− 3.0 (3.9)	0.15
Shoulder moment (N · m)	35.0 (16.6)^{a,b}	33.3 (15.4)^{a}	33.1 (16.2)^{b}	<0.001	25.7 (11.2)	24.5 (11.7)	0.006
Right corner lower than left (°)	9.6 (12.1)	10.2 (13.7)	10.3 (12.7)	0.83	11.1 (13.9)	11.5 (14.2)	0.85
Distance from tablet to eyes (cm)	32.6 (5.1)	32.5 (5.8)	32.6 (5.5)	0.99	33.1 (5.0)	33.3 (5.0)	0.76
Gaze angle down (°)	21.4 (17.3)	22.5 (14.8)	23.9 (14.6)	0.36	23.3 (17.1)	24.6 (15.4)	0.57
Torso angle forward (°)	0.8 (5.5)	1.8 (4.7)	1.7 (4.8)	0.15	2.3 (5.1)	1.5 (4.7)	0.17

Note: One set of tablets is large (233 mm × 147 mm) and one set is all small (147 mm × 93 mm). Significant differences between pairs within a set-row are indicated by a common superscript letters. All the values are given as mean (SD).
[1] Average subjective ratings, 1–7. Higher value is an improvement.
[2] Percentage of MVC – 50% APDF. Log transformation was used for RMANOVA analysis.

Table 6. Tablets with different surface texture ($N = 30$).

	Smooth versus rough surface texture		
	Large (smooth)	Large rubberised (rough)	p
Writing speed (WPM)	31.8 (7.6)	32.1 (7.9)	0.78
Overall usability[a]	3.7 (1.3)	4.0 (1.3)	0.32
Overall productivity[a]	3.9 (1.3)	4.2 (1.3)	0.07
Security from dropping the tablet[a]	3.1 (1.6)	3.8 (1.4)	0.03
Posture required for tablet use[a]	3.6 (1.4)	3.9 (1.3)	0.27
Fatigue in left hand or wrist[a]	2.7 (1.7)	2.5 (1.1)	0.54
Fatigue in the left forearm[a]	3.0 (1.5)	3.2 (1.2)	0.37
Fatigue in left shoulder[a]	3.7 (1.6)	3.6 (1.3)	0.88
Fatigue in neck[a]	4.0 (1.5)	3.8 (1.6)	0.15
Comfortable holding time (min)[a]	14.7 (10.0)	13.7 (8.8)	0.44
Left FDS[b]	16.9 (15.5)	17.4 (16.3)	0.52
Left EDC[b]	7.9 (9.5)	6.5 (6.1)	0.20
Left FCR[b]	15.9 (13.8)	16.0 (14.5)	0.42
Left UT[b]	6.2 (5.3)	6.6 (7.6)	0.85
Left ECR[b]	12.2 (14.2)	11.0 (11.3)	0.65
Wrist ulnar deviation (°)	17.0 (28.9)	20.5 (39.0)	0.52
Wrist extension (°)	21.6 (29.2)	19.0 (30.2)	0.23
Forearm supination (°)	15.6 (31.7)	17.4 (33.9)	0.20
Relative elbow height (cm)	− 3.1 (4.2)	− 2.9 (3.9)	0.32
Shoulder moment (N·m)	35.0 (16.6)	35.4 (15.8)	0.38
Right corner lower than left (°)	9.6 (12.1)	10.4 (13.9)	0.54
Distance from tablet to eyes (cm)	32.6 (5.1)	31.9 (5.0)	0.24
Gaze angle down (°)	21.4 (17.3)	22.7 (14.3)	0.53
Torso angle forward (°)	0.8 (5.5)	1.4 (4.9)	0.39

Note: All the values are given as mean (SD).
[a] Average subjective ratings, 1–7. Higher value is an improvement.
[b] Percentage of MVC – 50% APDF. Log transformation was used for RMANOVA analysis.

Table 7. Most preferred tablets and their mean preference ranking ($N = 30$).

	Tablet configurations								
	Large	Large rubberised	Large ledge	Large portrait ledge	Large handle	Medium	Small	Small ledge	p^1
Preference (%)[2]	3.3[a,b]	6.7[c,d]	6.7[e,f]	10.0	3.3[g,h]	13.3	26.7[a,c,e,g]	30[b,d,f,h]	0.02
Mean ranking[3]	2.9 (2.0)[a,b,c]	3.5 (2.1)[d,e,f]	4.0 (2.1)[g,h]	4.3 (2.2)	3.7 (2.0)[i,j]	5.5 (1.9)[a,d]	6.1 (1.8)[b,e,g,i]	6.0 (2.1)[c,f,h,j]	<0.001

Note: Participants were asked which tablet they preferred from 1 (least favourite) to 8 (most favourite). Significant differences between pairs within a row are indicated by a common superscript letters.
[1] Friedman's test and Nemenyi follow-up.
[2] Percentage of most favourite tablet.
[3] Mean ranking of tablets.

stylus. The order of preference was first taper, then large and then small. There were no significant differences in measured productivity.

4. Discussion

Tablet size (and weight) had an effect on usability, fatigue and biomechanics. Overall, subjects preferred the small and mid-size tablets to the large tablets. They reported improved usability and security from dropping the tablet and less fatigue with the small and mid-size tablets. They estimated that they could continuously hold the small and mid-size tablets for more than twice as long as the large tablet. Shoulder moment increased as tablet size and weight increased, which may explain the higher shoulder and neck fatigue, higher neck muscle activity and shorter holding time with the large tablet. There were few differences in usability, fatigue and holding time between the small and mid-small-sized tablets. It appears that reducing

Table 8. Stylus design ($N = 30$).

	Stylus configurations			
	Small (5.0 mm)	Large (7.6 mm)	Tapered (7.5–9.5 mm)	p
Productivity (numbers entered)	49.9 (12.7)	50.1 (11.0)	49.3 (14.0)	0.84
Overall usability[1]	4.3 (1.2)	4.9 (1.1)	5.0 (1.5)	0.10
Overall productivity[1]	4.8 (1.2)	4.9 (1.2)	5.0 (1.5)	0.82
Security from dropping the stylus[1]	4.0 (1.7)[a]	5.3 (1.1)[a]	5.2 (1.5)	0.03
Posture required for stylus use[1]	4.4 (1.3)	4.8 (1.3)	4.9 (1.5)	0.06
Fatigue in right hand or wrist[1]	4.3 (1.5)[a]	4.9 (1.4)	5.1 (1.6)[a]	0.047
Fatigue in the right forearm[1]	4.8 (1.5)	5.1 (1.3)	5.3 (1.4)	0.35
Fatigue in right shoulder[1]	5.0 (1.4)	5.2 (1.3)	5.4 (1.4)	0.31
Right FPB[2]	26.5 (53.5)	22.4 (44.0)	22.1 (39.1)	0.48
Right ECR[2]	25.7 (20.5)	27.2 (21.3)	26.5 (19.9)	0.06
Stylus tilt (° from vertical)	43.4 (25.4)	41.3 (21.8)	37.2 (19.6)	0.08
Preference (%)	20.0	26.7	53.3	0.061
Average ranking score	1.5 (0.8)[a]	2.1 (0.7)	2.4 (0.8)[a]	0.004

Note: Significant differences between pairs within a row are indicated by a common superscript letters. All the values are given as mean (SD).
[1] Average subjective ratings, 1–7. Higher value is an improvement.
[2] Percent of MVC – 50% APDF. Log transformation was used for RMANOVA analysis.

tablet size and weight below the mid-size tablet provides no additional advantages on usability, fatigue and holding time. There were no differences in measured productivity between any of the design conditions. The value of the productivity measures is limited, given the non-functionality of the tablet and the simulated tasks, but the measured productivity demonstrates that the rate of work was similar between tablet conditions.

Tablet size and weight also had an important effect on hand and wrist biomechanics. As tablet size increased, there was an increase in wrist extension and finger grip (FDS) and wrist extensor (ECR) muscle activity. The moment about the wrist increased as tablet size increased due to both the increased mass and the increased distance from the wrist to the tablet centre of gravity. For all tablets, the right side of the tablet was held approximately 10° below the left side. Knowledge of tablet angles during use may help with the design of tablet grips and for hardware (e.g. accelerometers). The viewing distance to the tablets was approximately 33 cm and the distance did not change significantly with tablet size.

The higher non-dominant hand pinch grip force (e.g. 17 vs. 13 or 11% MVC), required to hold the larger table, combined with ulnar deviation and wrist extension may increase the risk for distal upper extremity disorders if the duration of one-hand holding is long (Harris et al. 2011). Therefore, the duration and duty cycle of one-hand holding, especially for the larger size tablet, should be limited (Potvin 2012). The other option is to support the tablet on a stand on the work surface or in the lap; these two options are likely to reduce pinch force and awkward wrist postures (Young et al. 2012, 2013).

Orientation of the large tablet, portrait versus landscape, influenced hold time and wrist posture. Subject estimated hold time increased and there was less wrist extension in the portrait compared to landscape mode. This is likely due to the larger wrist moment with the tablet in landscape orientation. There was also more forearm and shoulder fatigue in the landscape mode. All other things being equal, these findings provide some support for the use of tablets in the portrait orientation over landscape orientation for one-handed use.

Grip shape had an effect on usability and fatigue but the results may have been confounded by differences in the weights of the tablets. The ledge and handle tablets weighed 10–15% less than the conventional flat tablet. For the large tablet, all usability and fatigue ratings, including security from dropping, were better for the ledge and handle grips compared to the conventional flat grip. Usability ratings and preferences were slightly better for the ledge grip compared to the handle grip but the differences were not significant. The handle and ledge grips provide additional coupling for the hand to the tablet to resist rotational forces due to the tablet moment at the grip. For the small tablet, the ledge grip improved security from dropping but had no other effects on usability or fatigue ratings. There was a slight but non-significant preference for the ledge grip over the flat grip for the small tablet. Follow-up tests demonstrated no significant interaction between tablet size and grip type.

For the stylus designs, subjects preferred the tapered stylus the most, followed by the large stylus. The small stylus was least preferred. Fatigue ratings of the right hand and wrist followed a similar trend. Security from dropping the stylus was also rated better for the large stylus than the small one. The findings match other studies of styluses (Kotani and Horri 2003), pens (Wu et al. 2006) and dental tools (Dong et al. 2006). For this type of precision work, larger diameter (up to 11 mm) and lighter tools are preferred.

A *post hoc* analysis of correlations of outcome measures revealed some interesting findings. There was a correlation between left hand/wrist, forearm, shoulder and neck fatigue to security from dropping ($r = 0.66$, 0.61, 0.57 and 0.45, respectively). As fatigue increased, users reported less security from dropping the tablet. The highest correlation was between fatigue of the hand/wrist and security, which highlights the interrelationship between hand fatigue and a sensation of a secure grip. The second interesting correlation was that downward gaze angle increased as subjects leaned their torso forward ($r = 0.74$) or decreased their elbow height ($r = 0.67$). It is likely that as the size and weight of the tablet increased, subjects brought the tablet in towards their body to reduce shoulder moment and compensated by leaning their torso forward and increasing head flexion and downward gaze angle (shoulder moment and gaze angle $r = 0.54$).

A limitation of this study was that not all design features were tested at all levels, e.g. this was not a full-factorial study. Differences within a feature set were examined while blocking on other features. This limited the ability to examine interactions between design features. The study design also limits the interpretation of preference scores because subjects do not have a full selection of all possible tablets. The results should be interpreted as preliminary input into the design of hand-held tablets because non-functional tablets were used. Productivity measures and usability ratings may be different if subjects were using functional tablets. The study only examined the effects of tablet design features among users with small hands. It is possible that findings from users with large hands, who are likely to be stronger, would be different. However, users with small hands are likely to be a higher risk of fatigue and difficulty with usability due to the size and weight of the tablet relative to their reduced grip span and strength.

Future studies should consider examining the effects of tablet size with functional tablets to more realistically assess productivity and error. A wider range of ledge and handle dimensions could be explored to identify designs that improve security with minimal increase in weight. In addition, studies with longer duration tasks are likely to better discriminate difference in fatigue between devices. Finally, studies in different postures, such as seated tablet use, could aid in design across modalities.

5. Conclusion

Overall, the findings should be carefully interpreted given the use of non-functioning tablets and simulated tasks. On the basis of usability, fatigue and biomechanics, this study supports the use of the small- to medium-sized tablets over large tablets when tablets are held with one hand. Larger tablets had significantly higher forearm muscle activity, shoulder moment and wrist extension and lower preference ratings and holding time. The weight of tablets increased with size so the effects of size may to be due to both weight and the increased distance between the grip and the centre of gravity of the tablet. Security, usability and fatigue were better with the ledge or handle grip compared to the conventional flat grip, especially for the large tablet. There was improved security from dropping when the tablet was coated with a rough rubberised texture. There was less fatigue when the tablet was held in portrait orientation compared to landscape orientation. Finally, the tapered and large diameter (7.6 mm) styluses were preferred over the small diameter (5.0 mm) stylus. These findings may assist tablet designers with the selection of tablet design features that help users work comfortably with reduced risk for fatigue and musculoskeletal disorders.

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