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Touch displays: the effects of palm rejection technology on productivity, comfort, biomechanics and positioning

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Direct touch displays can improve the human–computer experience and productivity; however, the higher hand locations may increase shoulder fatigue. *Palm rejection* (PR) technology may reduce shoulder loads by allowing the palms to rest on the display and increase productivity by registering the touched content and fingertips through the palms rather than shoulders. The effects of PR were evaluated by having participants perform touch tasks while posture and reaction force on the display were measured. Enabling PR, during which the subjects could place the palms on the display (but were not required to), resulted in increased wrist extension, force applied to the display and productivity, and less discomfort, but had no effect on the self-selected positioning of the display. Participants did not deliberately place their palms on the display; therefore, there was no reduction in shoulder load and the increased productivity was not due to improved hand registration. The increased productivity may have been due to reduced interruptions from palm contacts or reduced motor control demands.

Practitioner Summary: Since placing the palms on a touch display would decrease shoulder loads and provide for improved registration with the touched content, a laboratory study assessing the effects of palm rejection technology was performed. With palm rejection enabled, task speed increased and self-reported discomfort decreased even though palms were rarely placed on the display.

Keywords: tablet; touchscreen; gesture interaction; shoulder; wrist

1. Background

The use of touch sensing displays for computer input has increased in recent years due in part to their ease of use and compactness. Touch input on the display allows for intuitive, direct interaction between the user and the graphical objects on the display, unlike computer input with a mouse or touch pad. In addition, in settings with limited space, touch display use can free up the space used by a peripheral device, such as a mouse or keyboard (Shneiderman, 1991; Bhalla and Bhalla, 2010). However, touch interaction can occlude the display, and pointing accuracy may decrease with small enough targets. Additionally, the effects of touch display use on arm and neck load, from a biomechanical perspective, have not been well characterised.

Previous research on displays without touch input has shown correlations between the development of musculoskeletal disorders and awkward neck or shoulder postures during prolonged use (Burgess-Limerick, Plooy, and Ankrum 1998; Gerr, Marcus, and Monteilh 2004; Juul-Kristensen and Jensen, 2005). Current recommendations suggest that the top of a conventional display be placed at or slightly below eye level, approximately 50–70 cm from the eyes, to reduce loads on the neck and visual strain (Villanueva et al. 1997; Bauer and Wittig, 1998; Seghers, Jochem, and Spaepen 2003). However, due to the direct interaction that touch displays require with the hands, the recommended viewing angles for touch displays may be lower than for non-touch displays.

Direct touch interaction with the display requires that the hands be well above elbow height when seated, which is the recommended location for keyboard or mouse use. Therefore, direct touch will increase shoulder loads (Sauter, Schleiffer, and Knutson 1991) and muscular fatigue risk (Aarås, Westgaard, and Stranden 1988), especially with arms unsupported (Zhu and Shin, 2012). Shin and Zhu (2011) observed that touch display users moved the display lower and closer to the body compared to the self-selected positioning of a conventional visual display, and suggest that this was done to control the loads on the shoulder. However, such lower and closer display positions increase neck flexion and loading (Schultz, Batten, and Sluchak 1998). Thus, it appears that for touch display use, there is a biomechanical trade-off between lower and closer displays, which decrease shoulder moments but increase neck flexion, and higher and farther displays, which decrease neck flexion but increase shoulder moments.

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A potential solution that may mitigate the effects of the higher hand positions with touch display use is palm rejection (PR) technology. PR technology ignores touches from the palms as input, and works by various means such as through optical means or touch discrimination of the fingertips versus the palms. PR technology allows the user to rest his or her palms on the touch display while performing a task, potentially providing support for the arm, which may decrease the shoulder moment and the shoulder muscular effort, discomfort and risk (Erdelyi et al. 1988; Aarås et al. 1997; Gerr, Monteilh, and Marcus 2006) compared to an unsupported arm. With decreased shoulder loads, due to PR, users may choose to raise the display to decrease neck flexion and discomfort.

PR technology may also provide for greater control during touch tasks. With PR enabled, the palms can touch the display with the fingers registered to the touch targets through the palm and hand. Without PR, the hands are floating over the display with the fingers registered to the touch targets through the wrist, elbow and shoulder. Thus, the fingers must coordinate and compensate for elbow and shoulder perturbations, or the large muscles of the shoulder and elbow would have to perform fine motor control to precisely control the positioning of the fingers (Winter, 2009).

The purpose of this study was to evaluate the benefits and limitations of PR technology. One objective of this study was to evaluate the effects of PR technology on neck and shoulder loading and comfort. Specifically, the hypothesis was that PR would (1) reduce shoulder moment and (2) increase display height to reduce neck flexion. A second objective was to evaluate the effects of PR on productivity. The hypothesis was that registration of the palms with the display would increase the task speed.

2. Methods

2.1. Study design

This was a laboratory study evaluating the effect of PR technology on shoulder moment, productivity, self-selected display position and self-reported discomfort. The primary independent variable was the presence or absence of PR technology. Because tasks requiring relatively less palm motion may be more conducive to palm touching on the display (finger dragging likely requires less effort than simultaneous finger and palm dragging), a secondary independent variable was field size (spatial distribution of touches) at two levels. The sizes of the two fields, constant across subjects, were selected to represent tasks (1) requiring little to no palm motion and (2) requiring palm motion. This was a full factorial study of PR state and field size (2×2). Three independent tasks were performed which required moving graphical objects on the display with either one finger touch, two simultaneous finger touches or three simultaneous finger touches.

Dependent variables included vertical force on the display, estimated shoulder moment, self-selected display position, self-reported discomfort and productivity. The vertical force on the display was recorded from a force plate mounted between the touch display and the display support arm. Shoulder moment was computed with a static analysis of arm posture. Self-selected display position was assessed by deliberately positioning the display in an awkward position at the beginning of each task and requiring the subjects to adjust the display to their preferred location during the task. Discomfort measures were reported by the subjects after each task, and productivity was assessed as the task speed.

2.2. Subjects

Inclusion criteria for subjects included familiarity with touch display input (e.g. touch pad, smart phone). Exclusion criteria included self-reported neck, back and arm injuries as well as trouble sitting for extended periods of time. The 31 participants were residents of the San Francisco Bay Area and a sample of convenience, with efforts taken to recruit a diversified sample. Subjects consisted of 15 females and 16 males with a mean age of 40.8 (SD $\pm$ 15) years and age ranging from 18 to 65 years. The self-reported mean height and weight were 168.9 (SD $\pm$ 14.7) cm and 76.8 (SD $\pm$ 19.4) kg, respectively, and the ethnicity (2000 US census categories) was 14 Caucasian, 7 Asian-American, 3 African-American, 2 Pacific Islander, 2 Latino and 3 stating Other or a combination of categories. The mean right arm reach (from the shoulder to the tip of the middle finger) was 73.1 (SD $\pm$ 6.3) cm. Three subjects used prescription multifocal lenses. Two subjects wrote and pointed (mouse or trackpad) with the left hand and 29 subjects wrote and pointed with the right hand. The study was approved by the Institutional Review Board of the University of California, Berkeley, and participants provided informed consent.

2.3. Workstation and equipment

A touch display was mounted in series onto a force plate and a powered positioning system (Figure 1(a)). The touch display was a 22-inch, multi-touch capacitive display (2256PW, 3M, St. Paul, MN; 1680×1050 pixel resolution, pixel pitch = 0.282×0.282 mm). The six-axis force plate (M60101, Type SC-2030; Bertec Corporation, Worthington, OH) was mounted between the touch display and the display support arm to measure contact forces on the touch display. The force

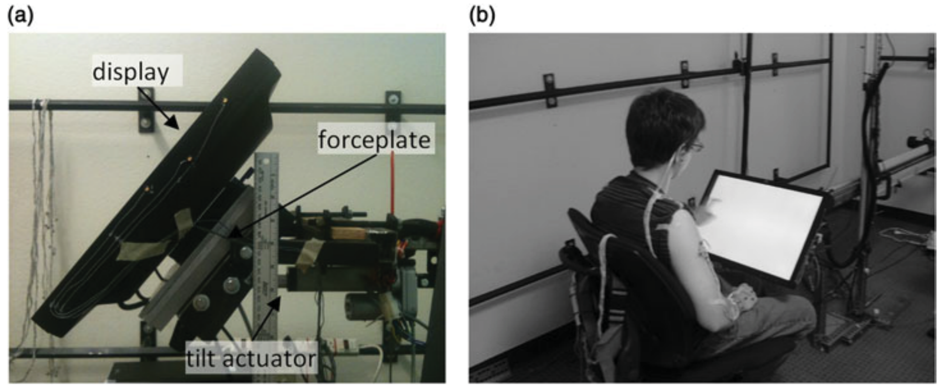

Figure 1. Experimental set-up. (a) The touch display was attached to the force plate and a three-axis powered positioning device. (b) Subjects adjusted the display location (height, distance and tilt) using a graphical controller. Triads of infrared emitting diodes were taped on the touch display and to the body at the following locations: inferior to the sternal notch, bilaterally on the upper arms over the lateral deltoid, on the dorsum of the forearms 3 cm proximal to the wrist crease and on the dorsum of the hands.

plate, calibrated as a function of the display angle in the gravity field, sampled data at 100 Hz, and averaged and stored the data at 1 Hz. To mitigate any effects of the effort required to move the display to the self-selected position, a powered display positioning system was used. Adjustment of the display (up/down, fore/aft and tilt) was performed by touching icons on the display. Holding the icons moved the display at approximately 3 cm s^{-1} and 15° s^{-1}. To decrease jarring of the apparatus, a motor controller was used such that when the icons were untouched the display decelerated, continuing to move for less than 1 cm and 1°. The height of the bottom of the display from the floor was adjustable from thigh height up to 125 cm. The tilt of the monitor surface was adjustable between vertical and horizontal. The fore/aft distance was adjustable over a 60-cm range, and the chair was castered.

Subjects were seated during the experiment. The chair had a swivelled seat pan and the armrests removed. The chair height was initially set such that the subject's feet were touching the floor and the thighs were approximately horizontal; subjects then adjusted the height to preference prior to testing. Because a desk surface may have interfered with the preferred height setting of the display, no desk was present.

A motion capture system (Northern Digital Optotrak 3020, Ontario, Canada) was used to determine the arm postures of the subjects and location of the touch display. Triads of infrared emitting diodes (IREDs) were mounted onto plastic plates and taped on the touch display and to the body at the following locations: inferior to the sternal notch, bilaterally on the upper arms over the lateral deltoid, on the dorsum of the forearms 3 cm proximal to the wrist crease and on the dorsum of the hands (Figure 1(b)). An additional triad was taped to the head and consisted of an IRED dyad taped anterior to the right tragus and a single IRED taped posterior to the right outer canthus. Each of the triads defined a local frame representing the underlying bony segment. The bridge of the nose between the eyes was digitised with respect to the head triad to define an eye-centre location. The three-dimensional (3D) coordinates of the IREDs were recorded at 20 Hz.

2.4. Tasks

Subjects performed three custom written graphics-manipulation tasks (LabVIEW v10; Buffalo, NY). All tasks involved the sorting of coloured targets into identically coloured bins. The tasks were completed by touching and dragging targets with the fingers across the display to the bins. If a finger was lifted off the display prior to binning, then the target remained at the position where the finger was lifted. One-touch tasks were performed using one finger. Two-touch tasks required the simultaneous use of any combination of two fingers, one from each hand. Three-touch tasks required the simultaneous use of any combination of three fingers from both hands to perform the task. When PR was enabled, the tasks could be performed regardless of whether there was more than the required number of touches, such as touches from the palms. When PR was disabled, the tasks could not be performed (graphical objects could not be moved with the fingers) if more touches were sensed than the number of required touches. This response was implemented to mimic the functional loss created with inadvertent touches. Prior to collecting any data, subjects became familiar with the tasks and PR by performing all three tasks, both with and without PR enabled. Subjects were instructed, and a demonstration was provided, that with enabled PR they could place or rest their palms on the display during the task and that with disabled PR placing or resting their palms on the display would cause the task to freeze. Subjects were also instructed that they could use any combination of hands (either hand or both) and fingers to perform the tasks, and were not provided with any instructions on how to

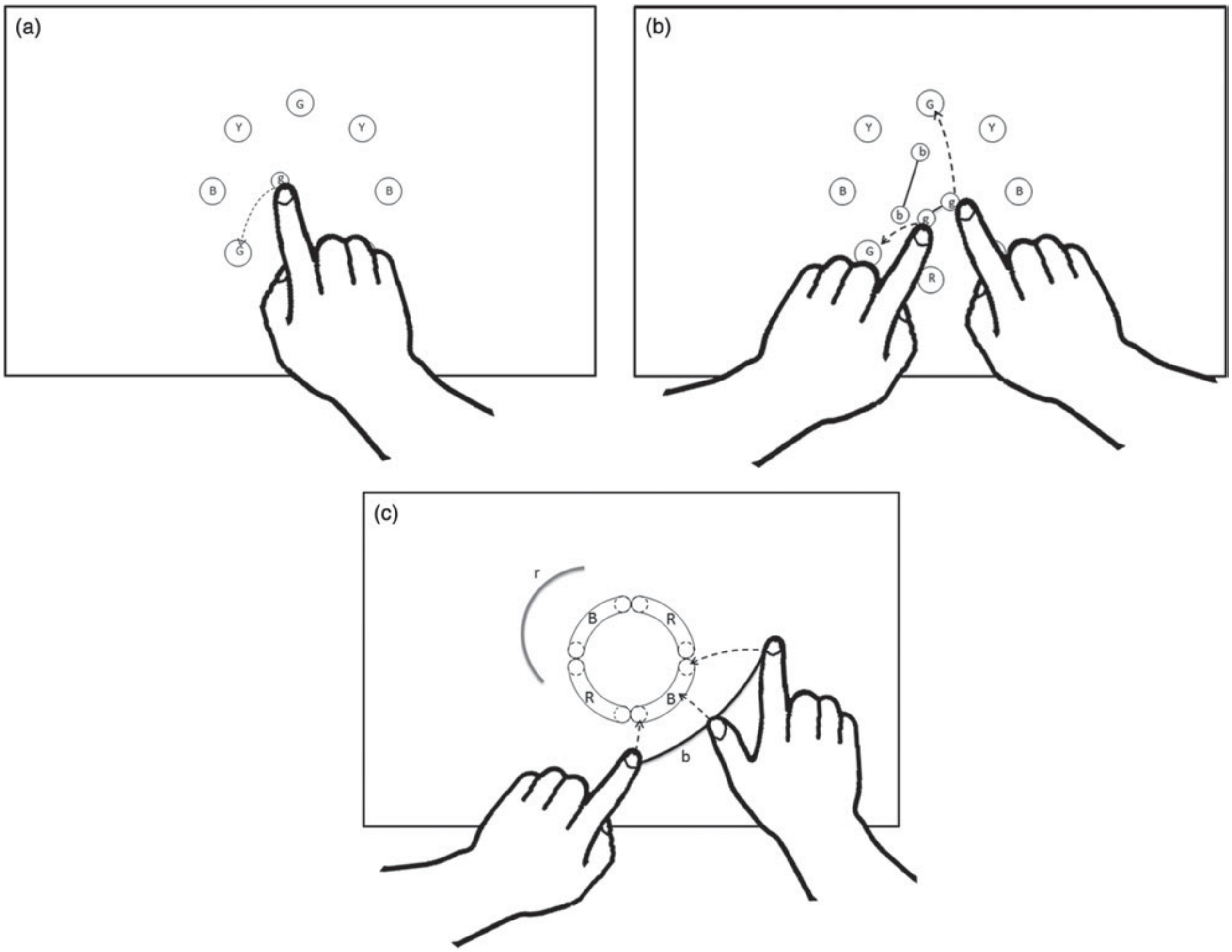

Figure 2. (a) One-touch tasks, (b) two-touch tasks and (c) three-touch tasks. For one-touch tasks, subjects dragged small circular targets into peripheral bins of corresponding colour using one finger. For two-touch tasks, subjects dragged small targets into peripheral bins of corresponding colour using two fingers. Each pair of targets, connected by a displayed line, had to be dragged into separate bins simultaneously. For three-touch tasks, subjects dragged each arc target (thin line) into bins of corresponding colour. Target arcs could only be moved with three simultaneous touches (the two endpoints and one intervening point on the arc). Target colours are indicated by lower-case letters and bin colours are indicated by upper-case letters.

position the non-involved hand or how fast to perform the tasks. It was believed that such a lack of instruction is similar to actual common usage, in which users self-select the task speed rather than are dictated the task speed.

The one-touch task required subjects to move circular touch targets, randomly located within a fixed field size centred about the middle of the touch display, into one of two circular bins of corresponding colour at the periphery of the field (Figure 2(a)). Each bin was one of four colours (red, yellow, green or blue) and thus there were eight bins. One bin was randomly placed at the periphery and then the remaining seven bins were placed every 45°, with one bin–colour pair diametrically opposed (180°), and the other three bin–colour pairs at 135°, 90° and 45°. The diameter of the targets, and the touch handle width, was 50 pixels (1.4 cm). The diameter of the eight bins was 75 pixels (2.1 cm). Two field sizes (diameter of peripheral bin placement, Figure 2(a)) were implemented: large (500 pixels, 14.1 cm) and small (200 pixels, 5.6 cm). At the beginning of the task, 12 targets, 3 each of the 4 different colours, were presented. When a target was placed fully within a bin and the finger was lifted off the display, the target disappeared, indicating that the target had been successfully placed. Upon placing all 12 targets into the colour-coded bins, the task was reset with a new set (panel) of 12 randomly located targets within the bin periphery. Multiple sets were completed for a total of 10 minutes, 5 minutes for each field size (large and small).

Similar to the one-touch task, the two-touch task required the moving of touch targets into bins. However, to promote two-handed interaction, targets were presented in sets of two, connected by a line, and could only be moved using two simultaneous touch inputs (one touch for each target). A total of 12 target pairs (50 pixel diameter, 1.4 cm), 3 pairs for each of the four distinct colours, comprised a panel (Figure 2(b)). Target, bin and field sizes and locations were the same as in the one-touch tasks. At the beginning of the task, 12 target-pairs, three each of the four different colours, were presented. When both targets of a target-pair were placed fully within different bins and both fingers were lifted off the display the targets disappeared, indicating that the targets had been successfully placed. Upon placing all 12 target-pairs into the colour-coded bins, the task was reset with a new set of 12 randomly located target-pairs within the bin periphery. Multiple sets were completed for a total of 10 minutes, 5 minutes for each field size.

The three-touch task promoted two-handed interaction and coordinated motions of three fingers by requiring subjects to resize, rotate, and move arcuate touch-targets into one of two arc-shaped bins (Figure 2(c)). Three simultaneous touch inputs were required to move the arc: one touch at each end of the arc and one touch at any point located between the two ends, with a targeting error of 25 pixels or less (the target handles were 50 pixels over the arc trajectory). Four arcs, two for each of the two different colours, were presented per panel, and the arcs were moved into one of two bins of corresponding colour. The four arcuate bins, located near the centre of the display, were 50 pixels (1.4 cm) wide and were 175 pixels (5 cm) from the centre of the display (bin diameter = 350 pixels). Large arcuate targets (large field) were defined as 600–1050 pixels (17.1–30 cm) in length (endpoint to endpoint), while small arcuate targets (small field) were defined as 180–250 pixels (5.14–7.14 cm) in length. The initial centre and angular orientation of each arc was randomised. Arcs were resized and positioned by adjusting the three touched locations; three spatial locations define an arc of a circle and the three touched locations defined the arc position.

2.5. Timeline

Testing time for each trial of PR state (e.g. enabled and disabled) was approximately 30 minutes with a 15-minute break between trials. The order of testing for PR state was randomised, with 16 subjects starting with PR enabled and 15 subjects starting with PR disabled. Within each 30-minute trial of PR state, each task type (one, two or three simultaneous touches) was presented for 10 minutes, with 5 minutes allotted for each of the two field sizes, with no rest breaks between tasks. To reduce the effects of fatigue, and because the task type was not an independent variable, the task order was the same in both PR trials, with the one-touch task performed first, then the three-touch task and finally the two-touch task. This order was randomly selected.

2.6. Dependent variables

2.6.1. Postures

Prior to task performance, 10 cycles of isolated cyclic joint motions were performed to estimate the shoulder, elbow and wrist joint centres with respect to the IRED triads. Transformations from the upper arm and forearm IRED triads to the shoulder, elbow and wrist joint centres were computed by means of the functional method (Cappozzo, 1984), a process of fitting dynamic marker data to a sphere, the centre of which defines the joint centre.

Five postures were computed for both arms. Shoulder flexion was defined as the angle between a vertical line and the shoulder-to-elbow line projected onto the sagittal plane, and shoulder abduction was defined as the angle between a vertical line and the shoulder-to-elbow line projected onto the frontal plane. Elbow flexion angle was defined as the angle between the shoulder-to-elbow line and the elbow-to-wrist line (full extension is 0°). Wrist extension and ulnar deviation angles were computed with respect to a reference posture in which (1) the dorsum of the hand was parallel to the forearm and (2) the third metacarpal-phalangeal joint, mid-point of the radial and ulnar styloids, and elbow were collinear. The average postures over the last 3 minutes of each test condition were reported.

2.6.2. Loads

A contact force and two joint moments were computed, both with respect to gravity. The vertically directed (parallel to the gravitational acceleration) contact force of the hands on the touch display (‘vertical hand force’) was computed using the force plate data. The left and right shoulder flexion moments, due solely to gravity, were computed using the postural and anthropometric data. Segment lengths and spatial orientations for the upper arm, forearm and hand were computed using the estimated joint centre locations. The segment weights and the segment-fixed centre of mass locations were estimated using subject-specific segment lengths and the regression equations of Shan and Bohn (2003). The flexion moments from each of the three segment weights were summed about the shoulder to estimate the total shoulder flexion moment. The shoulder moment estimation did not include vertical hand force. The vertical hand force and the shoulder flexion moments, averaged over the last 3 minutes of each condition, were reported.

2.6.3. Self-selected display position

To ensure that the subjects adjusted the touch display's position with minimal bias from the previous position, the touch display was deliberately moved to an awkward position before each task, with the display's (1) centre above the shoulders, (2) centre at approximately arms length away and (3) surface normal directed upwards. Prior to starting the task and during the tasks, the subjects were free to adjust the display, with a software-timed audible reminder provided every 2 minutes.

The self-selected display position was defined by five measures: viewing distance (from eye centre to display centre), viewing angle (included angle between eye horizon and line from eye centre to display centre), display tilt angle (angle between the display's surface normal and a horizontal line; vertical display surface is 0°), and height of the centre of the display above both the floor and the seated resting elbow height. The average position of the display over the last 3 minutes of each condition was defined as the self-selected display position.

2.6.4. Productivity

The task speed, defined as the rate of target binning (targets/min), was computed over the full time of each condition.

2.6.5. Self-reported discomfort

After each test condition, a computer-based survey was presented for the subject to record his or her discomfort levels at the eyes, neck, shoulder and forearm/wrist [10-cm visual analogue scale with verbal anchors of 'None' (score = 0) and 'Severe' (score = 1) and a score resolution smaller than 0.001].

2.7. Statistical analysis

Repeated-measures ANOVA tests were performed to assess whether PR and the field size had significant effects on the postures, loads, self-selected display position, productivity and discomfort. Because the tasks, defined by the number of simultaneous touches, represent unique interactions that likely cannot be interchanged in practice, separate repeated-measures ANOVAs were performed for each task. Significant ($\alpha = 0.05$) interaction effects (PR state $\times$ field size) were followed up with Tukey's tests for pair-wise comparisons. Due to a programming error, the small field size was not assessed for the one-touch task, and thus for the one-touch task a paired *t*-test was performed to assess the effect of PR on the dependent variables.

3. Results

3.1. One-touch task

With PR enabled, the viewing distance was significantly greater, the right elbow was significantly more flexed and there was a trend towards more shoulder flexion than with PR disabled (Table 1). The vertical hand force on the display more than doubled with PR enabled, and there were no significant differences in shoulder moments due to gravity. However, all discomfort measures were significantly less with PR enabled. There was no significant difference in task speed between PR states.

3.2. Two-touch task

All subjects chose to perform the task with two hands. Although the PR state significantly affected the right-side postures, with shoulder abduction and wrist extension increasing and ulnar deviation decreasing, the PR state did not affect self-selected display position (Table 1). The vertical hand force on the display tripled ($p = 0.001$) with PR enabled, and there were no significant differences in shoulder moments due to gravity. The task speed increased significantly (20%) with PR enabled for the small field size (Table 2).

3.3. Three-touch task

All subjects chose to perform the task with two hands. The main effect of PR state did not have a significant effect on vertical hand load on the display (Table 1). With PR enabled, the small field size demonstrated significantly larger vertical hand loads than the large field size (Table 2). There were no significant effects of PR on shoulder flexion moments due to gravity. Enabled PR significantly affected the shoulder abduction and wrist extension, with increases in both measures bilaterally (Table 1). Eye and forearm/wrist discomforts were significantly less with PR enabled (Table 1). Enabled PR was associated with a significant increase in task speed (15% faster); however, this effect was not demonstrated for either small or large fields individually (Table 2).

Table 1. Mean (SD) task results.

	Task								
	One-touch			Two-touch			Three-touch		
	PR state			PR state			PR State		
	Enabled	Disabled	p	Enabled	Disabled	p	Enabled	Disabled	p
Posture									
Right shoulder flexion angle	31.9 (15.7)	27.8 (17.3)	0.05	29.6 (18.5)	29.5 (14.3)	0.76	28.7 (18.2)	26.9 (17.7)	0.39
Left shoulder flexion angle	33.5 (12.3)	33.4 (13)	0.14	26 (10.8)	31.6 (12.3)	0.05	27.6 (9.7)	26.9 (12.6)	0.06
Right shoulder abduction angle	37.4 (19.6)	37.4 (19.6)	0.82	40 (20.4)	36.9 (19.1)	*0.007*	39.7 (19.5)	35.4 (20.4)	*0.009*
Left shoulder abduction angle	32.1 (12.1)	31.8 (11.5)	0.94	26.8 (10.5)	28.2 (12.6)	0.18	31.1 (10.3)	26.4 (13.0)	*0.001*
Right elbow angle	102.4 (10.1)	106.9 (12.3)	*0.007*	105.5 (10.1)	105.4 (12.0)	0.52	108.1 (9.0)	108 (9.4)	0.67
Left elbow angle	95.6 (11.3)	98.1 (13.3)	0.20	95.6 (13.1)	98.5 (9.0)	0.13	98.7 (12.4)	100.3 (11.6)	0.61
Right wrist extension angle	13.7 (15)	10.7 (14)	0.45	13.5 (14.2)	9 (14.6)	*0.01*	15.4 (14.6)	13.1 (14.5)	*0.05*
Left wrist extension angle	11.1 (16.7)	12.1 (13.2)	0.59	9.7 (14.8)	5 (15.4)	0.08	9.0 (13.8)	4.8 (15.5)	*0.01*
Right ulnar deviation angle	16.3 (11.7)	19 (8.8)	0.05	14.4 (11.0)	19.8 (7.9)	$<$ *0.001*	12.2 (11.5)	14.1 (8.1)	0.62
Left ulnar deviation angle	12.6 (11.9)	12.5 (12.7)	0.50	14.1 (11.5)	15.8 (13.1)	0.06	12.7 (8.9)	14.6 (11.5)	0.16
Loads									
Vertical hand force on display (N)	0.34 (0.45)	0.15 (0.19)	*0.02*	0.96 (1.11)	0.32 (0.30)	*0.001*	0.60(0.31)	0.55 (0.32)	0.32
Right shoulder flexion moment (Nm)	5.39 (1.57)	5.56 (1.63)	0.52	5.44 (1.47)	5.25 (1.53)	0.32	5.59 (1.52)	5.42 (1.44)	0.16
Left shoulder flexion moment (Nm)	5.01 (1.53)	5.18 (1.86)	0.48	5.20 (1.44)	5.22 (1.31)	0.39	5.60 (1.37)	5.64 (1.36)	0.78
Self-selected display position									
Viewing Distance (cm)	40.9 (5.6)	39.2 (6.8)	*0.003*	41.1 (4.4)	40.5 (6.5)	0.43	40.1 (5.4)	39.7 (6.4)	0.21
Viewing angle (degrees below horizontal)	40 (7.9)	42.3 (10.2)	0.09	45.1 (10.1)	46.1 (10.2)	0.50	45.2 (7.6)	45.4 (9.9)	0.14
Display angle (degrees from vertical)	38.3 (12.4)	40.8 (14.4)	0.22	48.6 (16.0)	49.0 (17.4)	0.81	43.2 (14.8)	45.9 (14.2)	0.06
Display centre above floor (cm)	94.6 (6.3)	94.9 (8.4)	0.73	92.0 (8.6)	91.9 (8)	0.89	92.0 (8.0)	93.0 (8.7)	0.98
Display centre above elbow (cm)	25.9 (4.6)	26.1 (6.7)	0.73	23.3 (6.1)	23.1 (6.2)	0.89	23.6 (5.4)	24.2 (5.6)	0.98
Productivity									
Task speed (targets/min)	44.8 (9.0)	44.4 (10.4)	0.73	12.15 (3.64)	10.95 (4.13)	$<$ *0.001*	6.33 (3.13)	5.49 (2.99)	*0.005*
Self-reported discomfort									
Eye discomfort	0.05 (0.1)	0.13 (0.2)	*0.005*	0.08 (0.15)	0.13 (0.22)	*0.04*	0.05 (0.12)	0.13 (0.20)	*0.007*
Neck discomfort	0.05 (0.1)	0.11 (0.15)	*0.001*	0.13 (0.17)	0.16 (0.23)	0.05	0.11 (0.16)	0.14 (0.18)	0.07
Shoulder discomfort	0.11 (0.16)	0.14 (0.18)	*0.02*	0.19 (0.21)	0.21 (0.24)	0.48	0.14 (0.17)	0.17 (0.23)	0.16
Forearm/wrist discomfort	0.09 (0.17)	0.16 (0.23)	*0.03*	0.14 (0.18)	0.21 (0.27)	0.05	0.10 (0.12)	0.16 (0.19)	*0.03*

Note: Italic cells indicate significant ($p \leq 0.05$) pairs. One-touch analysis considered only the large field size. Discomfort measures are from 0 to 1; a viewing angle of 0° means the line of sight is horizontal and a tilt angle of 0° means the display surface is vertical.

Table 2. Mean (SD) two-touch and three-touch results for interaction effects.

	Task									
	Two-touch					Three-touch				
	Field size					Field size				
	Small		Large			Small		Large		
	PR state		PR state			PR state		PR state		
	Enabled	Disabled	Enabled	Disabled	p	Enabled	Disabled	Enabled	Disabled	p
Vertical hand force on display (N)	1.29 (1.36)[a]	0.37 (0.39)[a]	0.63 (0.66)[b]	0.26 (0.16)[b]	< 0.001	0.60 (0.34)[a]	0.50 (0.29)[a]	0.59 (0.29)	0.61 (0.34)	0.03
Right shoulder flexion moment (Nm)	5.35 (1.44)	5.29 (1.53)	5.53 (1.53)	5.21 (1.55)	0.16	5.59 (1.52)	5.35 (1.54)	5.6 (1.44)	5.5 (1.46)	0.33
Left shoulder flexion moment (Nm)	5.19 (1.43)	5.28 (1.47)	5.2 (1.23)	5.17 (1.40)	0.42	5.54 (1.41)	5.66 (1.36)	5.65 (1.34)	5.62 (1.40)	0.20
Productivity (targets/min)	11.79 (3.76)[a]	9.83 (3.86)[a]	12.5 (3.54)	12.06 (4.15)	0.04	7.45 (3.40)	6.27 (3.23)	5.21 (2.39)	4.72 (2.56)	0.25

Note: Paired superscripts designate significant ($p < = 0.05$) pairs.

4. Discussion

4.1. Key findings

The key findings of this study were that enabled PR was typically associated with (1) more wrist extension, (2) more vertical hand reaction force applied to the display, (3) less discomfort and (4) faster task speed for two- and three-touch tasks. There were no meaningful effects of PR state on the self-selected display position. The increased productivity with PR was more pronounced in the small field than in the large field size.

A primary hypothesis of this study was that subjects would use the enabled PR state by registering the palms to the display to increase finger control and affect increased task speeds. A significant increase in the vertical force on the display, a surrogate for palm registration to the display, was demonstrated for the two-touch task with PR enabled, and this ostensible registration was associated with a significant increase in task speed. However, for the three-touch task, the PR state did not affect the vertical force on the display but did have a significant effect on the task speed. This unexpected finding motivated a post hoc analysis of the available software-recorded touch data to determine the percentage of time that extra touches (e.g. the palms) were actually occurring (Table 3). When PR was disabled, any extra touches would preclude task performance (targets could not be moved), and thus it is assumed that the percentage in the disabled state represents the percentage of time with inadvertent touching. Because the task could be performed with extra touches during the enabled PR state, the difference in percentages between the enabled and disabled PR states is assumed to represent the percentage of time with deliberate touching. For the three-touch task, inadvertent touching occurred approximately 13% of the time ('Disabled' mean of small and large fields, Table 3). Deliberate use of PR for the three-touch task (computed as the difference between 'Enabled' and 'Disabled' averages, Table 3) occurred approximately 7% of the time. For the one- and two-touch tasks, deliberate and inadvertent touches were rare, occurring less than 1% of the time. Therefore, it is unlikely that the productivity gain with PR enabled was due to registration of the palms to the display as hypothesised.

4.2. Palm rejection and motor control

Enabling PR may increase productivity by reducing motor control demands. With PR enabled, inadvertent touches with the palm while performing the touch task did not pause the task. To avoid palm contact with PR disabled (which would pause the task), both the locations of the fingertips relative to the targets and the distance of the palms to the display had to be well controlled. In fact, there was less wrist extension with PR disabled. Because less wrist extension would move the palms farther from the display, participants likely reduced the risk of palm contact by decreasing wrist extension. In addition, with PR disabled, the visual demands may be greater in order to assess the location of the palms relative to the display. Thus, with PR disabled, there are increased demands on both the visual and motor (upper extremity) systems. Such an increased 3D visuomotor control has been associated with decreased task speed (Grossman and Balakrishnan, 2004).

The differences in productivity by field size, for the two-touch task, provide additional evidence for the role of motor control. While PR caused a significant productivity benefit for the small field size, no such benefit was observed for the large field size (Table 2). The small field tasks would be expected to require greater motor control to discriminate the more densely distributed targets than those in the large field task (Figure 3); therefore, the effects of motor control on productivity would be more apparent with the small field task.

Because fatigue compromises motor control (Enoka and Duchateau, 2008), adopting less fatiguing postures is a way to maintain a level of motor control during fatiguing tasks. For the tasks performed later in the study (two- and three-touch tasks), wrist extension and shoulder abduction were both smaller when PR was disabled. Smaller shoulder abduction angles generally decrease muscle load, and hence rate of fatigue, by both decreasing the abduction moment due to gravity and

Table 3. Percentage of task time during which more than the required number of touches were recorded (e.g. palm or other finger contact).

	Field size				
	Small		Large		
	Enabled	Disabled	Enabled	Disabled	p
One touch	–	–	0.03 (0.06)	–	–
Two touch	0.8 (0.9)	–	0.6 (0.9)	–	–
Three touch	21.1 (15.9)[a]	12.4 (11.0)[a]	17.8 (13.3)	13.6 (11.3)	0.028

Note: Mean values (SD) are presented. Touch data were not stored for disabled PR for the one- and two-touch tasks. Paired superscripts designate significant pairs.

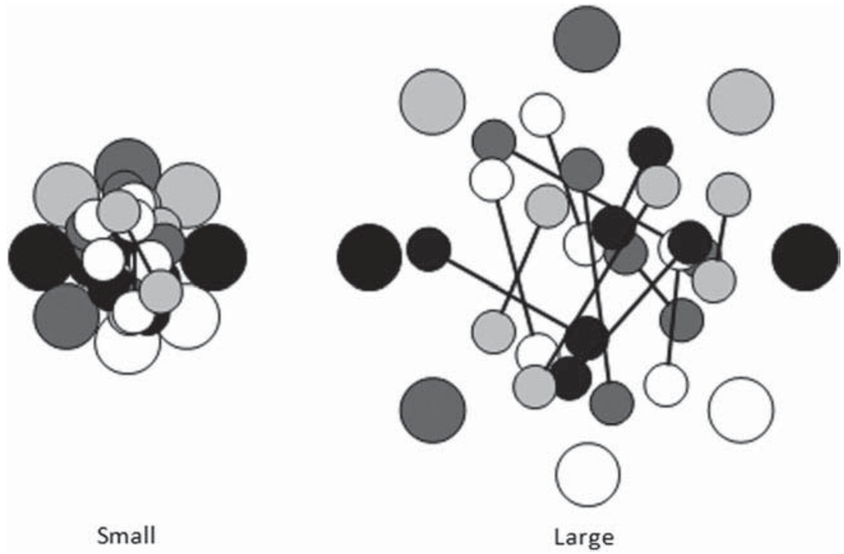

Figure 3. Example distribution of touch targets in the two-touch task for small and large field sizes. Touch targets are the smaller circles and bins are the larger, peripheral circles. The centre-to-centre distance between diametrically opposed bins was 5.6 cm for the small field and 14.1 cm for the large field. Greater motor control, for target discrimination, was likely required for the small field.

increasing the shoulder abduction strength (Hughes et al. 1999). Because greater motor control is required to avoid palm contact, adopting smaller shoulder abduction angles would help reduce fatigue and maintain the motor control.

Unlike the shoulder abductors, as wrist extension decreases, both the wrist extensor strength and the moment due to gravity increase (Delp, Grierson, and Buchanan 1996). Thus, it is not clear that fatigue would promote decreased wrist extension. More likely, smaller wrist extension was used with PR disabled to create a greater stand-off between the palms and the display to minimise the amount of inadvertent palm touching.

Possible consequences of increased motor control demands with PR disabled may explain why discomfort measures were generally higher with PR disabled. The greater visual demands to avoid palm contact may have increased the visual discomfort. The greater antagonistic muscle activity expected with PR disabled, to better control and stabilise the joints (Yamazaki et al. 1994) to avoid palm contact, may have increased the discomfort at the neck, shoulder, forearm and wrist. Higher discomfort in the two- and three-touch tasks may also be due to the increased sensitivity to discomfort with decreased productivity (Wærsted, Bjørklund, and Westgaard 1991; Lundberg et al. 2002; Zakerian and Subramaniam, 2009).

4.3. Self-selected display position

It was expected that with PR enabled, subjects would rest their palms on the display to decrease shoulder loads and move the display to a higher location to reduce neck flexion. That the subjects did not use the PR technology to rest the palms may explain why there were no significant differences in the self-selected viewing angle. The self-selected viewing angles in this study (40°–46° below the horizon) were larger than that (35°) in another touch display study (Shin and Zhu, 2011). The current study evaluated the self-selected display position without armrests, a desk or a keyboard, as these may have constrained the lower limit of the display. The Shin and Zhu protocol used armrests, which may explain their smaller viewing angle (i.e. higher display). Arguments can be made for either including or not including armrests while using a touch display; armrests can reduce shoulder loading, but they may also constrain the elbow and reduce postural options, in particular when touching over the whole surface of the display.

The self-selected viewing distance, approximately 40 cm, was similar to the Shin and Zhu (2011) touch display study, but was less than the distances reported in studies using non-touch displays (Jaschinski, Heuer, and Kylian 1998; Psihogios et al. 2001; Shin and Hegde, 2010), in which the displays were set near the limits of arm reach.

4.4. Loads

Although the force plate could not parse the hand reaction force between the left and right hands, the maximum possible reduction in shoulder moment could be estimated by allocating the measured vertical force to a single hand. The maximum estimated reduction in net shoulder flexion moments, across the duration of the tasks, was 2.1%, 6.3% and 3.7% for one-, two- and three-touch tasks, respectively, with PR enabled, and 1.0%, 1.8% and 3.4% with PR disabled. The reduction, as a percentage of strength, was even smaller. Shoulder flexor strength is 6 to 10 times that required to support just the arms (Hughes et al. 1999). Therefore, the reduction in shoulder flexion moment, from the vertical hand force, is at most 1% of maximum voluntary contraction (MVC). Furthermore, as noted above, it was rare for the palms to actually be touching the display (Table 3). The increase in vertical hand forces with PR enabled may have been due in part to greater durations of palm contact or the higher dynamic loads associated with faster task speeds.

Finally, the vertical force measured was averaged across the whole task time and was not representative of the force during times when the palms and fingers were necessarily in contact with the display. Because the force during palm contact may be of interest to the design of equipment (e.g. compliance of touch-display stands), an additional post hoc analysis was performed to determine the vertical force when the palms and fingers were in contact with the display for the three-touch task. Across all subjects, 128 contact events satisfied the timing criterion (>2 s continuous contact) imposed by the slow force storage rate (1 Hz) and touch contact storage rate (10 Hz). The average vertical force on the display for these 128 events was 0.96 N (0.17–1.88), which was slightly larger than the force averaged across all contact events (0.60 N). Because the force storage rate was 1 Hz, impact loads could not be assessed.

4.5. Limitations

The study findings may apply to a limited set of tasks and workstation set-ups. To decrease the constraints on the self-selected display positioning, no desk or input devices (e.g. keyboard or mouse) were present. Use of a desk with a keyboard may have resulted in the self-selected placement of the display farther away and higher than what was observed in this study. Additionally, whether the palms are deliberately rested or registered to the display may depend on the particular task. In the three-touch task, deliberate palm use occurred about 4% of the time with the larger field and about 9% of the time with the smaller field (Table 3). Although only two field sizes were assessed in this study, PR might be exploited more when interacting over small display areas that require little to no palm translation, in which pointing can largely be achieved by finger (flexion and abduction) and wrist (deviation) motions. When using touch input with a pronated forearm and relatively extended fingers, touching the display with the palms might have been avoided in this study so as to reduce wrist extension (Table 1). Maintaining the wrist in extension for long durations, especially in full pronation, is uncomfortable (Seligman, Boiano, and Anderson 1986; Khan, O'Sullivan, and Gallwey 2009; Asundi et al. 2012). Tilting the display flatter would have been more conducive to palm resting, but a flatter display would cause a divergence between the line of sight and the display normal; the preference is for these two lines to be nearly parallel, as demonstrated in this study and other studies (e.g. Psihogios et al. 2001; Shin and Hegde, 2010). Use of a stylus, with less pronation and similar to writing tasks, may promote palm registration for motor control and has been associated with a preference in flatter displays (Chan and So, 2009; Yen, 2011). Because the duration of exposure to each test condition was short, the discomfort ratings may not be predictive of working with a touch display for a full day. A longer exposure to PR technology may lead to more deliberate resting of the palms on the display.

The equipment used in this study was not able to discriminate between display and bezel touches. However, bezel resting was not likely in this study due to the size of the display and the location of the touched content. The distance between the bezel and the lower touch region (11–15 cm) was too large to easily rest the palms on the bezel.

While it is possible that the rejection software implemented in this study rejected untargeted finger touches (and not solely palm touches), it is believed that the duration of finger rejections was small compared to the duration of the tasks. The distribution of rejected touches with respect to the nearest accepted touch is more consistent with PR than with finger rejection, with finger rejection estimated to account from 10% to 20% of the total rejected touches (Figure 4). With rejections occurring about 15% of the task time (Table 3), the duration during which finger touches were rejected may represent from 1% to 3% of the total task time.

5. Summary and recommendations

The aim of this research was to evaluate the effects of PR technology on productivity, usability and biomechanics. The key findings were that PR technology (1) increased task speed by 10% to 20% for the two- or three-touch tasks, (2) generally reduced discomfort, (3) was rarely used to intentionally support the palms on the display and, therefore, (4) provided no benefit to shoulder unloading. It appears that a primary value of PR was eliminating errors due to unintentional palm contact. A longer exposure to the PR technology may have led to more deliberate use of the technology with increased palm resting and reduced shoulder loads.

Whether or not to recommend the implementation of PR technology depends on the costs versus benefits. Enabling PR was associated with productivity and comfort benefits for the tasks assessed in this study. Postural responses to enabled PR demonstrated both benefits (decreased ulnar deviation) and costs (increased wrist extension), with the average effect size

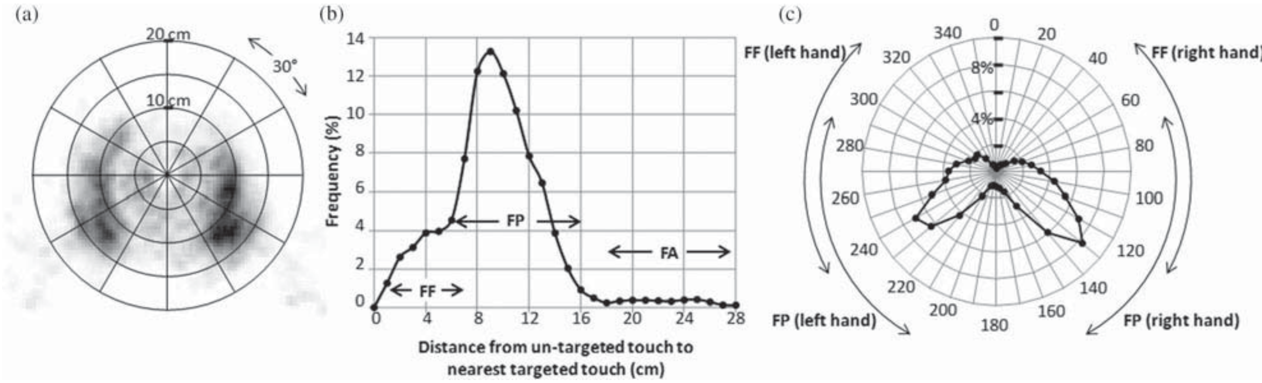

Figure 4. Distribution of rejected touches with respect to the nearest accepted touch for the three-touch task. (a) Relative distribution by both distance and direction. Origin represents the nearest accepted touch and darker regions represent locations of more frequent rejected touches. (b) Frequency of rejected touches by distance. (c) Frequency of rejected touches by direction. Accepted touches of the thumb and index fingers would tend to place the palm laterally from approximately 60° downwards (index finger to thenar eminence) to approximately 20° upwards (thumb to hypothenar eminence) and ranging from about 5 cm (thumb to thenar eminence) to 15 cm (index finger to hypothenar eminence) (FP). Middle, ring and pinky distances from the index finger would tend to range from about 2 to 7 cm (Rogers et al. 2008), in directions from 30° downwards (fingers flexed) to 45° upwards (fingers extended) (FF). Finger to forearm distances would be larger than the hand length (FA).

less than 5° (Table 1). Assuming that gestures are not likely to be deliberately performed with the palm and that implementing PR technology is not financially costly, the implementation of PR technology, with a user option to disable, is recommended for tasks similar to those tested in this study

Although no tasks in which the palms deliberately and often touch the display were assessed in this study, the use of PR technology with such tasks may result in a preference for lower and flatter displays (relative to those values in Table 1) so as to decrease the wrist extension required to touch both fingertips and palms. Therefore, when specifying the range of adjustability of displays, designers should consider the types of tasks to be performed.

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