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Thumb motor performance varies with thumb and wrist posture during single-handed mobile phone use

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ABSTRACT

Design features of mobile computing technology such as device size and key location may affect thumb motor performance during single-handed use. Since single-handed use requires the thumb posture to vary with key location, we hypothesize that motor performance is associated with thumb and wrist joint postures. A repeated measures laboratory experiment of 10 right-handed participants measured thumb and wrist joint postures during reciprocal tapping tasks between two keys for different key pairs among 12 emulated keys. Fitts' effective index of performance and joint postures at contact with each key were averaged across trials for each key. Thumb motor performance varied for different keys, with poorest performances being associated with excessive thumb flexion such as when tapping on keys closest to the base of the thumb in the bottom right corner of the phone. Motor performance was greatest when the thumb was in a typical resting posture, neither significantly flexed nor fully extended with slight CMC joint abduction and supination, such as when tapping on keys located in the top right and middle left areas on the phone. Grip was also significantly affected by key location, with the most extreme differences being between the top left and bottom right corners of the phone. These results suggest that keypad designs aimed at promoting performance for single-handed use should avoid placing frequently used functions and keys close to the base of the thumb and instead should consider key locations that require a thumb posture away from its limits in flexion/extension, as these postures promote motor performance.

1. Introduction

Given the mobile nature of smartphones, users often hold the device with a single hand forcing only the thumb to activate the keys. Berolo et al. (2011) report that individuals among a university population spend on average more than 3.5 h/day texting, emailing, scheduling and Internet browsing on their mobile phones, and commonly reported pain at the base of the thumb. The design of the phone's input space often mimics a computer workstation layout with a keypad located at the base and the display at the top. The mobile phone user must adapt their thumb and hand postures to the constraints of this design layout, which may impact performance.

Evidence exists that performance is affected by different layout factors such as key locations and movement directions. Hogg (2010) reported greater perceived effort for key locations in the bottom right corner of the phone. Park and Han (2010a) reported lower transition times for keys in the middle of the phone. They also reported an increased number of errors for bottom right corner keys. Both Karlson et al. (2008) and Trudeau et al. (2012) demonstrated that performance was better for movements in the top right/bottom left orientation of the phone. Wobbrock et al. (2008) reported a significant effect of movement direction on thumb speed and performance for sliding tasks. Hogg (2010) reported greater perceived effort and poorer typing speed for thumb movements along the top left/bottom right orientation. Most of these studies hypothesize that thumb posture may play a role in explaining the variations in performance measured across key locations and movement directions, yet none measure posture at specific key locations.

We aimed to determine if thumb motor performance, defined by the effective index of performance calculated from Fitts' Law, is affected by biomechanical factors such as thumb and wrist postures during single-handed use of a mobile phone device. We hypothesize that variations in motor performance across keys could be due to the different thumb/wrist postures required to reach the keys. This hypothesis was verified using a 3-step

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approach: first, we tested if motor performance varied for different keys on the surface of the phone, which we expected given previous study findings. Next, we tested whether this association could be explained by biomechanics by determining if thumb/wrist postures varied for different key locations, and whether these postures were associated to motor performance.

2. Methods

Ten right-handed healthy adults (5 men, 5 women) provided informed consent before participating in the repeated measures experiment. Mean ($\pm$SD) age and right hand length were 27.0$\pm$7.0 yrs and 18.7$\pm$1.7 cm respectively. The Harvard School of Public Health Office of Human Research Administration approved all forms and protocols.

2.1. Reciprocal tapping trials

While holding a mobile phone with their right hand, participants accomplished trials that involved tapping with their thumb between 2 of the 12 emulated keys on an Apple iPhone 3® (Fig. 1). The selection and presentation of the key pairs was randomized for every participant to achieve a representative sample of all the possible incoming tap directions for each key during the 1 h 30 min experiment duration. An average of 47$\pm$6 trials were analyzed per participant. Participants were allowed to slightly adjust their grip between trials. Instructions to participants included "complete the task as fast and as accurately as possible". For each trial, 6 s of data collection started once the subject indicated they were comfortable with the tapping task. Participants rested for 90 s after every 15 trials.

2.2. Measured kinematics

Phone, thumb, hand, and forearm 3D kinematics were measured using an active-marker motion capture system (Optotrak Certus, Northern Digital Inc., Waterloo, Canada). Clusters of three infrared light emitting diodes (IREDs) secured to a rigid plate were mounted to the phone, right forearm, dorsal surface of the hand, and proximal phalange of the thumb, which were treated as rigid body segments, and two IREDs were fixed to the thumb nail (Fig. 2). The IRED placement used in this study builds on previous methods for measuring thumb kinematics (i.e., Kuo et al., 2002, 2003; Li and Tang, 2007; Hogg, 2010) by accounting for the established degrees of freedom of each joint (Cooney et al., 1981; Hollister et al., 1995) while minimizing physical and visual obstruction for the participant. The IRED 3D trajectories were recorded to a personal computer at 100 Hz, then digitally filtered through a low-pass, fourth order Butterworth filter with a 10 Hz cutoff frequency. Cluster orientations were transformed to describe the anatomical segment location and orientation along with the joint centers via the relative location of digitized bony landmarks (Winter, 2005).

Wrist and thumb joint angles were calculated from the Euler angles of the rotation matrices describing the orientation of the joint's distal segment relative to the proximal segment (Winter, 2005). The first Euler angle rotation was flexion/extension, the second was abduction/adduction and the third was pronation/supination. CMC joint flexion and extension were defined as the movement of the thumb ulnar/radialward respectively in a plane parallel to the palm, and CMC abd/adduction were defined as the movement of the thumb away/toward the second metacarpal. Joint angles were expressed relative to a reference posture where the forearm, hand and fingers were aligned, and the thumb was held straight along the palm such that it was pronated by 90° relative to the index finger in order to align the long axes of the first metacarpal and the trapezium (Cooney et al., 1981).

For a given tap toward a specific key within a trial, the horizontal distance the thumb tip moved, the movement time from the previous tap, and the position of the thumb's distal IRED were pulled from the continuous data at the instant that the tap was completed. The thumb and wrist joint angles, and the location of the CMC joint relative to the phone and to the key being tapped as parameters that describe grip, were also pulled from the data. The instant of a tap completion was defined as when the vertical (Z) position of the thumb's most distal IRED relative to the phone reached a local minimum (with respect to time) with a relative horizontal position in the vicinity of the key.

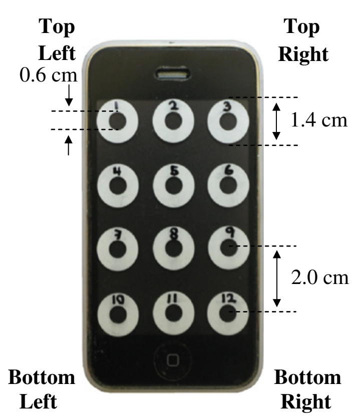

Fig. 1. Position and size of the 12 emulated keys. The emulated keys were 3 ring binder hole reinforcement stickers. The hole provided tactile information to the users for the center of the emulated key.

2.3. Measured thumb motor performance

For each key within a trial, an across tap average movement time, average distance, average joint postures and an effective index of performance (IP_e) were calculated. According to ISO9241-9, the effective index of performance is given by $IP_e = ID_e/MT$, where MT and ID_e are the average movement time and effective index of difficulty, respectively (Fitts, 1954; Douglas et al., 1999; Soukoreff and Mackenzie, 2004; Wobbrock et al., 2008). ID_e was calculated as $ID_e = \log_2(A_e/W_e + 1)$, where A_e is the horizontal distance between the keys involved in the trial, and W_e is the effective target width, given as $W_e = 4.133\text{SD}$. Here, SD is the standard deviation of the thumb tip IRED horizontal (X, Y plane) position on the phone's surface about the mean horizontal position for all taps on a specific key during the trial.

2.4. Statistical analyses

For each key, calculated parameters (i.e., IP_e, W_e, MT, thumb and wrist joint angles, and CMC joint location) were averaged across all trials containing that key within each participant allowing for 12 observations (1 for each key) per participant. To determine whether thumb motor performance varied across different keys we employed a mixed-effects analysis of variance (ANOVA) model with participant as the random effect and the key's categorical identification as the fixed effect. Similar models were fit for movement time and effective target width as the dependent variables. To determine whether posture varied across different keys we employed mixed-effects ANOVA models for each joint angle and

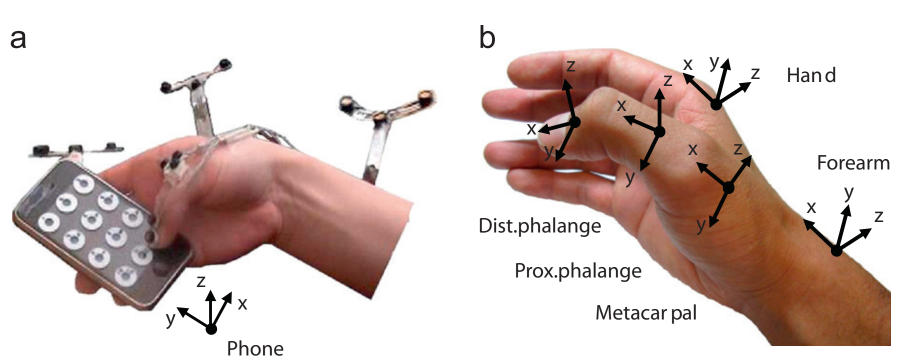

Fig. 2. (a) IRED placement on the phone, forearm, hand and thumb, and coordinate system for the phone. (b) Coordinate systems on the forearm, hand and thumb. Joint flexion (+) and extension (−) occur about the Y-axis; abduction (+) and adduction (−) occur about the Z-axis; supination (+) and pronation (−) occur about the X-axis. For the phone, the X-axis points from left to right, the Y-axis points up along the long edge of the phone's portrait orientation, and the Z-axis is normal to the phone's surface.

for the distance between the CMC and the key being tapped, with key as the fixed effect. For all ANOVAs, post-hoc Tukey's HSD tests determined if differences in the dependent variables existed between the specific keys. To test whether thumb motor performance varied with posture, we fit mixed regression models for each joint angle and the distance between the CMC and key being tapped, with effective index of performance as the dependent variable. All statistical analyses were run using JMP Software (SAS Institute, Cary, NC).

3. Results

Effective index of performance varied significantly across the 12 keys (Table 1). The effective indices of performance for keys located in the top right corner along with the center keys, i.e. keys 3, 5, 6, 7, and 8, were greater compared to keys located in the top left and bottom right and left corners. Key 12 in the bottom right corner of the phone was associated to the longest movement time (326 (54) ms), whereas key 2 had the largest effective target width (5.7 (2.0) mm).

Table 1
Average (and standard deviation) values for effective index of performance (bits/s), effective target width (mm) and mean movement time (ms) for each key. Key identifier was a significant effect ($p<0.001$) for all dependent variables. The values are laid out congruent with the relative positon of the keys on the phone (Fig. 1)[a].

IPe: effective index of performance (bits/s)[b]			
Keys 1, 2, 3	11.8 (2.4)^{A,B,C}	11.5 (2.0)^{B,C}	13.1 (1.9)^{A}
Keys 4, 5, 6	12.4 (2.3)^{A,B,C}	12.0 (2.1)^{A,B,C}	12.9 (2.4)^{A,B}
Keys 7, 8, 9	12.6 (2.6)^{A,B,C}	12.1 (2.4)^{A,B,C}	11.5 (2.7)^{B,C}
Keys 10, 11, 12	11.7 (2.0)^{A,B,C}	11.9 (1.8)^{A,B,C}	11.3 (1.9)^{C}
We: effective target width (mm)[c]			
Keys 1, 2, 3	5.3 (2.4)^{A,B}	5.7 (2.0)^{A}	4.7 (1.4)^{A,B,C}
Keys 4, 5, 6	4.7 (1.9)^{A,B,C}	4.8 (1.8)^{A,B,C}	4.5 (1.6)^{B,C}
Keys 7, 8, 9	4.3 (1.6)^{B,C}	4.7 (1.4)^{A,B,C}	4.1 (1.4)^{C}
Keys 10, 11, 12	4.1 (1.7)^{C}	4.3 (1.5)^{B,C}	4.2 (1.7)^{C}
MT: mean movement time (ms)[d]			
Keys 1, 2, 3	282 (37)^{B,C}	275 (43)^{C,D}	266 (40)^{C,D}
Keys 4, 5, 6	265 (36)^{C,D}	250 (32)^{D}	260 (36)^{C,D}
Keys 7, 8, 9	269 (44)^{C,D}	261 (51)^{C,D}	302 (53)^{A,B}
Keys 10, 11, 12	319 (53)^{A}	303 (47)^{A,B}	326 (54)^{A}

[a] The superscript letters in the table report the results from the Tukey post-hoc analysis: same letters denote groups without significant differences. Values with different letters are ranked such that A > B > C. Color gradients are shown to highlight trends: darker indicates better motor performance, smaller effective target width (i.e., better precision) and faster movements respectively.
[b] Higher numbers indicate better motor performance.
[c] Lower numbers indicate better precision.
[d] Lower numbers indicate faster movements.

Thumb and wrist joint angles at contact with the key varied significantly across keys (Table 2). The greatest postural differences were between the top left and bottom right corners. For the bottom right corner, the wrist was flexed and adducted, the CMC joint was flexed and pronated, and the IP and MCP joints were in their most flexed postures compared to all other key locations. For the top left corner, the wrist was extended and more adducted, the CMC was extended and supinated, the MCP joint was extended, and the IP joint was less flexed than for any other key. The greatest difference in flexion/extension angles was between the top left and bottom right corners except for the CMC joint. CMC and MCP abduction differences were greatest between the top right and bottom left corners, with greatest CMC abduction and least MCP adduction angles associated with the bottom left corner.

Grip differences across the 12 keys were apparent from the differences in the distance between the CMC joint and the key being tapped (Table 3). This distance was greatest for keys in the top left (106 ± 2 mm) and shortest for keys in the bottom right corner of the phone (87 ± 4 mm). These two corners were also the extremes with respect to the distance of the CMC joint relative to the phone, which can be seen in Fig. 3 showing the average 3D position of the CMC joint relative to the phone's horizontal (Fig. 3a) and vertical (Fig. 3b) planes at the instant of tap completion. When tapping on keys in the top left corner, the CMC joint was closer to the phone in the horizontal plane and higher above the phone in the vertical plane compared to the bottom right corner.

Effective index of performance varied significantly with several of the joint angles. For each significant association found, Fig. 4 presents the average effective index of performance versus the average posture necessary to reach each key. Effective index of performance had a non-linear association with IP joint flexion (Fig. 4a; $p=0.010$) and MCP joint flexion (Fig. 4b; $p=0.014$) such that it was poorest when these joints were at either extremes in

Table 2
Average (and standard devation) values for the joint angles (°) at the instant when the thumb tip contacted the key, for each key. Joint angles were expressed relative to a reference posture where the forearm, hand and fingers were aligned, and the thumb was held straight along the palm such that it was pronated by 90° relative to the index finger, with the wrist straight. The values are laid out congruent with the relative positon of the keys on the phone (Fig. 1). Key identifier was a significant effect ($p<0.001$) for all joint angles. Flexion, abduction and supination are positive, whereas extension, adduction and pronation are negative[a].

Wrist flexion (°)			
Keys 1, 2, 3	−24 (6)^{H}	−18 (7)^{G,H}	−15 (9)^{F,G}
Keys 4, 5, 6	−18 (5)^{G,H}	−14 (7)^{E,F,G}	−8 (7)^{C,D,E}
Keys 7, 8, 9	−12 (5)^{D,E,F}	−6 (6)^{B,C}	0 (7)^{A}
Keys 10, 11, 12	−7 (4)^{C,D}	0 (5)^{A,B}	5 (5)^{A}
CMC flexion (°)			
Keys 1, 2, 3	−10 (6)^{G}	−9 (6)^{G}	−10 (6)^{G}
Keys 4, 5, 6	−2 (5)^{E,F}	−5 (6)^{F,G}	−4 (4)^{F,G}
Keys 7, 8, 9	5 (4)^{B,C,D}	2 (5)^{C,D,E}	0 (6)^{D,E,F}
Keys 10, 11, 12	12 (4)^{A}	9 (4)^{A,B}	8 (6)^{A,B,C}
MCP flexion (°)			
Keys 1, 2, 3	−13 (3)^{G}	−12 (3)^{G}	−12 (2)^{G}
Keys 4, 5, 6	−8 (3)^{F,G}	−5 (4)^{E,F}	−6 (3)^{E,F}
Keys 7, 8, 9	−3 (3)^{D,E}	0 (4)^{B,C,D}	3 (4)^{B,C}
Keys 10, 11, 12	0 (2)^{C,D}	5 (2)^{A,B}	9 (3)^{A}
IP flexion (°)			
Keys 1, 2, 3	17 (6)^{G}	22 (10)^{F,G}	23 (11)^{E,F,G}
Keys 4, 5, 6	24 (9)^{E,F}	40 (13)^{D}	37 (13)^{D}
Keys 7, 8, 9	31 (8)^{E}	47 (10)^{C}	56 (10)^{A,B}
Keys 10, 11, 12	30 (8)^{E}	50 (7)^{B,C}	58 (8)^{A}

Wrist abduction (°)			
Keys 1, 2, 3	−22 (2)^{E}	−22 (3)^{E}	−20 (3)^{D,E}
Keys 4, 5, 6	−20 (3)^{D,E}	−17 (3)^{B,C,D}	−14 (3)^{A,B,C}
Keys 7, 8, 9	−17 (4)^{C,D}	−16 (4)^{A,B,C}	−14 (4)^{A,B}
Keys 10, 11, 12	−17 (4)^{A,B,C,D}	−16 (4)^{A,B,C}	−13 (4)^{A}
CMC abduction (°)			
Keys 1, 2, 3	30 (2)^{A,B}	22 (2)^{C}	13 (3)^{D}
Keys 4, 5, 6	31 (2)^{A,B}	23 (3)^{C}	12 (2)^{D}
Keys 7, 8, 9	32 (2)^{A}	23 (3)^{C}	15 (3)^{D}
Keys 10, 11, 12	33 (1)^{A}	29 (2)^{B}	20 (4)^{C}
MCP abduction (°)			
Keys 1, 2, 3	−8 (2)^{B,C}	−15 (2)^{D,E}	−19 (3)^{F}
Keys 4, 5, 6	−8 (2)^{B}	−15 (2)^{D,E}	−19 (3)^{F}
Keys 7, 8, 9	−6 (2)^{A,B}	−12 (2)^{C,D}	−16 (4)^{E,F}
Keys 10, 11, 12	−2 (2)^{A}	−7 (3)^{B}	−10 (4)^{B,C}
CMC supination (°)			
Keys 1, 2, 3	5 (8)^{A,B}	7 (10)^{A,B}	11 (13)^{A}
Keys 4, 5, 6	−7 (8)^{C,D,E}	−2 (10)^{B,C,D}	0 (8)^{B,C}
Keys 7, 8, 9	−16 (5)^{F,G}	−12 (7)^{E,F}	−9 (11)^{D,E,F}
Keys 10, 11, 12	−25 (5)^{H}	−23 (6)^{G,H}	−21 (9)^{G,H}

[a] The superscript letters in the table report the results from the Tukey post-hoc analysis: same letters denote groups without significant differences. Values with different letters are ranked such that A > B > C > …. Color gradients are shown to highlight trends: darker indicates greater angles.

Table 3
Average (and standard devation) values for the distance between the CMC joint 3D position and the key being tapped (mm) at the instant when the thumb tip contacted the key, for each key. Key location was a significant effect ($p<0.001$). The values are laid out congruent with the relative positon of the keys on the phone (Fig. 1)[a].

Keys 1, 2, 3	106 (2)^{A}	104 (3)^{A,B,C}	100 (3)^{C,D}
Keys 4, 5, 6	104 (2)^{A,B}	99 (4)^{D,E}	95 (4)^{F}
Keys 7, 8, 9	102 (2)^{B,C,D}	95 (4)^{E,F}	89 (4)^{G}
Keys 10, 11, 12	101 (2)^{B,C,D}	94 (3)^{F}	87 (4)^{G}

[a] The superscript letters in the table report the results from the Tukey post-hoc analysis: same letters denote groups without significant differences. Values with different letters are ranked such that A > B > C > …. Color gradients are shown to highlight trends: darker indicates longer distances.

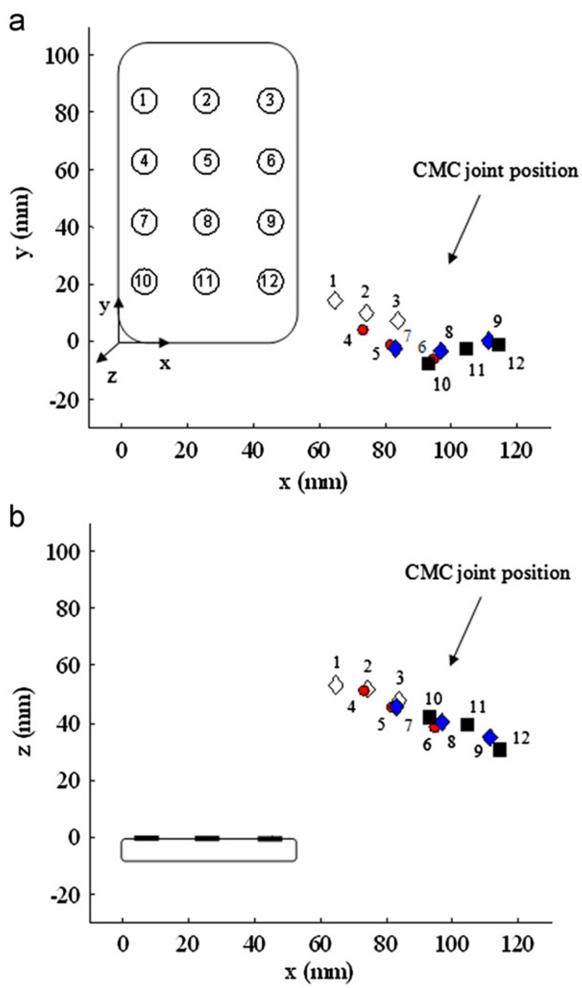

Fig. 3. Average CMC joint 3D position with respect to the bottom left corner of the phone at the instant when the thumb tip contacted the key, for each key. Both the (a) top view (i.e., the (*X*, *Y*) plane) and (b) side view (i.e., the (*X*, *Z*) plane) of the phone's coordinate system are presented.

flexion and extension. Effective index of performance was also non-linearly associated with CMC joint abduction (Fig. 4c; $p<0.001$) such that it was poorest when the CMC was between 20° and 25° of abduction. Effective index of performance also increased with CMC supination ($p=0.004$).

4. Discussion

The aim of this study was to determine if motor performance is associated with thumb and wrist posture during single-handed use of a mobile phone device. By measuring thumb/wrist posture and effective index of performance for different keys located across the surface of the phone, we determined that variations in thumb motor performance across keys could be explained by the thumb/wrist postures required to reach the keys.

Thumb motor performance was poorest for the key located in the bottom right corner of the phone (11.3 ± 1.9 bits/s), which is consistent with results from previous studies. Park and Han (2010a, 2010b) found that keys in the bottom right corner of the phone were associated with poor transition times and a greater number of errors. Other studies have found that directional movements toward the bottom right corner were associated to lower performances (Trudeau et al., 2012) and greater perceived effort (Karlson et al., 2008; Hogg, 2010). These data are also consistent with results from Parhi et al. (2006) who found poorer subjective ratings of mean comfort for taps on keys located at the top left and bottom right corners of the phone compared to keys located at the top right and bottom left corners.

Holding the phone in the hand while tapping with the thumb resulted in significantly different postures for reaching keys at different distances from the base of the thumb. Postural differences were most significant between keys in the top left and bottom right corners of the phone because these corresponded to the farthest and closest key locations from the base of the thumb respectively. To tap on key 1 in the top left corner of the phone the CMC joint was elevated above the phone in an attempt to shorten the distance to the target. The remaining distance was covered by extending the thumb. Conversely, to reach keys in the bottom right corner, users assumed a different grip in which the wrist was flexed while the fingers were observed to be extended. This was likely achieved to position the key in a location that was not too close to the base of the thumb and therefore within reach while maintaining balance of the phone in the palm. The distance between the CMC joint and the key being tapped was similar for keys in the top right and bottom left corners of the phone, which suggests that they could be reached by using primarily the thumb without requiring as much variation in grip.

The variations in motor performance and postures for reaching different keys as described above are consistent with the associations found between posture and motor performance, which supports the main hypothesis of the study. Poor motor performances at the extremes of the thumb's range of motion in flexion and extension suggest that the thumb performs best when it is neither significantly flexed nor fully extended. This result may be due to an increase in passive forces when the MCP and IP joints approach their limits in flexion or extension (Keir et al., 1996). An increase in passive forces requires greater effort and therefore more fluctuations in the number of motor neurons recruited (Kandel et al., 2000). This may increase the control effort required to align the thumb with the key before contact, which is consistent with the greater movement times measured in this study for taps in the bottom right and top left corners of the phone (Table 1).

Variations in motor performance across keys when the thumb was in a slightly flexed posture were a result of changes in the CMC joint's posture in the abduction/adduction and pronation/supination axes. The valley in the non-linear association between effective index of performance and CMC joint abduction (Fig. 4c) corresponds to when the CMC joint was in the middle of its range of motion, which was the posture required to tap on the keys in the middle of the phone (Table 2). In this posture, the surface area under the thumb was greater given its flat orientation relative to the phone's surface. Park and Han (2010b) hypothesize that a larger surface area of the thumb might be related to poor target selection accuracy, which is consistent with the larger effective target widths (i.e., poorer precision) measured in this study for the middle of the phone compared to keys on the left and right edges.

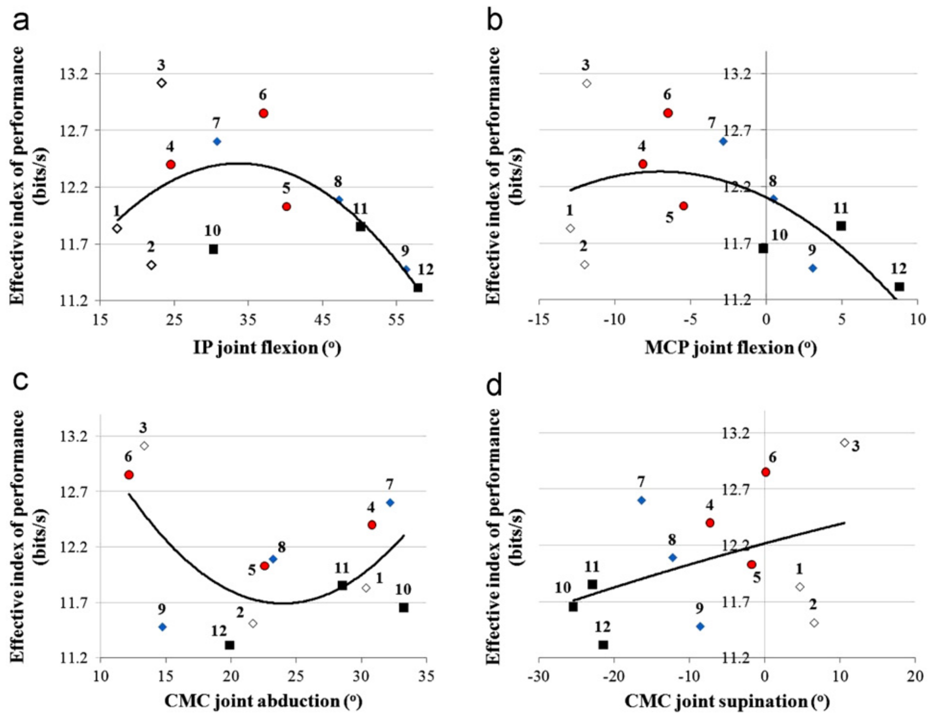

Fig. 4. Significant associations from the mixed univariate models fitted between motor performance and each of the posture metrics. For better visualization, average effective index of performance is plotted versus average posture for each key, and the mean trendline is fitted. (a) Non-linear association between effective index of performance (IP_e) (bits/s) and interphalangeal (IP) joint flexion (°). (b) Non-linear association between effective index of performance (bits/s) and metacarpophalangeal (MCP) joint flexion (°). (c) Non-linear association between effective index of performance (bits/s) and carpometacarpal (CMC) joint abduction (°). (d) Linear association between effective index of performance (bits/s) and CMC joint supination (°).

There were limitations to the methods of this study. First, only right-handed participants were considered and therefore the results are not applicable to left handed users. Next, the reciprocal tapping tasks were different from commonly performed activities such as typing or Internet browsing. However, they provided a convenient way of measuring motor performance using standard Fitts′ Law motor performance metrics and reflect the elemental tasks involved in commonly performed activities. In addition, the emulated keys were not functional. However, the 3 ring binder hole reinforcement stickers had tactile feedback which provided participants with sensory information about their accuracy. We calculated the postures at the instant at which the thumb "bottomed out", which we expect are similar to the postures required to activate a functional key. Next, only 12 keys were used to represent the whole surface of the phone. The 4×3 grid provided the ability to measure motor performance for the same distribution of key locations across participants. Parameters that may have an association with thumb motor performance such as movement direction and visual obstruction due to the thumb itself were not considered in the analysis because these are intrinsic characteristics of the key location which is a true design factor as opposed to a consequence of the task, and is the main independent variable of interest in the study. Finally, since the study's inclusion criteria was not restricted to specific demographics such as phone model owned and experience, the results are generalizable to a wide range of single-handed mobile phone users.

5. Conclusion

Our results demonstrate that, for single-handed mobile phone use, variations in thumb motor performance across different keys is a function of the thumb/wrist postures required to reach the keys. More specifically, motor performance is greatest for thumb postures that are away from the limits of its range of motion in flexion and extension, and for postures in which the thumb is slightly abducted and supinated. Based on these results, input space designs aimed at promoting thumb motor performance should avoid key locations that require excessive thumb flexion or extension such as the bottom right and top left corners of the phone respectively. Keys should instead be placed in the top right and middle left areas of the phone as the postures required to tap on these areas lead to greater precision and lower tapping movement times, and therefore promote thumb motor performance.

Conflict of interest statement

The authors have no conflicts of interest for this study.

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