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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.

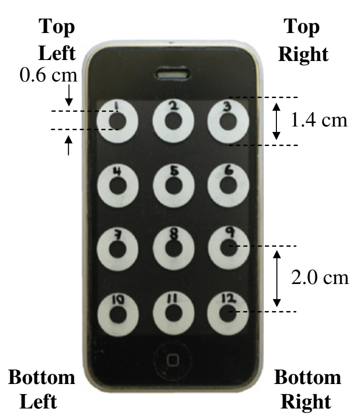

Fig. 1. Position and size of the 12 emulated keys. The emulated keys were 3 ring binder hole reinforcement stickers. The hole provided tactile information to the users for the center of the emulated key.

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

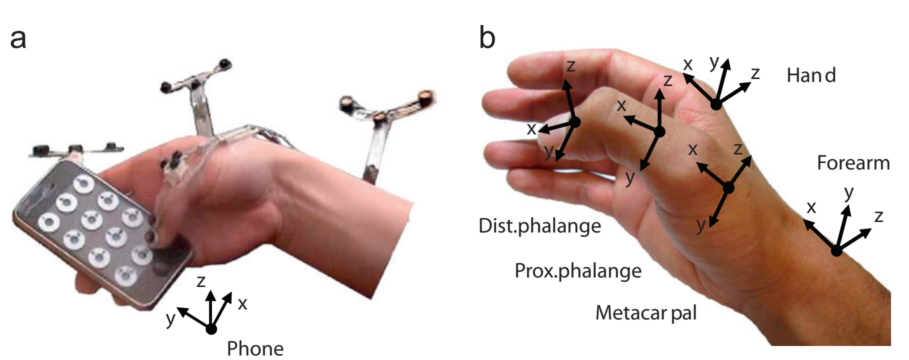

Fig. 2. (a) IRED placement on the phone, forearm, hand and thumb, and coordinate system for the phone. (b) Coordinate systems on the forearm, hand and thumb. Joint flexion (+) and extension (−) occur about the Y-axis; abduction (+) and adduction (−) occur about the Z-axis; supination (+) and pronation (−) 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.