Title
Computer Input Devices: Design for Well-Being and Productivity

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Publication Date
2013

Peer reviewed|Thesis/dissertation

Computer Input Devices: Design for Well-Being and Productivity

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A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Health Sciences

in the

Graduate Division

of the

University of California, Berkeley

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Fall 2013

Abstract

Computer Input Devices: Design for Well-Being and Productivity

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Objective: Three studies evaluated human computer interaction with alternative keyboard designs, new tablet features, and a 3D gesture-command set for their effects on biomechanics, comfort, and productivity.

Background: Keyboard key spacing, tablet designs, and the design of hand gestures for human computer interaction have been guided primarily by past practices and design convention because few studies are available that can guide design based on productivity, usability, and biomechanics.

Method: Experienced typists (N=89, 26 female) typed on keyboards which differed in horizontal and vertical key spacing while productivity, biomechanics, and subjective usability and fatigue were recorded. Thirty subjects (15 female) evaluated tablet design features (e.g., 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. Thirty subjects (15 female) performed user derived gestures for 34 common computer commands. A gesture set is proposed based on user preference, match, easiness, effort, gesture popularity, and musculoskeletal postural risks.

Results: Reducing horizontal key spacing, from 19 to 17 mm, had no significant effect on productivity or usability ratings but with 16 mm horizontal spacing, the same ratings, muscle activity and postural factors were significantly worse. Reducing vertical key spacing, from 18 to 17 to 16 mm, had no significant effect on productivity or usability, but at 15.5 mm vertical spacing these measures were worse. The study evaluating table design features supported the use of smaller to mid-sized tablets, tablets with a ledge or handle shape on the back and tablets surfaced with a rubberized 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 (7.5–9.5mm) or larger grip (7.6mm) had better usability and biomechanics than one with a smaller grip (5mm). For the gesture study, 34 different commands were linked to 84 different gestures with a total of 160 gesture-command combinations. A proposed gesture set using 13 gestures for the 34 commands is proposed using the six outcome measures with adjustment by expert opinion.

Conclusions: The study findings support key spacing on a computer keyboard from 17 to 19 mm in the horizontal direction and 16 to 19 mm in the vertical direction. Based on short-term tasks emulating functional tablets: smaller and medium sized tablets, portrait instead of landscape orientation, a back grip, and rubberized grip texture improved usability and security from dropping. We present a method for developing a 3D gesture language for common commands for human-computer interaction which considers subjective preference, ease of forming gesture, hand biomechanics and other factors.

Dedicado ao meu tio

Dedicated to my uncle

Carlos Alberto Pereira de Almeida

1971-2013

Acknowledgements

First and foremost, I would like to acknowledge my primary advisor and dissertation chair, Professor David Rempel whose mentorship, knowledge, and direction was instrumental to the creation of this dissertation and my professional and personal growth. Professor Alice Agogino, my coadvisor and dissertation chair, who has been a role model and provided academic advice. Professor Kathie Hammond for agreeing to be a dissertation chair and challenging and encouraging me to reach my full potential. Professor Hiroshi Ishii for welcoming me into his lab group and providing me the opportunity to increase my academic and professional development. Professor Juan Wachs for his input on Chapter 5. The laboratory personnel, including Betsy Llosa, Matt Camilleri, and Alan Barr who supported, encouraged and came to my rescue countless times. The undergraduate student researchers, Harini Sadeeshkumar, Tevis Miller, and Kunwoo Park for their dedication and commitment to this research. Kirsti Smouse for her editing. And all the study participants whose time and input made this research possible.

My dad, Abel Pereira, whose faith, support, and encouragement has never wavered. The large number of friends and family not listed who provided the foundation and support for me to complete this dissertation. Specifically, Connie and Ozzie Ozyjowski, for their past guidance and patience and their continued advice and friendship. My friends, Jen Boffi, Andre Schirotzek, Sruti Gurunath, Jess Brown, and Nisha Parikh, for their support, encouragement, and understanding. Dan Odell, Vince Lane, Manuel Chirouze, Steve Morin, and Jonathan Sheffi for their friendship and mentorship that had such an impact.

I am grateful for the multiple sources of funding I received in support of this research. This research was supported in part by: a training grant from the National Institute for Occupational Safety and Health (T42 OH008429), the Office Ergonomics Research Committee, and a gift from Microsoft. In addition funding from the Portuguese Pinto/Fialon Graduate Fellowship and the University of California, Berkeley, School of Public Health, Alumni Scholarship.

Chapter 1: Introduction

Scope of Problem

Total personal computer (PC) use in 2008, which predominately use keyboard input, exceeded one billion and is projected to pass two billion in 2014 (Lunden 2008). Computer use now spans nearly all age groups, with 80% of kindergarten students, 91% of elementary school students, and 97% of high school students using computers (National Center for Education Statistics, 2005). Tablet computers are also growing in usage. There are expected to be 665 million media tablets in use by 2016 (Lunden 2012). As of 2012, half of all adults in the US owned a tablet or smart phone (Smith 2012). Tablet input uses a similar QWERTY keyboard layout to that of a PC. However the keys are non-mechanical and the devices have greater mobility. A relatively new input method is gesturing recognition which senses and interprets human gestures. Although gesture interaction is not currently a common computer input, product releases expected this year, such as Leap Motion and MYO, will make gesturing interaction readily accessible to typical consumers (Leap Motion; Leap Motion Inc., San Francisco, CA and MYO; Thalmiclabs, Kitchener, Canada).

Human Computer Interaction and Musculoskeletal Disorders

Overall, there are three types of risk factors linking human computer interaction (HCI) to musculoskeletal disorders (MSDs). The first is biomechanical, such as head rotation, shoulder flexion, mouse use, keyboard height, non-neutral wrist, and telephone use. The second is psychosocial which includes job pressure, fear of job loss, and low support from supervisor and coworkers. The third is work organization which includes long hours on a computer, limited breaks, work deadlines, extensive overtime, surges in workload, and low decision latitude. Other risks include visual demands, glare, bifocal use, age, and gender. This dissertation focuses on addressing biomechanical risk factors.

HCI encompasses the design, study, and planning of the interaction between people and computers including PCs, tablets, and smartphones. Interaction methods include keyboards, mice, trackballs, 2D gesture and 3D gesture. HCI has been linked to MSDs (Gerr 2006). Cumulative one year incidence rates of 10% or more for upper extremity symptoms have been reported among office workers (Gerr 2002; Jensen 2003; Lassen 2004). Approximately a quarter of all cases reporting symptoms result in loss of productivity (van den Heuvel 2007). Typically, productivity loss is due to decreased performance at work. Every year the US economy loses an estimated $45 billion to $54 billion due to MSDs from decreased productivity, compensation, and lost wages (IOM 2001). MSDs can affect the body's nerves, tendons, muscles, joints, and ligaments. Work related MSDs include tendonitis of the hand and wrist, carpal tunnel syndrome, and epicondylitis. Most MSDs develop over time and often occur due to the worker environment such as poorly designed workstations (Kennedy 2010). Repetitive, sustained, or forceful movements may compromise the soft tissues by causing tears, edema and fibrosis of the tendons and compression of the nerves (van Tulder 2007; Helliwell 2004). MSD hand risk factors include sustained awkward postures, rapid or repeated motions, contact stress, and repeated or sustained pinch or grip (Latko 1999; Silverstein 1986). Hand and wrist tendonitis have strong associations with the risk factors of repetition, force, and postures (Harris 2011; Armstrong

1987; Byström 1995; McCormack 1990). Carpal tunnel syndrome caused by swelling of the median nerve traveling through the carpal tunnel (Rempel 1995) has been associated with sustained or repeated non-neutral wrist postures and forceful gripping through a number of epidemiological studies (Becker 2002; Geoghegan 2004; Ferry 2000; Gell 2005; Bonfiglioli 2013; Silverstein 2010. Many HCI interventions promote neutral postures and/or reduction of contact stress to reduce MSD risks.

Several studies have shown correlations between HCI and corresponding MSD and risk factors. One such study surveyed 6,943 computer users at baseline and one year follow up (Kryger 2003). Seven days prevalence of forearm pain was 4.3%. One year incidence of reported symptom cases was 1.3%. Increased risk of new forearm pain was associated with use of a mouse for more than 30 hours per week, and keyboard use more than 15 hours per week.

A recent epidemiological study reported relative risks (RR) of computer use. A prospective cohort study observed 1,951 office workers for two years (Huysmans 2012). Data on self-reported risk factors were collected. Although not significant, a multivariate model found users who self-reported greater than four hours of work per day to have an increased RR of 1.4 (0.9-2.2). Those who reported greater than four hours a day of computer use during leisure time had significantly increased RR of 1.5 (1.1-2.2) compared to those who used less than four hours a day of computer use during leisure time. Females had an increased RR compared to males of 1.4 (1.2-1.8). Older users (40-68) had a higher relative risk of 1.2 (1.0-1.5) compared to younger users. The largest risk was associated with disabling arm-wrist-hand symptoms within the past year with a RR of 4.0 (3.1-5.2). Preventing initial disabling arm-wrist-hand symptoms would remove the largest risk factor according to Huysmans et al. (2012).

In 2004, 206 random graduate students in electrical engineering and computer science were surveyed investigating risk factors associated with upper extremity and neck pain (Schlossberg 2004). Almost half the students had finger, hand, and wrist pain associated with computer use. Seventeen percent and 26% had forearm/elbow and shoulder/neck pain associated with computer use, respectively. Almost two-thirds of all the graduate students had one or more regions with recurrent pain associated with computer use. Ten percent of the students rated the pain as unbearable. The majority of the onset of pain occurred during the first year of graduate school even though computer use went up each year of graduate school.

In summary, upper extremity musculoskeletal disorders (MSDs) are the leading cause of pain and disability among keyboard workers and have been on the rise (Bernard 1997; Tittiranonda 1999). Workers who use keyboards have a prevalence rate of upper extremity MSDs of 20-40% (Bernard 1994; Polanyi 1997). Keyboard users can experience increased rates of MSD with increased keyboard use (Gerr 2006).

HCI Design and MSDs

As described above, biomechanical factors, such as posture, effect development of MSDs. Some HCI design factors have been shown to decrease the risks and rates of MSDs. For example, changes that promote more neutral postures in keyboard height, mouse location and design, and screen location, can decrease regional pain and MSDs (Kryger 2003; Psihogios 2001).

Keyboard Design and MSDs

Several keyboard design factors are linked to MSD risks. For example, abnormal keyboard position, defined as the center of the keyboard placed to the right or left of the trunk, can increase upper extremity symptoms while use of arm/wrist support decreases symptoms (Kryger 2003). Keyboard vertical position has a significant association with neck/shoulder pain and hand/arm problems (Sauter 1991). Keying with inner elbow angle greater than 121°, no head extension, and presence of armrest are associated with lower risks of neck and shoulder symptoms and disorders (Marcus 2002). However, keying with elbow height below the height of the home row (e.g., J key) and using a telephone shoulder rest were associated with greater MSD symptoms and disorders. Horizontal location of the keyboard greater than 12 cm from the edge of the desk was associated with a lower risk of hand and arm MSD symptoms and disorders. Use of a keyboard higher than 3.5 cm above the desk, key activation force greater than 48 grams, and mouse use with radial wrist deviation greater than five degrees were associated with higher MSDs of the hand and arm. Number of hours keying per week was also associated with hand and arm MSD symptoms and disorders. These results suggest that MSD symptoms and disorders could be prevented by addressing workstation and keyboard designs.

Keyboard design has been directly related to user pain severity, functional hand status, and comfort (Tittiranonda 1999). Studies have shown subjective fatigue decreased when keyswitch force was decreased (Radwin 1999) and split keyboards reduced aches, pains, and tiredness (Chen 1994; Marek 1992). For example the Microsoft Natural Keyboard compared to a typical keyboard, demonstrated improving trends of pain severity and hand function following 3 months of keyboard use. The Microsoft Natural Keyboard had an opening angle of 12.0 compared to zero in a typical keyboard and increased lateral inclination; these design features reduced sustained wrist ulnar deviation, forearm pronation, and wrist extension (Rempel 2007). There was also a significant correlation between improvement of pain severity and greater satisfaction with the keyboards. Early research by Kroemer et al. (1972) examined the standard typewriter keyboards. Kroemer et al, suggested that: keys should be arranged in hand grouping to simplify finger motion; separated by hand; and the keyboard sections should be declined laterally to reduce muscular strain. The results suggest that keyboard users may experience a reduction in hand pain with alterative geometry keyboards.

In addition to geometry, keyboard keyswitch design can influence hand pain and MSD risk. Keyswitch design was evaluated with a clinical trial of computer users with hand paresthesias (Rempel 1999). Conventional keyboards, only different in key switch design, were used for twelve weeks. Differences in key switch design resulted in reduction of hand pain and improved physical examination findings.

Narrow wrist rests have shown increased wrist pain (Lassen 2004; Marcus 2002). A randomized control study by Rempel et al. (2006) demonstrated that a forearm support can prevent neck/shoulder disorders and right upper extremity pain.

Changes in lighting and workplace setup have shown significant differences over two to six years (Aarås 2001). Groups with new higher illumination lighting systems reported a significant reduction in visual discomfort. Groups with new work stations that supported their forearms on the table top reported significant reduction of shoulder and neck pain.

Mouse design that promotes more neutral wrist posture has been shown to reduce pain development (Aarås 2001). The study followed participants with previously developed pain and divided them into control and intervention groups. After six months, there was a significant reduction in neck, shoulder, forearm, wrist, and hand pain. The results indicate importance of an increased neutral position of the forearm when using a computer mouse. Additional laboratory tests on speed and accuracy of the intervention mouse showed it fell within the range of typical mice. Another study of the same mouse design demonstrated that it may have protective effects of the ulnar nerve function at the wrist however there were no other significant effects (Conlon 2009).

Notebook computers, like keyboards, have design factors that can influence discomfort and pain. For example, users of notebook computers who placed the computer on a desk reported less discomfort and difficulty of use compared to users who placed the computer on a lap or lap desk (Asundi 2010). Use of a lap desk improved postures compared with the lap. Small notebook mice were found to promote less neutral postures and higher muscle activity (Hengel 2008). Longer term use of smaller mice could increase MSDs from the increased biomechanical exposures. Users reported that while participants preferred smaller mice for portability, the larger mice scored higher on comfort and usability.

Tablets

Tablet computer use has seen large increases in applications such as house controls, books, retail, auto navigation, and home health care (Jana 2011). No national or international guidelines exist for tablet and mobile devices. Case studies have noted potential musculoskeletal risks (Ming 2006; Storr 2007) of increased cellphone use and texting. A mobile hand-held device study among university students and faculty found that neck, shoulder and thumb pain increased with hours of use (Berolo 2011). Laboratory studies of tablet use have demonstrated increased left arm muscle activity (Lozano, 2011) which may increase left arm fatigue and risk for musculoskeletal disorders (Fischer 2009; Werner 2005). One of the few studies of tablet use evaluated seated children using tablets placed on a table (Straker 2008). Compared to desktop computer use, tablet use was associated with more neck and trunk flexion, more flexed and elevated shoulders, and greater muscle activity around the neck. However, there was a greater variation of both posture and muscle activity with tablet use which, the authors noted, may offset the non-neutral postures and higher muscle activity. Tablets have shown higher productivity compared to paper surveys; surveys administered on tablets have more complete and accurate responses (Galliher 2008).

Use of a stylus with a tablet can provide greater accuracy and precision than input with the finger. The additional precision is beneficial to those with limited mobility, especially for older users (Greenstein 1997). However, writing with a pen has been tied to MSDs such as mogigraphia, a special case of tenosynovitis, better known as writer's cramp (Udo 2000). The Udo et al., authors propose that increasing the diameter, and therefore grip area, can reduce the grip pressure and lower the risks of MSDs. A study of ball point pens with a diameter of 8 mm compared to a concave grip diameter of 11.9-13.6 mm found a significant reduction of user pain and right thumb muscle activity with the 11.9-13.6 diameter pen (Udo 1999). Few studies have evaluated the effect of stylus diameter on performance. Wu et al. (2005) and Kotain et al. (2003) found significant differences on performance and subjective preference based on stylus diameter

Gesture Recognition

The design and selection of 3D hand gestures has the potential to create a more intuitive, natural, powerful, and productive human-computer interaction than traditional input devices (Ni 2011; Wachs 2011). It also has the potential to make HCI more comfortable. The imminent release of relatively inexpensive motion capture technology is expected to lead to an explosion of 3D hand gesture input systems and languages. Currently no basic overarching HCI gesturing language has been designed. The ultimate designs of the common gestures and the gesture language for these systems are likely to follow natural language principles, but given past experience, the new gesture languages are not likely to be guided by knowledge of hand postures that are comfortable or follow ergonomic principles. Most sign language interpreters, who typically perform gesturing for up to 2 to 3 hours per day, suffer from hand pain (Rempel 2003). There is a concern that 3D gesturing for HCI may increase MSD risk since gesture input is likely to be done for many hours per day.

Chapters

This dissertation describes four studies that examine how different designs of devices and methods for human computer interaction affect biomechanics, usability, and productivity. Chapters 2 and 3 focus on horizontal and vertical key spacing and its effects on typing speed, error, usability, and biomechanics on users with small and large hands. Chapter 4 focuses on one-handed tablet use and the effects of design features on usability and biomechanics in users with small hands. Chapter 5 focuses on the creation of a 3D gesture language based on user defined commands and consideration of the biomechanical risks of specific gestures.

As computer devices increase in mobility and decrease in size, there is a need reduce the keyboard footprint to meet new size constraints. Decreased key spacing is a possible method. Few studies have evaluated the effects of key spacing on productivity, usability, and biomechanical factors; therefore, international standards that specify the spacing between keys on a keyboard have been guided primarily by design convention set in the 1950's. Current design standards recommend a key spacing of 19 mm. In Chapter 2, experienced male typists with large fingers typed on five keyboards that differed only in horizontal and vertical key spacing (19x19, 18x19, 17x19, 16x19, and 17x17 mm) while typing speed, percent error, fatigue, preference, extensor carpi ulnaris (ECU) and flexor carpi ulnaris (FCU) muscle activity, and wrist extension and ulnar deviation were recorded. The study provides new insight for reduced horizontal key spacing for productivity, biomechanics, and usability. This chapter was accepted by the peer reviewed *Journal of Human Factors*.

The experiments described in Chapter 3 were a continuation of the Chapter 2 methods but focused on vertical key spacing and involved subjects with both large and small hands. Experienced females with small fingers and males with large fingers typed on five keyboards which differed only in horizontal and vertical key spacing (17x18, 17x17, 17x16, 17x15.5, and 18x16 mm) while the same measurements as Chapter 2 were recorded. The study adds to Chapter 2 and provides insight for reduced vertical key spacing for productivity, biomechanics, and usability. Chapter 3 has been accepted by the peer reviewed *Journal of Human Factors*.

Tablets computers are being rapidly adopted in commercial and home settings; however, there are no guidelines on design features of tablets to optimize usability and reduce MSD risks. Chapter 4 evaluates tablet size, weight, orientation, grip shape, texture, and stylus shape on productivity, usability, and biomechanics when the tablet is held with just the left hand. Thirty subjects tested eight tablets and three styluses. Chapter 4 provides insight in tablet size and features for productivity, usability, and biomechanics. These design parameters may be important when designing tablets that will be held with one hand. This chapter has been accepted by the peer reviewed *Journal of Ergonomics*.

Chapter 5 focuses on the development of a user defined 3D gesture language for common HCI commands based on subjects' natural gestures and ergonomic considerations. Usability interviews of 30 subjects covered 34 commands. Post-hoc analysis examined video of the gestures for six factors: 1) posture related risk factors (e.g., extreme wrist extension/flexion, full supination/pronation, asynchronous finger postures, and finger extension); 2) gesture popularity; and user subjective ratings of 3) preference, 4) easiness, 5) effort order, and 6) gesture match. Chapter 5 provides a 3D gesture set created from the previously mentioned six measurements and insight into development of 3D HCI for user defined gesture and ergonomics. This chapter is being submitted to *PLOS ONE Journal* for peer review.

Chapter 6 is a summary of all study findings and includes recommendations for future studies.

Chapter 2: The effect of keyboard key spacing on typing speed, error, usability, and biomechanics: Part 1

Introduction

As laptop computers have become smaller, some laptop designs have accommodated the smaller size by decreasing the spacing between keys. Advantages of a smaller keyboard include a smaller, lighter laptop and improved portability; reduced cost to manufacture; better usability for users with smaller hand sizes and shoulder widths; and reduced reach to the computer mouse (Rempel 2007). However, the key spacing on the majority of laptop and desktop keyboards follows the national and international standards of 19 mm. Mini-keyboards, with key spacing less than the conventional 19 mm, are available on some netbooks and as specialty external keyboards.

The recommended center-to-center key spacing (e.g., key pitch) on keyboards is established by international (ISO) and American (ANSI/HFES) standards (ISO9241-410, 2008; ANSI/HFES 100, 2007). The current ISO and ANSI/HFES standards recommend that the horizontal and vertical distance between adjacent key centers (Figure 1) for keys in the alphanumeric and numeric zones, be 19 mm ± 1 mm. These recommendations are based on conventional industry practice and early research (Clare 1976).

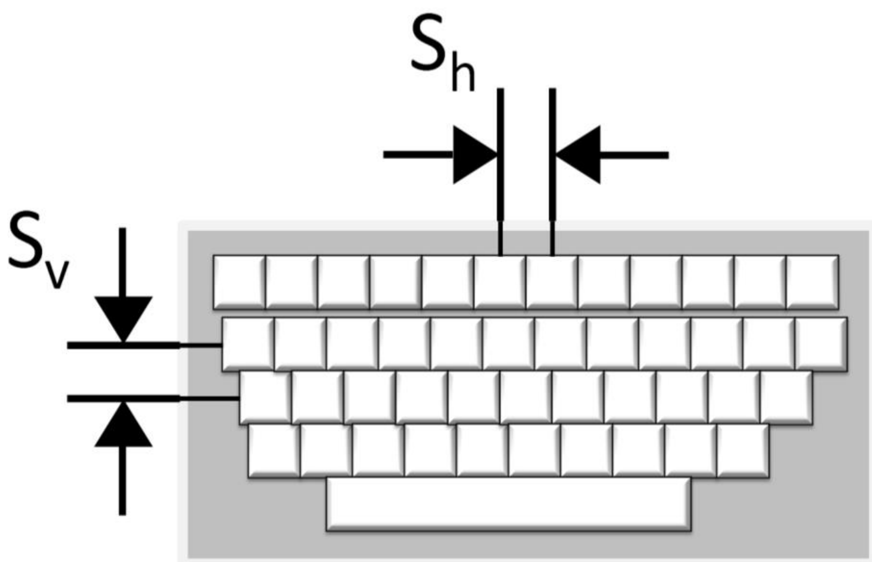


Figure 1. Horizontal (S_h) and vertical (S_v) key spacing on a conventional keyboard. From ANSI/HFES 100-2007 Human Factors Engineering of Computer Workstations, copyright 2007 Human Factors and Ergonomics Society, Inc. Used with permission.

The effect of key spacing on performance has been evaluated in only a few studies. A study from by Yoshitake (1995) in Japan evaluated the relationship between key spacing and typing performance on a conventional keyboard using key spacings of 19.7, 19.1, 16.0, 15.6, and 15.0 mm. For subjects with small fingers (average middle finger length and width of 7.85 cm and 1.90 cm, respectively) there was no difference in performance between keyboards. However, for subjects with large fingers (average middle finger length and width of 8.48 cm and 2.24 cm, respectively) the performance decreased when the key spacing was 16.0 mm or less. The performance of the small-fingered group did not decrease even for the key spacing of 15.0 mm. Applying these results to North American and European populations may be problematic, because the 89th percentile Japanese adult male middle finger length is equal to the 58th percentile US adult male (Nippon Shuppan Service 1996; Pheasant 1996). Other limitations of the study included the small study sample size (N=8), performance based on a single-word task, and the key top sizes differed between keyboards potentially confounding the results. A different study, carried out on numerical keypads, found greater input time and percent error when key spacing was 21 mm compared to 19 mm (Deiniger 1960). Again, the key top sizes differed between conditions.

In 1972, a literature review on keyboard design and operation reported no industry or military standards for basic key characteristics, including spacing. Rather "it is due to design conventions rather than empirical data…that the typical spacing between key centers on these keyboards is 18.1 mm," (Alden 1972). In 1987, Ilg examined 16 keyboard parameters including horizontal and vertical key spacings of 14.3, 16.6, 19.0, and 21.4 mm (Ilg 1987). Thirty users typed on each keyboard while performance, percent error and user preference were recorded. An analysis using a variable that combined the 3 outcomes rated the 19.0 mm horizontal and vertical key spacing as preferable over the other key spacings. However, the study had some shortcomings such as, nonrandomized keyboard order, large difference in key spacing tested, and combining outcomes into a single metric. These studies did not evaluate the effects of key spacing on biomechanical or physiologic measures.

The purpose of this study was to determine whether reducing horizontal or vertical key spacing below the conventional 19 mm key spacing would modify typing speed, percent error, muscle activity, wrist posture and usability among computer users with large fingers. Based the Yoshitake study (1995), it is likely that computer users with small fingers would readily adapt to keyboards with smaller key spacing; therefore, this study focused on subjects with larger fingers – those most likely to be affected by smaller key spacings. The null hypothesis was that there is no difference in typing speed, percent error, muscle activity, wrist posture, preference, or fatigue for touch typists with large fingers when they type on keyboards with reduced key spacing in comparison to a keyboard with standard key spacing. This paper, Part 1, primarily examines spacing in the horizontal direction in touch typists with large fingers. Part 2 primarily examines spacing in the vertical direction in touch typists with large and small fingers.

Methods

In this laboratory study, 37 subjects performed touch-typing tasks in five different keyboard test conditions. The independent variables were the five keyboard spacings. Dependent variables were typing speed, percent error, subjective ratings and rankings of usability and fatigue, keyboard preference, left and right wrist ulnar deviation posture, and forearm muscle activity. The study was approved by the University Institutional Review Board and subjects signed a consent form.

Subjects

Eligibility criteria were male gender, age between 18 to 65 years, the ability to touch type at least 30 words per minute, and a middle finger length (from palmar proximal metacarpophalangeal crease to tip of finger) of 8.7 cm or proximal interphalangeal joint breadth (at proximal interphalangeal joint) of 2.3 cm or more.

Females were not recruited because these finger dimensions are greater than the 99th percentile of the female North American population. 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 in prior studies. A sample size of 30 was estimated using a two tailed alpha of 0.05, a beta of 0.80, and the mean and standard deviation of typing speed of large fingered typists from the Yoshitake study (1995).

The study population had a mean right middle finger length of 8.74 cm ± 0.30 cm (range 7.65 to 9.47 cm; 8.61 to 97.5 percentile) and a right mean middle finger width of 2.22 cm ± 0.15 cm (range 1.91 to 2.51 cm; 1.25 to 94.3 percentile). Most subjects qualified on finger length. Right hand length (palmar distal wrist crease to end of middle finger) was also recorded. The study population had a mean right hand length of 11.5 cm ± 0.53 cm (range 10.6 to 12.7 cm). The finger length and breadth thresholds were the 75th percentile based on male hand anthropometry from the US military (Greiner 1991). The mean subject height and weight were 183.4 cm ± 8.4 cm and 88.1 kg ± 20.2 kg.

Keyboard Test Conditions

A customizable keyboard system (DX1; Ergodex, Mountain View, CA) was used to build five keyboards that differed only in horizontal and vertical key spacing (Figure 2). Four keyboards varied in horizontal key spacing 19.0, 18.0, 17.0, and 16.0 mm (all with 19.0 mm vertical key spacing) and one keyboard had a horizontal and vertical key spacing of 17.0 mm. Accuracy of key spacing was ±0.1 mm. All keyboards were the conventional QWERTY layout and did not include a backspace. The dimensions of the tops of all key caps were 14.7 mm horizontally and 13.7 mm vertically. Each key was individually tested and the key activation force ranged from 63 to 77 grams-force. The bases of the keys for some keyboards were shaved to meet the key spacing requirements but this did not alter the function or force displacement characteristics of the keys.

Figure 2. Keyboard with 19x19 mm key spacing.

Practice Session

On the day of the study, subjects first warmed up by touch-typing on the 16x19 mm keyboard for five ten-minute sessions with three-minute breaks between sessions. Before continuing with the experiment, subjects rested for 15 minutes.

A typing program (Typing Master Pro, Helsinki, Finland) presented text and highlighted and underlined the word to be typed, on the screen, which was typed by the subjects. Typing passages were from news articles and books with grammar at the 8^{th} or 9^{th} grade reading level (McLaughlin 1969). Passages did not include numbers or punctuation other than capitalization that required shift key use. All practice sessions contained the same five passages given in the same order. The program calculated gross typing speed and percent error. Percent error was equal to incorrectly typed words multiplied by the average word length of five, divided by total keystrokes, and reported as a percent. Gross typing speed was equal to total keystrokes divided by typing duration (e.g., keystrokes per minute (KPM)). KPM was divided by the standard word length of 5-keystrokes to calculate typing speed in word per minute (WPM). WPM is a common metric for reporting productivity (Simoneau 2003; Rempel 2007).

Workstation Set-up

The subjects were provided a chair with an adjustable height seat pan, adjustable back-support angle and tension, and five casters (Aeron, Herman Miller, Zeeland, MI). The work surface was adjustable in height and the keyboards and a conventional 2-button mouse could be placed at any location on the work surface. The monitor (20 inch diagonal) was adjustable in horizontal and vertical tilt angle and distance. Prior to the start of the experiment, chair height was adjusted so participants' feet rested comfortably on the floor, work surface height was set to subject elbow height, and the keyboard was placed 18 cm from the edge of the work surface in front of the subject. Subjects were familiarized with the adjustments and during the practice session were instructed to adjust the workstation and keyboard to the most comfortable position. During the experiment subjects were not permitted to alter workstation or keyboard position.

Typing Tasks

A random number generator was used to assign test order of keyboards and typing passages. For each keyboard test condition, subjects typed three of fifteen possible passages in 5-minute blocks. All subjects typed all fifteen passages. Productivity measurements were calculated from the average of the three trials per keyboard condition. They were instructed to type as fast but as accurately as possible. They took a 1-minute break between blocks and a 5-minute break between keyboard test conditions.

Usability and Fatigue Ratings

After each keyboard was used, usability and fatigue were assessed with the ISO keyboard questionnaire (ISO9241-410; 2008). The seven questions included force required to activate the keys, keying rhythm, fatigue in hands or wrists, fatigue in arms, fatigue in shoulders, posture required for keying, and overall use. At the end of the study, the keyboards were rank ordered from least to most favorite.

Forearm Electromyography

Muscle activity of two muscles that move the wrist in ulnar deviation, extensor carpi ulnaris (ECU) and flexor carpi ulnaris (FCU), were recorded with surface electromyography (EMG) (TeleMyo 2400T, Noraxon USA Inc, Scottsdale, AZ). Self-adhesive silver-to-silver chloride snap electrodes (active diameter of 10 mm and a center-to-center distance of 20 mm) were placed on cleaned, shaved skin using anatomical landmarks (Perotto 2005). EMG activity of both muscles was sampled from both the right and left arm at 1500 Hz. The data were normalized to the EMG activity during maximum exertion obtained by having the subject perform three three-second maximum voluntary contractions (MVC) for each muscle (Shergill 2009). The MVC value for the ECU and FCU were calculated from the highest value of an averaging 1000 ms moving window across the three maximum exertions in resisted wrist ulnar deviation while the forearm was horizontal in pronation and the wrist in a neutral posture.

Wrist Posture Measurement

Wrist flexion/extension and ulnar/radial deviation were measured continuously for both wrists using two inline electrogoniometers (2D goniometer SG-65, Noraxon USA Inc, Scottsdale, AZ). The goniometers were secured to the dorsal surface of the hand and distal forearm and calibrated with the wrist in neutral (0 degrees of flexion, 0 degrees of ulnar deviation) and the forearm in pronation. Goniometer output was recorded and reported as degrees deviated from neutral posture.

Statistical Analysis

Differences between keyboards were evaluated using repeated-measures analysis of variance (RMANOVA) with the Tukey follow-up test for mean typing speed, percent error, and 50% amplitude probability density functions (APDF50) of the EMG (SAS Institute, Cary, NC). Trial order was also assessed with RMANOVA. Differences in usability scores, fatigue scores, and keyboard preference were analyzed using Friedman's matched group analysis of variance test with Nemenyi multiple comparison test.

Results

Gross typing speed was significantly slower ($p < 0.001$) and percent error was significantly higher ($p < 0.001$) for 16x19 compared to the other key spacings (Figure 3). There were no significant typing speed or percent error differences between the other key spacings, including vertical spacing of 19mm and 17mm. There was no significant effect of trial order on typing speed or percent error, indicating no learning effect. In addition, there were no significant changes in any of the subjective measures, such as fatigue, with respect to time or keyboard order.

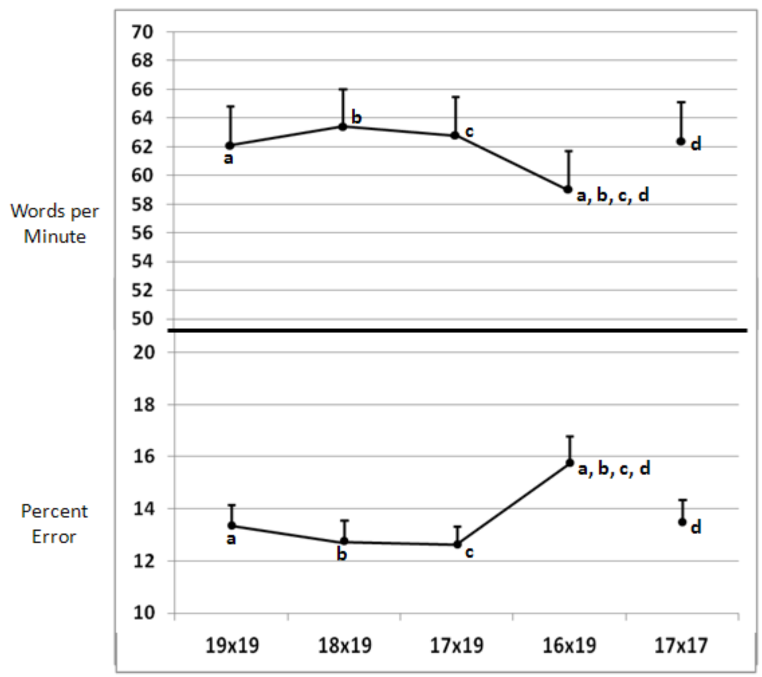


Figure 3. Mean words per minute and percent error by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are SEM. (N=37).

Median muscle activity (e.g., APDF50) and mean wrist posture by keyboard are summarized in Figure 4. Significant differences were observed between keyboards for APDF50 muscle activity for the left ECU ($p = 0.008$), right ECU ($p < 0.001$), and right FCU ($p < 0.001$). For the left ECU, muscle activity was significantly greater for the 19x19 keyboard compared to the 17x19 and 17x17 keyboards. For the right ECU, muscle activity was significantly greater for 19x19 than all other keyboards. For the right FCU, muscle activity was significantly greater for 19x19 than 17x19 and 17x17. In addition, right FCU muscle activity was greater for 18x19 compared to 17x17. There were no significant differences between keyboards for the left FCU ($p = 0.085$).

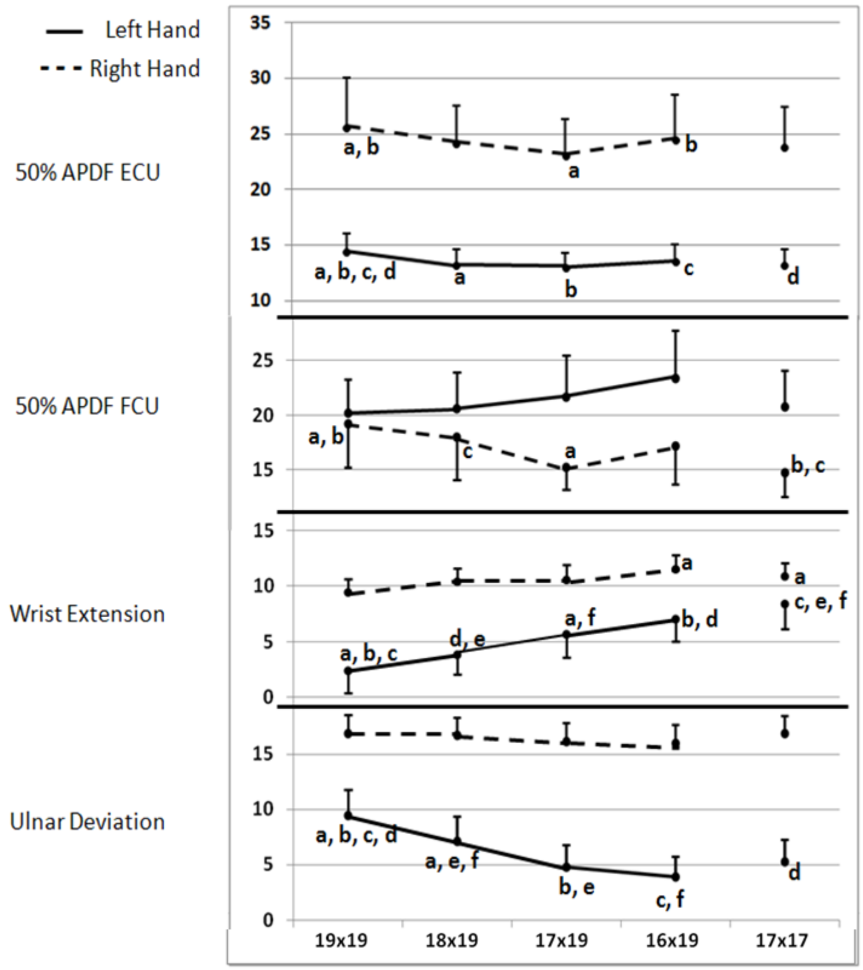


Figure 4. Muscle activity, wrist extension and ulnar deviation during typing by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are SEM. (N=35).

Left wrist extension was significantly greater for 17x17 compared to 19x19, 18x19, and 17x19 ($p < 0.001$). It was also significantly greater for 16x19 compared to 19x19 and 18x19 and it was significantly greater for 17x19 than 19x19. Right wrist extension was significantly greater for 16x19 than 17x17 ($p < 0.001$). Left wrist ulnar deviation was significantly greater for 19x19 when compared to all other keyboards ($p < 0.001$). It was also significantly greater for 18x19 compared to 17x19 and 16x19. For right ulnar deviation, no significant differences between keyboards were observed ($p = 0.14$). Average keyboard placement from the edge of the work surface was 6.5 (± 3.7) cm.

Subjective fatigue and usability ratings are summarized in Figure 5. Across all subjective ratings, 16x19 received the worst ratings compared to the other keyboards, while the differences between the other keyboards were not large. Specifically, for *force required to activate keys* and *keying rhythm*, 16x19 was rated significantly worse compared to all other keyboards ($p < 0.001$). For *fatigue in hands or wrists*, 16x19 was rated worse compared to 19x19 and 17x19 ($p = 0.001$).

Fatigue in arms was significantly rated worse for keyboard 16x19 compared to 19x19 ($p = 0.005$). For *fatigue in shoulders*, 16x19 was rated significantly worse than keyboards 19x19, 18x19, and 17x17 ($p < 0.001$). *Posture required for keying* was rated significantly worse for 16x19 compared to 18x19 and 17x19 ($p < 0.001$). Overall, subjects least *preferred* 16x19 in comparison to the other keyboards ($p < 0.001$). There were no significant differences in preference between the other keyboards.

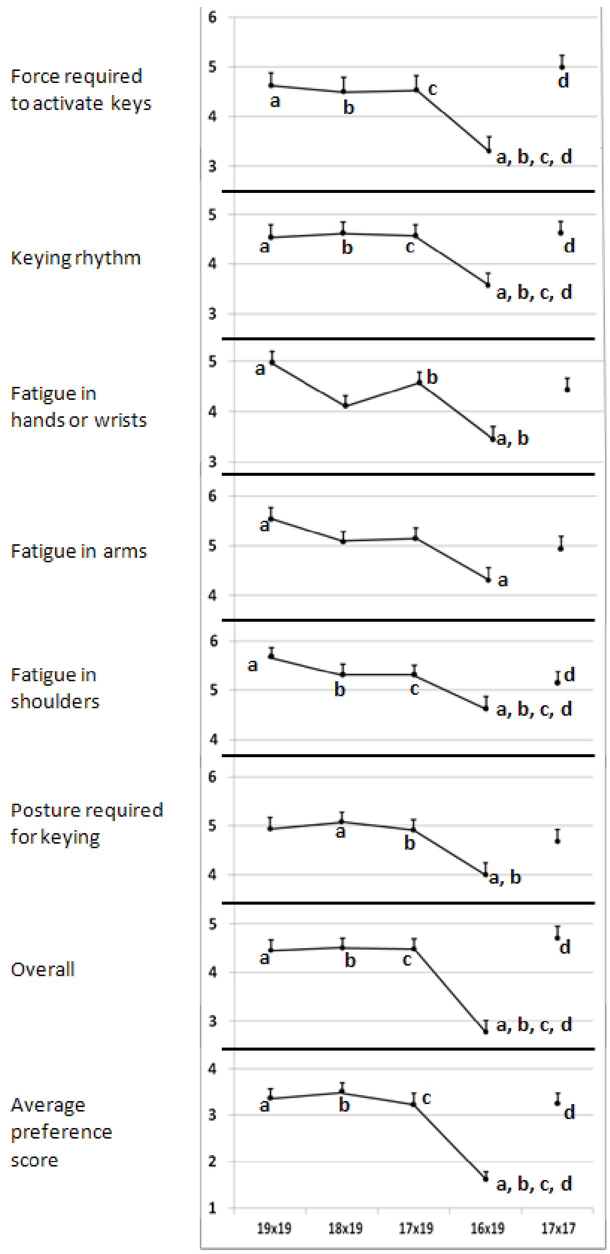


Figure 5. Subjective usability ratings of keyboards (1=poor characteristic and 7=good characteristic). Significant differences between keyboards are noted by a common superscript (Friedman's test and Nemenyi follow up). For preference, keyboards were rank ordered from 1-least favorite to 5-most favorite. Error bars are SEM. (N=37).

Discussion

No significant differences in gross typing speed, percent error, and subjective usability ratings were measured between the keyboards with 17, 18 and 19 mm horizontal key spacing. However, typing speed, percent error, and usability ratings were significantly worse for the keyboard with horizontal key spacing of 16 mm compared to the other keyboards. For vertical key spacing (e.g., 17 and 19 mm) there was no significant difference in these outcome measures. These findings match those of Yoshitake (1995) who reported that subjects with large fingers had no difference in typing speed when the horizontal and vertical key spacing was 16.7 or 19.0 mm. However, the typing speed decreased when horizontal and vertical key spacing was 16.0 mm or lower. Although the Yoshitake study (1995) did not specifically report typing error rates for large fingered subjects, the combined data, across all finger sizes, showed a trend of increasing errors at horizontal and vertical key spacing of 16mm.

Typically, during typing on a conventional keyboard, percent error decreases with decreasing typing speed. However, typing speed decreased and percent error increased with the horizontal 16 mm key spacing. This supports a finding that decreased horizontal key spacing, not changes in typing speed, was the cause of increased error. Increased error may be due to striking two keys because the fingertips are too large or because the precision of finger motor control is poor for the horizontal 16 mm spacing. In addition, one might expect that smaller key spacing would allow for faster typing speeds due to the shorter travel distance of the fingers. The decrease in typing speed implies that biomechanical factors, such as fingertip size or inadequate motor control precision, are interfering with productivity measurements.

Users reported an increase of key force to activate keys with horizontal 16 mm key spacing compared to all other spacings. Since the actual mean key activation forces were the same for all keyboards, this perception may have been due to fingers touching each other with the horizontal 16 mm key spacing. There was a non-significant increase in forearm muscle activity levels for the horizontal 16 mm spacing compared to both the 17x19 mm and 17x17 mm spacing, which could have been due to the interference of adjacent fingers, such as crowding on home row or while reaching for adjacent keys. For the horizontal 16 mm spaced keyboard, a post-hoc evaluation of the correlations between productivity and error and finger length and breadth, revealed a small correlation ($r=0.33$) between increasing finger width and increasing error and decreasing productivity and an opposite relationship with finger length ($r=-0.40$). These findings suggest that key spacing may be limited by finger width, not finger length.

Overall, however, the effects of key spacing on wrist posture and forearm muscle activity were minimal. There was a trend for muscle activity to increase in the left and decrease in the right forearm with decreasing horizontal key spacing, but the differences were low, only 2-5%. Similar, small differences for the FCU and ECU, were observed by Simoneau et al. (2003) when evaluating the effects of the slope of a conventional keyboard on forearm muscle activity. In a different study comparing auditory feedback, Gerard et al. (2002) reported significant differences in forearm muscle activity of 1-2% between keyboard conditions from two hours of recorded EMG signals. Ergonomic modifications for meat packing jobs have reported reductions of 2-5% in forearm muscle effort (Cook 1999). Therefore, while the observed differences are small, these small differences may be important for tasks preformed for many hours a day.

In this study, as the key spacing decreased, left wrist ulnar deviation decreased and left wrist extension increased. A similar pattern occurred on the right side but the differences were not significant. We previously observed a similar relationship between extension and ulnar deviation when other keyboard design features were modified (e.g., split keyboard) (Rempel 2007).

A limitation of the study was the simple alpha typing task without numbers or punctuation. It is possible that increased numerical input or input using the punctuation keys could have altered the findings. Another potential limitation was the short duration of keyboard use. However, the finding that typists performed equally well on 17, 18, or 19 mm horizontal spacing, suggests that these result are likely to be stable over time. Studies evaluating other characteristics of keyboards (e.g., stiffness or auditory feedback) have observed stable performance across multiple days of testing (Gerard 1999; Gerard 2002). For the keyboard with 16 mm key spacing in our study the lack of performance changes across the three test trials suggests that the measured differences were due to the smaller key spacing and not to a lack of familiarity with the small key spacing. Another limitation of the study is that it did not include typists with small fingers and did not include females. Subjects with smaller fingers may have demonstrated improved typing performance with the smaller key spacing. Indeed the results of Yoshitake (1995) suggest that typists with small fingers will do well with key separations down to 15 mm of horizontal and vertical key spacing.

In conclusion, this study finds that there is little difference in typing speed, percent error and usability measures between keyboards with horizontal key spacing between 17 and 19 mm among typists with large fingers. However, a keyboard with horizontal key spacing of 16 mm was associated with a significant reduction in productivity measures and usability ratings. Differences in wrist posture and forearm muscle activity were small, on the order of 2-5%. The effect of key spacing on muscle activity was balanced between the right and left arms. An interesting effect of key spacing on posture was the increased left wrist extension with horizontal or vertical key spacing of 16 or 17 mm, respectively. This may be mitigated by the observed, simultaneous reduction in ulnar deviation. Based on these findings, keyboard designers are encouraged to consider designing keyboards with horizontal and vertical key spacing of 17 or 18 mm to gain the benefits of smaller keyboards (e.g., smaller and lighter laptops; reduced cost to manufacture; better usability for smaller users; and reduced reach to the computer mouse) while still accommodating the needs of typists with large fingers.

Chapter 3: The effect of keyboard key spacing on typing speed, error, usability, and biomechanics: Part 2

Introduction

This study complements "The Effect of Keyboard Key Spacing on Typing Speed, Error, Usability, and Biomechanics: Part 1" (Pereira 2012) that evaluated the effects of keyboard spacing, primarily in the horizontal direction, on male typists with large hands. As previously discussed, international and national standards (ISO9241-410, 2008; ANSI/HFES 100, 2007) recommend key spacings of 19x19 mm; a recommendation that is based on design convention rather than empirical data. Potential advantages of a smaller keyboard include smaller, lighter, and more portable laptops; reduced manufacturing costs; improved usability for users with smaller hand sizes; and reduced reach to the computer mouse (Rempel 2007).

In Part 1, we primarily evaluated the effects of horizontal key spacing (19x19, 18x19, 17x19, 16x19, and 17x17 mm [horizontal x vertical]) on typing speed, percent error, usability, forearm muscle activity, and wrist posture (Pereira 2012). The conventions for horizontal and vertical spacing are illustrated in Figure 1. Subjects were experienced male typists (N=37) with large fingers (75^{th} percentile: middle finger length ≥ 8.7 cm or finger breadth of ≥ 2.3 cm; Greiner 1991). Typing speed, error and usability ratings were significantly worse for the keyboard with the 16x19 mm key spacing compared to the other keyboards. Biomechanical measures were also worse for this keyboard. There were few differences in productivity, usability and biomechanics between horizontal key spacings of 19, 18 or 17 mm.

A similar study by Yoshitake (1995) also found that for subjects with large fingers (average middle finger length and proximal interphalangeal joint (PIP) width of 8.48 cm and 2.24 cm, respectively) the performance was lower when the key spacing was 16.0 mm or less. However, for subjects with small fingers (average middle finger length and PIP width of 7.85 cm and 1.90 cm, respectively) there was no difference in performance between keyboards even for the key spacing down to 15.0 mm. Limitations of the study included the small study sample size (N=4 for the large and small finger group), performance was based on a single-word task, and the key top size changed with key spacing potentially confounding the results.

The findings in Part 1, on effects of changes in horizontal key spacing, may not apply to vertical key spacing. Wrist and finger motion and motor control are different in horizontal (ulnar/radial) and vertical (extension/flexion) directions. Change in key spacing in the vertical direction requires changes in wrist and extrinsic finger extensor/flexor as well intrinsic finger flexor/extensor motor control (Dennerlein 1998; Repp 2005). Changes in key spacing in the horizontal direction requires the same changes plus changes in the finger adduction and wrist ulnar/radial motor control. Part 1 also did not include typists with small fingers; therefore, the Yoshitake (1995) finding, that typing productivity for subjects with small fingers was not influenced by key spacing, could not be confirmed.

The primary purpose of this, Part 2, study was to determine whether reducing vertical key spacing would modify typing speed, percent error, muscle activity, wrist posture and usability ratings among female typists with small fingers and male typists with large fingers. The alternative hypothesis was that there is a difference in typing speed, percent error, muscle activity, wrist posture, preference, or fatigue for female typists with small fingers or male typists with large fingers when they type on keyboards with reduced vertical key spacing in comparison to 18 mm key spacing.

Methods

Detailed methods can be found in Part 1 (Pereira 2012) but a summary of methods including differences from Part 1 are presented here. In this laboratory study, 26 female subjects with small fingers and 26 male subjects with large fingers performed touch-typing tasks on five different keyboard test conditions. Other inclusion criteria were age between 18 and 65 years and the absence of upper extremity symptoms. The independent variables were the keyboard key spacings, primarily vertical spacing, and hand size. Dependent variables were typing speed, percent error, left and right wrist ulnar deviation posture, forearm muscle activity, subjective ratings and rankings of usability, fatigue, and keyboard preference. The study was approved by the University Institutional Review Board and subjects signed a consent form.

Subjects

Females were required to have a right middle finger length (from palmar proximal metacarpophalangeal crease to tip of finger) of less than 7.71 cm or a proximal interphalangeal (PIP) joint breadth of less than 1.93 cm. Males were required to have a right middle finger length of at least 8.37 cm or PIP joint breadth of at least 2.24 cm. The finger length and breadth thresholds were based on the 50th percentile values from Greiner et al. (1991). Right hand length (palmar distal wrist crease to end of middle finger), hand breadth (between radial side of metacarpal II and ulnar side of metacarpal V), and middle finger distal interphalangeal (DIP) joint breadth, were also recorded. The subject population hand anthropometry measures and the corresponding population percentiles are summarized in Table 1. The mean female and male subject height and weight were 161.7 ± 4.7 cm and 54.5 kg ± 3.5 kg and 181.9 ± 4.7 cm and 81.2 kg ± 13.2 kg, respectively.

Table 1. Mean female and male right middle finger and hand anthropometry values, ranges, and population percentiles.

	Female (N=26)			Male (N=26)		
Measurement	Mean cm (SD)	Range cm	% (Range)	Mean cm (SD)	Range cm	% (Range)
Middle finger length	7.39 (0.40)	6.65-8.30	26 (3-87)	8.57 (0.26)	7.80-9.09	64 (9-90)
PIP width	1.80 (0.11)	1.67-2.00	15 (2-70)	2.30 (0.10)	2.10-2.46	65 (17-91)
DIP width	1.62 (0.12)	1.46-1.80	20 (1-80)	1.99 (0.08)	1.85-2.09	55 (20-78)
Hand length	17.0 (0.87)	15.7-19.1	20 (1-89)	19.4 (0.83)	18.4-21.4	50 (15-98)
Hand width	7.69 (0.31)	7.14-8.36	25 (1-86)	9.13 (0.86)	8.57-10.0	60 (14-99)

Keyboard Test Conditions

A customizable keyboard system (DX1; Ergodex, Mountain View, CA) was used to build five conventional QWERTY layout keyboards that differed only in vertical and horizontal and key spacing. Four keyboards varied in vertical key spacing 18.0, 17.0, 16.0, and 15.5 mm (all with 17.0 mm horizontal key spacing) and one keyboard had a vertical key spacing of 16.0 mm and horizontal spacing of 18.0 mm. The conventions for key spacing are presented in Figure 1. The 19 mm vertical spacing was not tested because our previous study found no difference in outcomes between vertical key spacings of 17 and 19 mm.

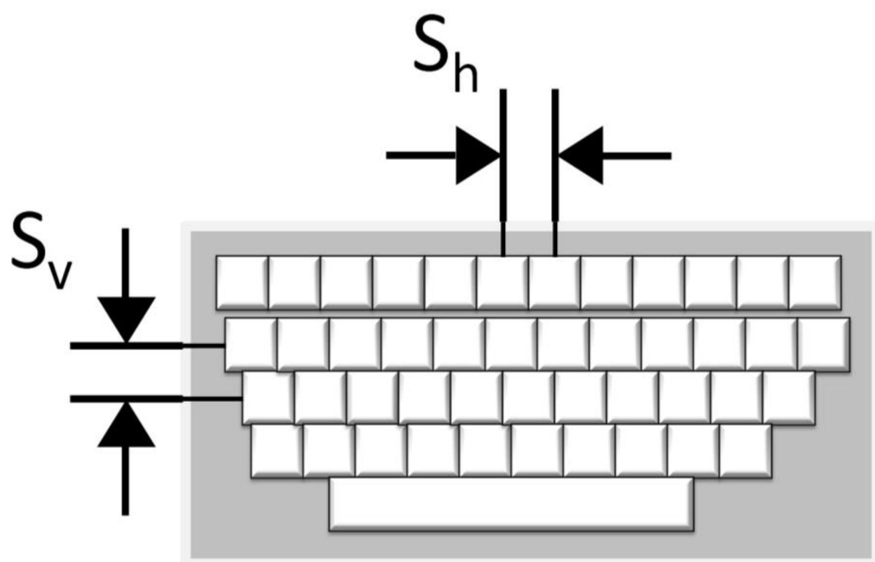


Figure 1. Horizontal (S_h) and vertical (S_v) key spacing on a conventional keyboard. From ANSI/HFES 100-2007 Human Factors Engineering of Computer Workstations, copyright 2007 Human Factors and Ergonomics Society, Inc. Used with permission.

Set-up and Typing Tasks

Subjects warmed up for 50 minutes on the 17x16 keyboard and during that time the chair and work surface height were adjusted to the most comfortable configuration. After the warm up session, subjects were not permitted to adjust the setup. They then completed three 5-minute typing tasks with each keyboard. A random number generator assigned keyboard test order. For each keyboard test condition, subjects typed three of fifteen possible passages in 5-minute blocks. Subjects were instructed to type as fast but as accurately as possible.

Objective Outcome Measures

Gross typing speed and percent error were calculated from the typing tests. Surface electromyography (EMG) of the extensor carpi ulnaris (ECU) and flexor carpi ulnaris (FCU) were recorded (TeleMyo 2400T, Noraxon USA Inc, Scottsdale, AZ) and summarized as 50% amplitude probability density functions (APDF50). Wrist flexion/extension and ulnar/radial deviation from neutral were measured continuously for both wrists using electrogoniometers (2D goniometer SG-65, Noraxon USA Inc, Scottsdale, AZ).

Subjective Usability and Fatigue Ratings

After each keyboard was tested, subjects completed a usability and fatigue questionnaire. At the end of the study, subjects ranked the keyboards from least to most preferred.

Statistical Analysis

Differences in objective outcome measures between keyboards were evaluated using repeated-measures analysis of variance (RMANOVA) with Tukey follow-up. Differences in subjective outcomes between keyboards were evaluated with Freidman's matched group analysis of variance with Nemenyi multiple comparison test (SAS Institute, Cary, NC).

Results

For both females with small fingers and males with large fingers, gross typing speed was significantly slower ($p < 0.001$ and $p = 0.006$, respectively) and error rate was significantly higher ($p < 0.001$) for the 15.5 mm vertical key spacing compared to the other vertical key spacings (Figures 2 and 3). There were no significant differences in typing speed or error rate between the keyboards with key spacings of 16, 17 and 18 mm. There was no significant effect of trial order on typing speed or percent error, indicating no learning effect.

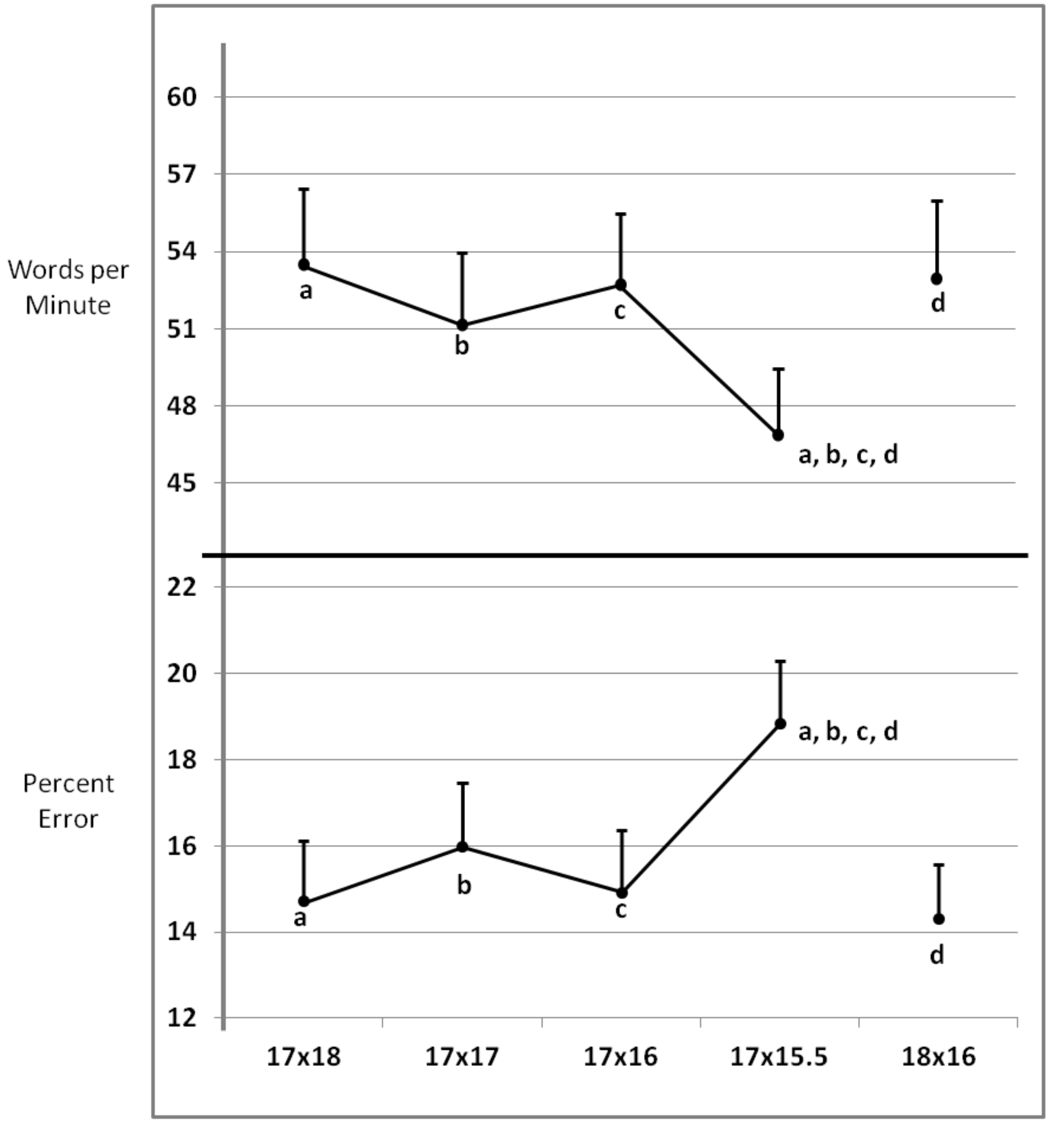


Figure 2. Females with small fingers: productivity and error. Mean words per minute and percent error by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. N=26. Error bars are SEM.

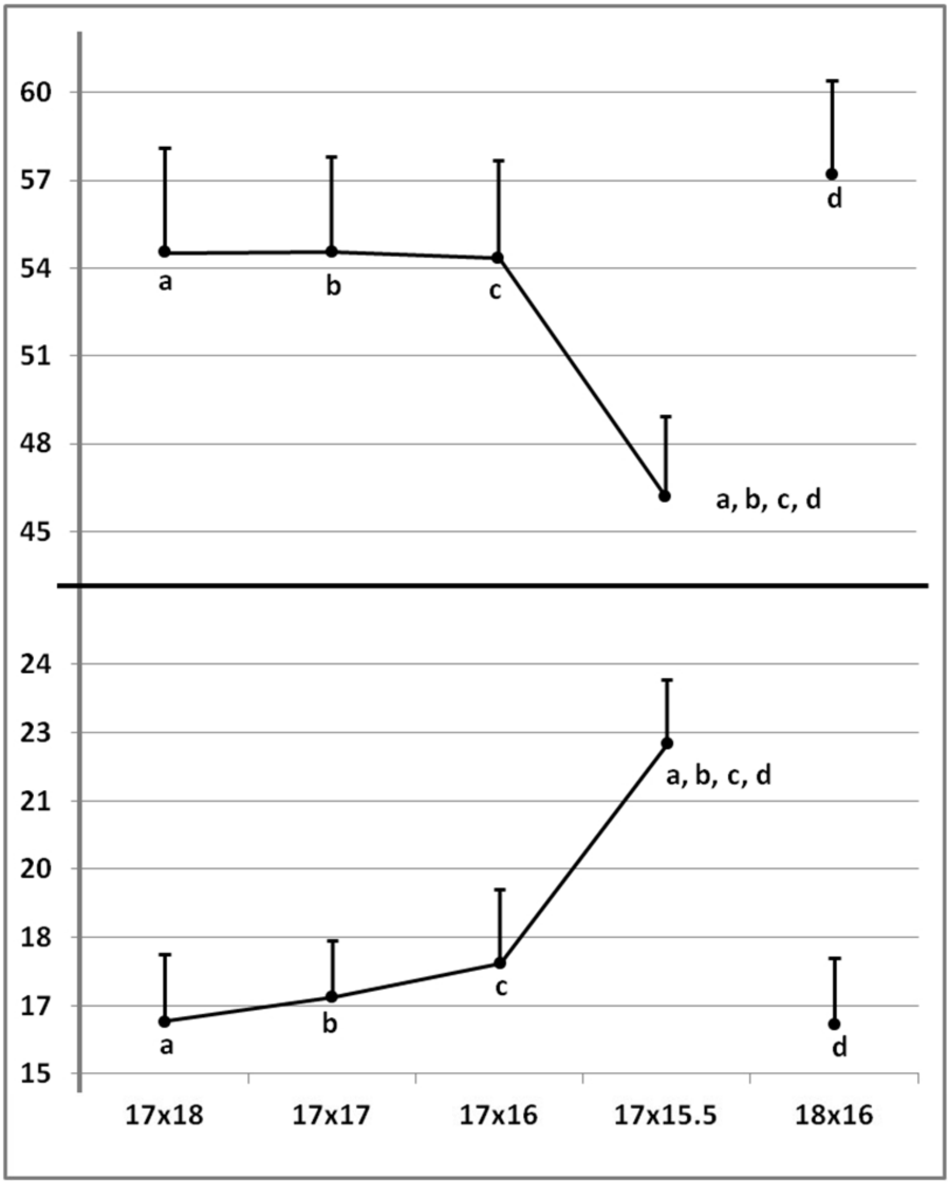


Figure 3. Males with large fingers: productivity and error. Mean words per minute and percent error by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. N=26. Error bars are SEM.

Median muscle activity and wrist posture by keyboard are summarized in Figures 4 and 5. No significant differences in median muscle activity were observed between keyboards for either females with small fingers or males with large fingers. Mean right wrist extension in females with small fingers was significantly greater for 17x15.5 compared to the other keyboards (p = 0.004). Mean left wrist extension in males with large fingers was significantly greater for 17x15.5 compared to 17x17 (p = 0.04). Average keyboard placement from the front edge of the work surface to the center of the home row keys was 22.6 (± 5.5) cm.

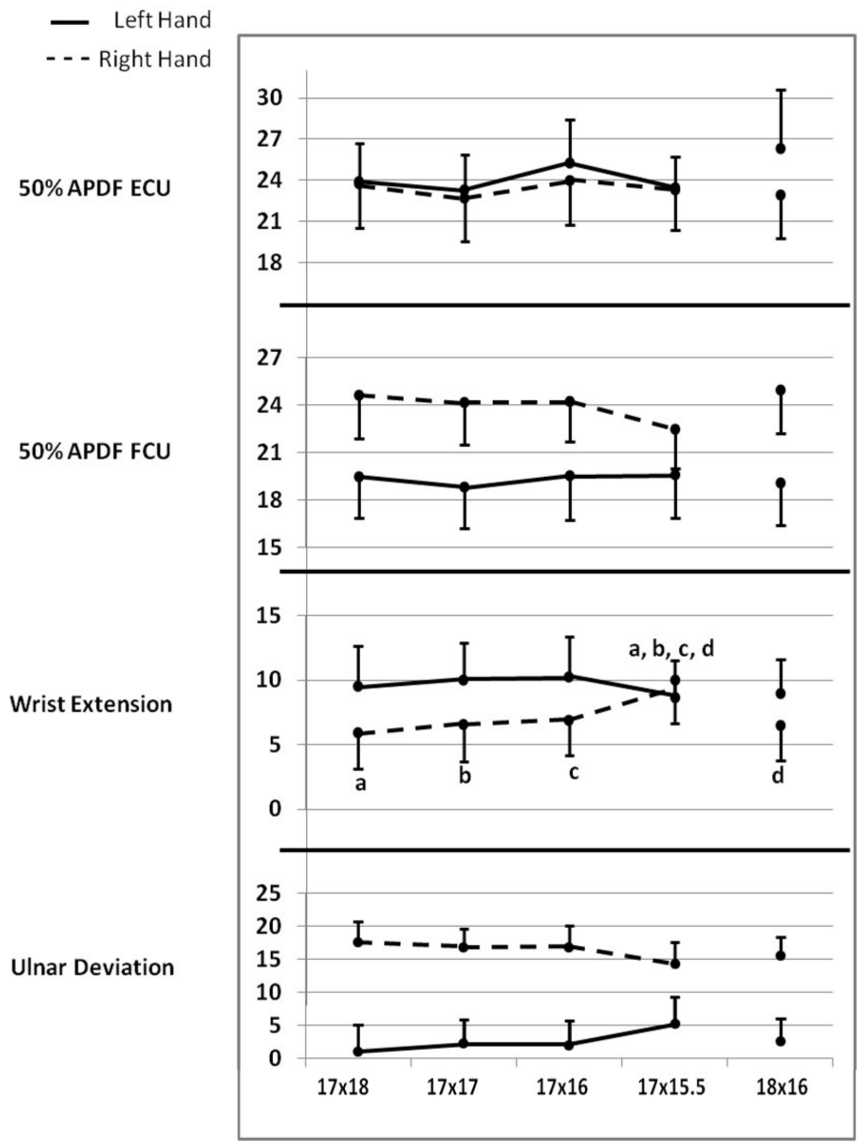


Figure 4. Females with small fingers: median muscle activity and mean wrist extension and ulnar deviation during typing by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are SEM.

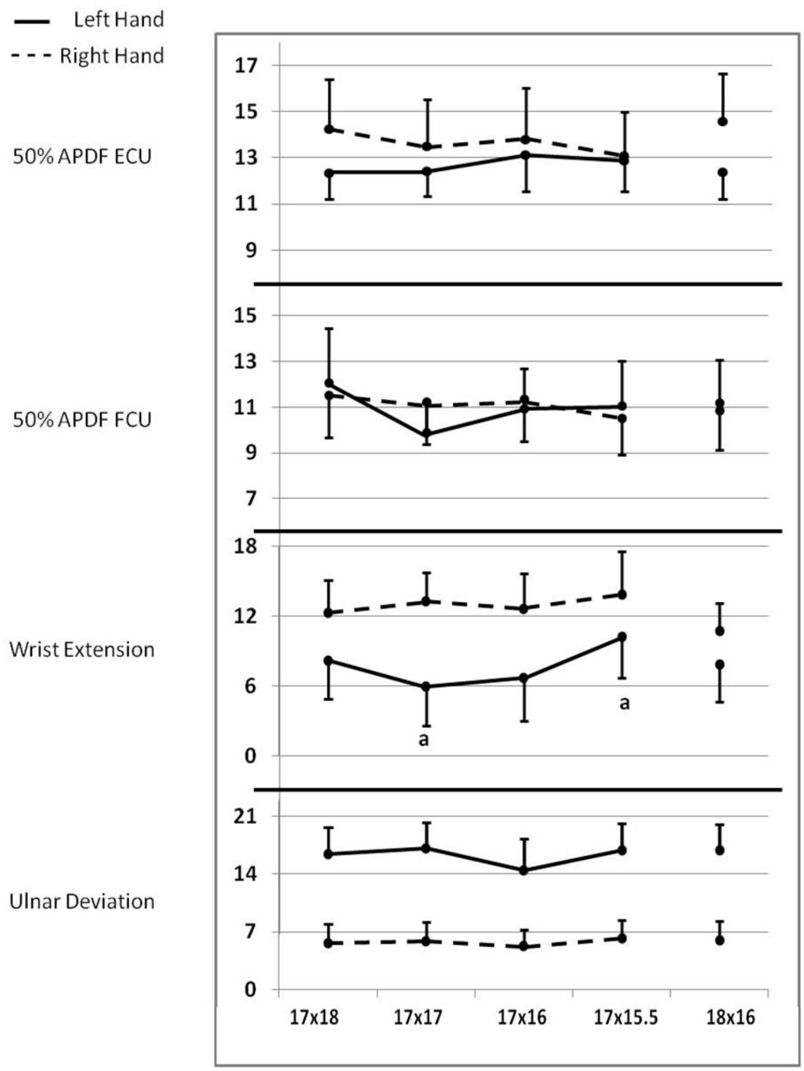


Figure 5. Males with large fingers: median muscle activity and mean wrist extension and ulnar deviation during typing by keyboard (key spacing: horizontal x vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are SEM.

Subjective comfort and usability ratings are summarized in Figures 6 and 7. Across all subjective ratings, among both females with small fingers and males with large fingers, 17x15.5 received the worst ratings, compared to the other keyboards. The differences in ratings between keyboards other than 17x15.5 were not large. Male subjects, when judging *force required to activate keys* and *keying rhythm*, rated 17x15.5 significantly worse compared to all other keyboards ($p < 0.001$). On the same outcome, females rated 17x15.5 significantly worse than 17x18 or 17x17 ($p < 0.001$). For *fatigue in hands or wrists*, males reported 17x15.5 to be worse compared to 17x18, 17x17 or 17x16 ($p < 0.001$) while female subjects reported that 17x15.5 was worse than 17x18, 17x17, or 18x16 ($p < 0.001$). There were no significant differences in ratings for *fatigue in arms* for females or males and no significant differences in *fatigue in shoulders* and *posture required for keying* for females. For *fatigue in shoulders*, males rated 17x15.5 significantly more fatiguing than 18x16 ($p = 0.005$). For p*osture required for keying*, males rated

17x15.5 significantly worse than all other keyboards ($p < 0.001$). For *overall* ratings, female subjects rated 17x15.5 significantly lower than 17x18 or 17x17 ($p < 0.001$) and male subjects rated 17x15.5 significantly lower compared to all other keyboards ($p < 0.001$). Females least *preferred* the 17x15.5 keyboard compared to the 17x18 and 17x17 keyboard and *preferred* the 17x17 keyboard over the 17x16 ($p = 0.001$). Male subjects least *preferred* the 17x15.5 compared to all other keyboards ($p = 0.005$).

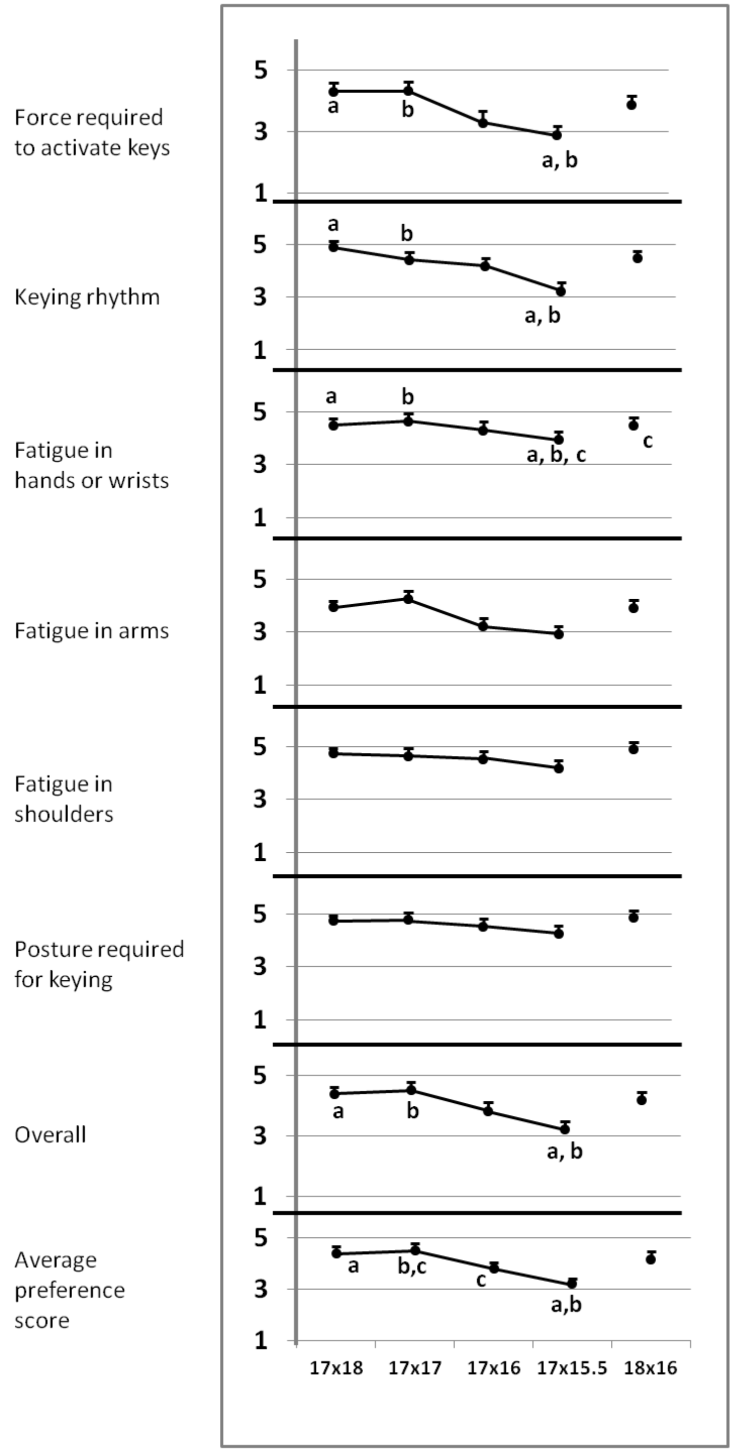


Figure 6. Female with small fingers: mean subjective usability ratings of keyboards (1=poor characteristic and 7=good characteristic). Significant differences between keyboards are noted by a common superscript. For preference, keyboards were rank ordered from 1-least favorite to 5-most favorite. Error bars are SEM.

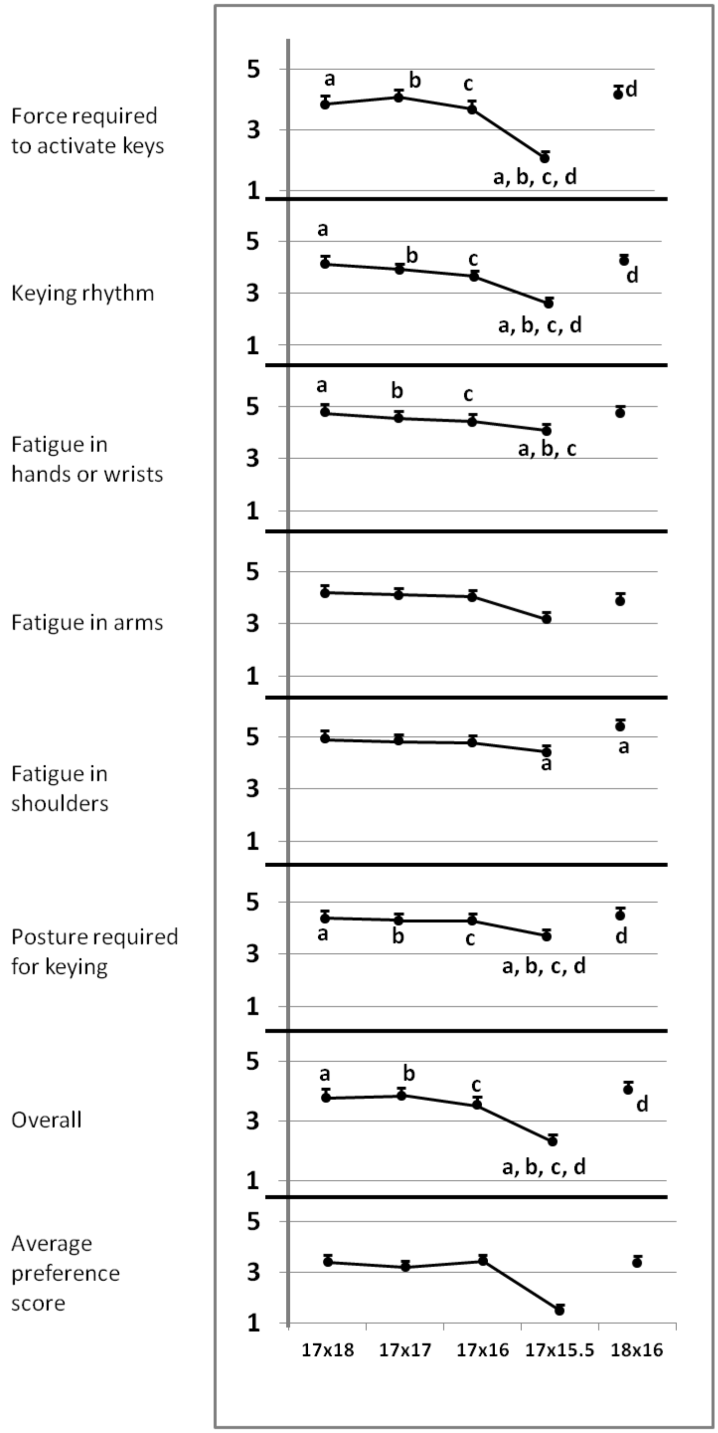


Figure 7. Males with large fingers: mean subjective usability ratings of keyboards (1=poor characteristic and 7=good characteristic). Significant differences between keyboards are noted by a common superscript. For preference, keyboards were rank ordered from 1-least favorite to 5-most favorite. Error bars are SEM.

Discussion

There were no significant differences in gross typing speed, percent error, and subjective usability ratings between the keyboards with 16, 17 or 18 mm vertical key spacing for females with small fingers or males with large fingers, with the exception that females with small fingers preferred a vertical key spacing of 17 over 16 mm. However, typing speed, percent error, and usability ratings were significantly worse, for both females with small fingers and males with large fingers, for the keyboard with vertical key spacing of 15.5 mm compared to the other keyboards. There were no significant differences in outcome measures between the two keyboards that differed only in horizontal key spacing (e.g., 17x16 versus 18x16 mm).

Yoshitake (1995) found no significant differences in performance for subjects (N=18) who typed on keyboards with 5 different key spacing that ranged from 15 to 19 mm (both the horizontal and vertical spacing changed simultaneously). Yoshitake observed a trend toward reduced productivity with the 15 mm spacing, but the variance was high, and, therefore, the differences were not significant. In a post-hoc analysis, Yoshitake evaluated just the fastest typists, because their variance was less. In the subset with large fingers (N=4) the typing speed was reduced when vertical and horizontal key spacing was 16.0 mm or less, a finding that was similar to ours. However, in the subset with small fingers (N=4) there was no significant difference in typing speed even down to a key spacing of 15 mm. This finding is different from ours and may be due to the post-hoc selection of the small subset with small fingers, high typing speed or low variance. The small sample sizes in these post-hoc analyses limits the ability to draw major conclusions. The Yoshitake paper did not report the genders of the two subsets.

Part 1 of our study primarily evaluated horizontal key spacing and found no differences in typing speed, percent error, and subjective usability ratings between keyboards with different horizontal spacings, 17x19, 18x19 and 19x19 mm, but the outcome measures were significantly worse with the smallest horizontal key spacing, 16x19 mm (Pereira 2012). The current study is complementary in that there were no differences on these measures with keyboards of different vertical spacings, 17x16, 17x17 and 17x18 mm; however, a vertical spacing of 17x15.5 mm was significantly worse. These findings also match the findings in Part 1 that compared two keyboards with different vertical key spacing, 17x19 vs 17x17. Combining the two studies provides evidence that horizontal spacing may be as low as 17 mm while vertical spacing may be as low as 16 mm. Although the typical 19x19 keyboard was not directly compared in Part 2, in Part 1, the 17x17 keyboard was not significantly different from the 19x19 keyboard.

The wrist and forearm biomechanical differences between key spacing were minimal and only evident at the smallest vertical key spacing. At the 15.5 mm key spacing wrist extension was increased for the right female and left male wrist in comparison to the other key spacings. There were no significant differences in muscle activity between vertical key spacings. Since the location of the keyboard on the work surface was the same between keyboards, within a subject, this effect was due to the smaller key spacings and not to the workstation setup. In Part 1, we observed a similar finding with an increased left wrist extension and a decreased left ulnar deviation for large handed males when horizontal key spacing was reduced to 16 mm. The mean location of the keyboards, from the front edge of the work surface to the home row, was 19.5 cm in Part 1 and 22.6 in Part 2. Overall, the findings suggest that there is little difference in forearm biomechanical loads between the vertical key spacings of 16, 17 and 18 mm. However, at 15.5 mm, the increased wrist extension may indicate an increased risk for fatigue (Weir 2002).

The biomechanical or motor control basis for the slight difference in vertical and horizontal minimal key spacing (e.g., 16 vs. 17 mm) are likely related to differences in finger and wrist motion control and the need to prevent finger collision. Rapid movement of the fingers between vertically oriented keys requires clearance of the PIP and DIP joints and the fingertips which is done by tight coordination of the extrinsic finger and wrist extensors and flexors with the intrinsic hand muscles that extend and flex the MCP and PIP joints (Kuo 2006). Changes in key spacing in the horizontal direction will involve the same control of muscle activity plus changes to the finger abductors and wrist movers in ulnar/radial deviation. Therefore, changes in horizontal key spacing may require more complex changes in motor control than changes in vertical key spacing.

A potential limitation of the study was that while the vertical spacing between keys changed between the test conditions, the size of the keycaps remained constant. It is possible that if the key cap size was reduced in proportion to the key spacing, similar to the Yoshitake study, the error rate and productivity may not have declined at the smallest key spacing. However, changing both factors would have introduced a new independent variable. A second potential limitation is the use of custom-built keyboards using the ErgoDex system which required the manual placement of each key on a plate. However, the layout of the keys matched the conventional keyboard layout and the accuracy of key placement was high (± 0.1 mm). The activation force of the ErgoDex keys was between 0.65 N and 0.76 N, which is within the ISO requirements of 0.5 N and 0.8 N (ISO9241-410, 2008).

In conclusion, this study finds minimal differences in typing speed, percent error and usability measures between keyboards with vertical key spacing between 16 and 18 mm for both females with small fingers and males with large fingers. However, a keyboard with vertical key spacing of 15.5 mm was associated with a significant reduction in productivity and usability ratings. In our previous, Part 1 study, we observed a similar trend but with horizontal key spacing: 16 mm was significantly worse than 19, 18, and 17 mm. Based on these findings, keyboard designers may consider designing keyboards with a vertical key spacing of as little as 16 mm and horizontal spacing as little as 17 mm to gain the benefits of smaller keyboards, such as smaller and lighter laptops; reduced manufacturing costs; and reduced reach to the computer mouse.

Chapter 4: Holding a tablet computer with one hand: effect of tablet design features on biomechanics and subjective usability among users with small hands

Introduction

The use of tablet computers and smart phones 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 2012). As computer technology moves towards higher mobility through the use of handheld tablets and smart phones, there is a need for empirical evidence of tablet and smart phones 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. 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 be smaller than 100 mm high, x 255 mm long, by 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 (Storr 2007 and Ming 2006). Among university students and faculty, increasing hours of use of hand-held mobile devices was associated with increased neck, shoulder and thumb pain (Berolo 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 EMG, compared to the dominant arm (Young 2012; Lozano 2011). The increased posture deviation from neutral and sustained muscle activity pose an increased risk for musculoskeletal disorders, fatigue and discomfort in the non-dominant arm compared to the dominant arm (Werner 2005; 2009). In addition, mobile device use is associated with greater head and neck flexion when compared to desktop computer use (Heasman 2000; Young 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 2008). Tablet use was associated with more neck and trunk flexion, more flexed and 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 studies were 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 handheld objects (Augurelle 2003). A tool with a large finger contact area in comparison to a small contact area is perceived as lighter (Flanagan 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 percent of the strength of a power grip and is associated with an increased risk of musculoskeletal disorders for the same applied force (Silverstein 1986). An increased applied grip force, whether pinch or power grip, is associated with increased risk of musculoskeletal disorders (Harris 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 (e.g., Galaxy Note, Samsung) but few studies have evaluated the effect of stylus design, such as diameter, on performance, usability, and biomechanics. A study of four different diameter styluses (5.5, 8, 11, and 15mm) and three lengths (80, 110, and 140mm) found a productivity and preference advantage for the 8 mm diameter stylus (Wu 2005). At least a 100 mm length 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 ball point 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 1999). A pilot study of five adults compared use of a tablet and stylus to 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 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 use instead of two across 18 different tasks (Karlson 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 which may decrease the risk of dropping the tablet, decrease musculoskeletal disorder risk and improve comfort, usability, and productivity.

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.

Subjects

Eligibility criteria were 1) age between 18 to 65 years, 2) own or regularly use a touch screen tablet or smart phone, 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 50^{th} 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 meters (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.

Fifteen females and fifteen males participated in the study. Subject age, height, weight, hand anthropometry, grip strength, and visual acuity are summarized in Table 1.

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

Tablet Test Conditions

Non-functional tablet models were created in three different sizes (and weights) approximating the size of the iPad2 (241x186x9 mm; 613 g), Kindle Fire (189x120x11 mm; 400 g) and Samsung Galaxy Note (147x83x10 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 summarized in Table 2. The first test set (A) was tablet size (weight) with 3 levels: Large, Medium, and Small, all with Flat grip shape. The second (B) was tablet size (weight) with 2 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 3 levels: Flat, Ledge, and Handle grip, all on Large tablets. The fifth (E) was grip shape with 2 levels: Flat and Ledge, both on Small tablets. The sixth (F) was texture with 2 levels: Smooth and Rubberized/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 degree angle for 40 mm and had corner radius of 4.25 mm.

The smooth surface texture was flexible urethane paint (Color Coat, Satin Black, SEM Products INC, Rock Hill, SC) and the Large Rubberized 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 screen shot 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.

Table 2. Descriptive parameters and test sets for eight tablet configurations. All tablets except one were used in landscape orientation.

Tablet	Design Features				Test Sets[1]			
	Size (mm)	Weight (g)	Grip Shape	Texture	Size	Orientation	Grip	Texture
Large	233x147	694	Flat	Smooth	A		D	F
Large Rubberized	233x147	694	Flat	Rough		C		F
Large Ledge	233x147	601	Ledge	Smooth	B	C	D	
Large Portrait Ledge	147x233	599	Ledge	Smooth				
Large Handle	233x147	620	Handle	Smooth			D	
Medium	190x120	446	Flat	Smooth	A			
Small	147x93	241	Flat	Smooth	A		E	
Small Ledge	147x93	218	Ledge	Smooth	B		E	

[1]Test sets have a common letter and identify conditions compared within a design feature

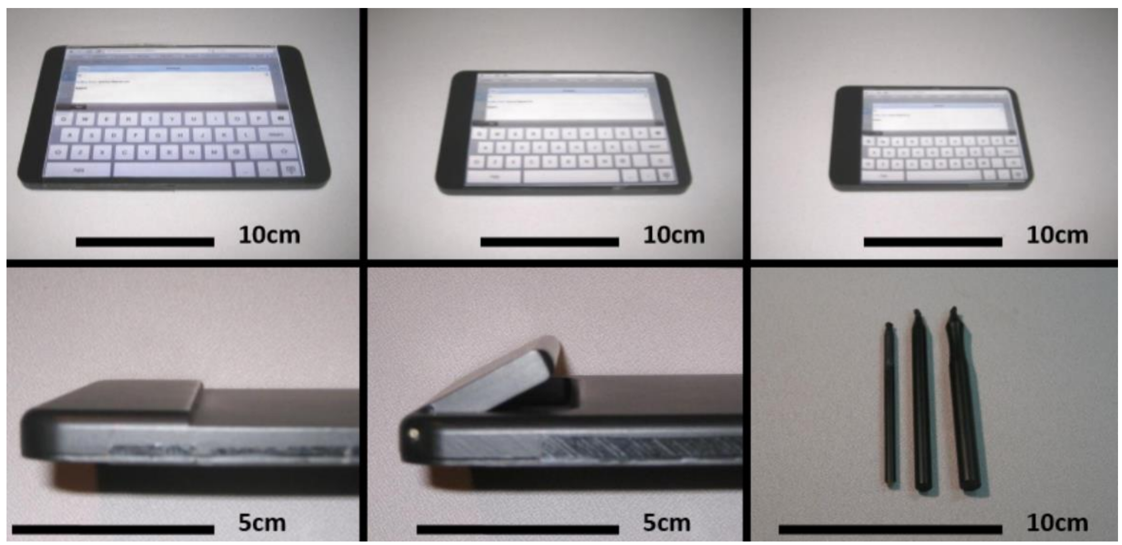


Figure 1. From top left hand corner moving clockwise: Large tablet, Medium tablet, Small tablet, styluses (Small, Large, and Tapered), Large Handle tablet, and Large Ledge tablet. The ledge and handle grip are on the side of the tablet that is held with the left hand.

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.

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 3-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 5-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.

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 middle size tablet (190x120 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 randomized.

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 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 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 7-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.

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) stabilizes 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 stabilizing 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 center-to-center 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 normalized to the maximum voluntary electrical exertion obtained by having the subject perform three 3-second maximum voluntary contractions (MVC) for each muscle (Shergill 2009). The MVC values were calculated from the highest value of an averaging 1000 ms moving window across the three maximum exertions. The APDF 50% (Shergill 2009) was calculated for each muscle across the 4-minute test for each tablet and stylus test, representing the 50^{th} percentile muscle exertion over the course of the task.

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 3-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 centers was recorded in reference posture according to placement to anatomical landmarks (Meskers 1998; Wu 2005). 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 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 center of mass of the upper arm, lower arm, hand, and tablet. Mean joint postures were calculated across the 4-minute tasks for each tablet and stylus configuration.

Statistical Analysis

The outcome measures are summarized 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 repeated-measures 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 analyzed using the chi-squared test followed up with partitioned chi-squared tests. Correlation coefficients between outcome measures were calculated and reported for variables with high correlation. Data were initially examined separately for each gender but since there were few important differences the data were combined to increase power.

Results

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

Tablet Size

Differences in usability ratings and biomechanical measures by tablet size are summarized in Table 3, first for 3 tablets with a flat grip and then for 2 tablets with a ledge grip. Higher usability numbers represent better ratings. For the comparison of 3 different sized tablets with a flat grip, the subjective *overall usability* and *productivity* ratings for the Medium tablet were significantly better than 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 favored 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.

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

	Large v Medium v Small Tablets (Flat Grip)				Large v Small Tablet (Ledge Grip)		
	Large 694 g 233x147 mm	Medium 446 g 190x120 mm	Small 241 g 147x93 mm	*p*-value	Large Ledge 601 g 233x147 mm	Small Ledge 218 g 147x93 mm	*p*-value
Writing speed (WPM)	31.8(7.6)	31.8(7.0)	32.7(9.2)	$p = 0.66$	32.3(8.0)	31.6(7.2)	$p = 0.518$
Overall usability[1]	3.7(1.3)[a]	4.8(1.3)[a]	4.7(1.4)	$p = 0.008$	4.2(1.3)	4.7(1.2)	$p = 0.084$
Overall productivity[1]	3.9(1.3)[a]	4.9(1.3)[a]	4.6(1.3)	$p = 0.004$	4.3(1.2)	4.5(1.4)	$p = 0.545$
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]	$p = 0.003$	4.0(1.3)	4.8(1.6)	$p = 0.005$
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]	$p = 0.007$	4.1(1.2)	5.1(1.7)	$p = 0.002$
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]	$p = 0.005$	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)	$p = 0.14$	7.3(11.1)	9.9(12.6)	$p = 0.28$
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]	$p = 0.005$	6.1(7.9)	5.3(5.1)	$p = 0.93$
Left ECR[2]	12.2(14.2)	9.8(10.5)	11.6(10.0)	$p = 0.095$	10.7(10.7)	11.2(10.6)	$p = 0.35$
Wrist ulnar deviation (°)	17.0(28.9)	27.2(36.0)	28.7(35.1)	$p = 0.090$	22.1(29.8)	28.6(27.4)	$p = 0.12$
Wrist extension (°)	21.6(29.2)[a]	19.3(30.4)[b]	12.7(29.5)[a,b]	$p = 0.002$	19.6(32.8)	12.2(30.5)	$p = 0.006$
Forearm supination (°)	15.6(31.7)	17.4(32.5)	17.3(31.2)	$p = 0.46$	14.9(30.9)	15.7(29.4)	$p = 0.64$
Relative elbow height (cm)	-3.1(4.1)	-2.8(3.7)	-2.8(3.7)	$p = 0.16$	-2.9(3.9)	-3.0(3.9)	$p = 0.60$
Shoulder moment (N·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)	$p = 0.14$	10.2(13.7)	11.5(14.2)	$p = 0.26$
Distance from tablet to eyes (cm)	32.6(5.1)	33.8(5.3)	33.2(5.0)	$p = 0.053$	32.5(5.8)	33.3(5.0)	$p = 0.14$
Gaze angle down (°)	24.4(17.3)	21.9(15.2)	23.3(17.1)	$p = 0.43$	22.5(14.8)	21.9(15.2)	$p = 0.27$
Torso angle forward (°)	0.8(5.5)	1.4(4.9)	2.3(5.1)	$p = 0.069$	1.8(4.7)	1.5(4.7)	$p = 0.60$

[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 Orientation

There were no significant differences in muscle activity between use of the tablet in portrait or landscape orientation (Table 4). Wrist extension was significantly less in the portrait orientation compared to landscape. 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. There were no significant differences in measured productivity.

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

	Landscape v Portrait Orientation		
	Large Ledge 601 g Landscape	Large Portrait Ledge 599 g Portrait	*p*-value
Writing speed (WMP)	32.3(8.0)	33.3(7.1)	*p* = 0.39
Overall usability[1]	4.2(1.3)	4.4(1.3)	*p* = 0.39
Overall productivity[1]	4.3(1.2)	4.1(1.4)	*p* = 0.49
Security from dropping the tablet)[1]	3.9(1.6)	4.5(1.5)	*p* = 0.11
Posture required for tablet use[1]	4.0(1.3)	4.3(1.3)	*p* = 0.16
Fatigue in left hand or wrist[1]	3.0(1.3)	3.4(1.4)	*p* = 0.13
Fatigue in the left forearm[1]	3.3(1.4)	3.8(1.5)	*p* = 0.05
Fatigue in left shoulder[1]	3.8(1.4)	4.3(1.7)	*p* = 0.06
Fatigue in neck[1]	4.1(1.2)	4.3(1.4)	*p* = 0.45
Comfortable holding time (min)[1]	16.5(11.4)	20.3(13.6)	*p* = 0.04
Left FDS[2]	14.7(13.5)	15.8(16.2)	*p* = 0.51
Left EDC[2]	7.3(11.1)	6.9(7.8)	*p* = 0.60
Left FCR[2]	14.6(13.3)	14.2(13.1)	*p* = 0.81
Left UT[2]	6.1(7.9)	6.5(7.6)	*p* = 0.17
Left ECR[2]	10.7(10.7)	11.9(13.2)	*p* = 0.79
Wrist ulnar deviation (°)	22.1(29.8)	20.6(27.7)	*p* = 0.71
Wrist extension (°)	19.6(32.8)	13.4(25.7)	*p* = 0.006
Forearm supination (°)	14.9(30.9)	13.2(27.3)	*p* = 0.26
Relative elbow height (cm)	-2.9(3.9)	-3.0(4.0)	*p* = 0.63
Shoulder moment (N·m)	33.2(15.4)	33.4(15.5)	*p* = 0.77
Right corner lower than left (°)	10.2(13.7)	10.9(12.7)	*p* = 0.59
Distance from tablet to eyes (cm)	32.5(5.8)	32.9(5.0)	*p* = 0.45
Gaze angle down (°)	22.5(14.8)	22.6(16.4)	*p* = 0.97
Torso angle forward (°)	1.8(4.7)	1.6(4.1)	*p* = 0.72

[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 Grip Shape

The differences between the grip shapes, for both large and small tablets, are summarized 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 v flat) for the small tablet were much less than the effects on the large tablet (Table 5). The only usability rating difference was an increased *security from dropping the tablet* with the ledge shape 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.

Table 5. Tablets with different grip shapes but common orientation (landscape) and texture (smooth). One set of tablets are large (233x147 mm) and one set are all small (147x93 mm). Mean (S.D.). Significant differences between pairs within a set-row are indicated by a common superscript. (N=30)

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

[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 Surface Texture

Differences between the conventional smooth tablet surface versus a rubberized, rough tablet surface for the large tablet size are summarized 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.

Table 6. Tablets with different surface texture. Mean (S.D.). (N=30)

	Smooth v Rough Surface Texture		
	Large Smooth	Large Rubberized Rough	*p*-value
Writing speed (WPM)	31.8(7.6)	32.1(7.9)	*p* = 0.78
Overall usability[1]	3.7(1.3)	4.0(1.3)	*p* = 0.32
Overall productivity[1]	3.9(1.3)	4.2(1.3)	*p* = 0.07
Security from dropping the tablet)[1]	3.1(1.6)	3.8(1.4)	*p* = 0.03
Posture required for tablet use[1]	3.6(1.4)	3.9(1.3)	*p* = 0.27
Fatigue in left hand or wrist[1]	2.7(1.7)	2.5(1.1)	*p* = 0.54
Fatigue in the left forearm[1]	3.0(1.5)	3.2(1.2)	*p* = 0.37
Fatigue in left shoulder[1]	3.7(1.6)	3.6(1.3)	*p* = 0.88
Fatigue in neck[1]	4.0(1.5)	3.8(1.6)	*p* = 0.15
Comfortable holding time (min)[1]	14.7(10.0)	13.7(8.8)	*p* = 0.44
Left FDS[2]	16.9(15.5)	17.4(16.3)	*p* = 0.52
Left EDC[2]	7.9(9.5)	6.5(6.1)	*p* = 0.20
Left FCR[2]	15.9(13.8)	16.0(14.5)	*p* = 0.42
Left UT[2]	6.2(5.3)	6.6(7.6)	*p* = 0.85
Left ECR[2]	12.2(14.2)	11.0(11.3)	*p* = 0.65
Wrist ulnar deviation (°)	17.0(28.9)	20.5(39.0)	*p* = 0.52
Wrist extension (°)	21.6(29.2)	19.0(30.2)	*p* = 0.23
Forearm supination (°)	15.6(31.7)	17.4(33.9)	*p* = 0.20
Relative elbow height (cm)	-3.1(4.2)	-2.9(3.9)	*p* = 0.32
Shoulder moment (N·m)	35.0(16.6)	35.4(15.8)	*p* = 0.38
Right corner lower than left (°)	9.6(12.1)	10.4(13.9)	*p* = 0.54
Distance from tablet to eyes (cm)	32.6(5.1)	31.9(5.0)	*p* = 0.24
Gaze angle down (°)	21.4(17.3)	22.7(14.3)	*p* = 0.53
Torso angle forward (°)	0.8(5.5)	1.4(4.9)	*p* = 0.39

[1] Average subjective ratings, 1-7. Higher value is an improvement.
[2] Percent MVC - 50% APDF. Log transformation was used for RMANOVA analysis.

Preference Across All Tablets Design Features

After using all the tablets, subjects ranked all in order from their *least favorite* to *most favorite*; the percentages of subjects who rated each tablet as their most favorite are summarized 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 more than the large tablet, with or without a ledge.

Table 7. Most preferred tablets and their mean preference ranking. Significant differences between pairs within a row are indicated by a common superscript. (N=30)

	Tablet Configurations								
	Large	Large Rubberized	Large Ledge	Large Portrait Ledge	Large Handle	Medium	Small	Small Ledge	*p*-value [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]	$p = 0.02$
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]	$p < 0.001$

Note: Participants were asked which tablet they preferred from 1 (least favorite) to 8 (most favorite).
[1]Friedman's test and Nemenyi follow-up
[2]Percent most favorite tablet
[3]Mean ranking of tablets.

Table 8. Stylus design. Mean (S.D.). Significant differences between pairs within arow are indicated by a common superscript. (N=30)

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

[1]Average subjective ratings, 1-7. Higher value is an improvement.
[2]Percent of MVC - 50% APDF. Log transformation was used for RMANOVA analysis

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).

Stylus Design

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

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 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 center 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 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 2012; 2013).

Orientation of the large tablet, portrait vs. 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 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 grip 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 most preferred the Tapered stylus, 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 2003), pens (Wu 2005) and dental tools (Dong 2006). For the stylus, pen, and dental precision work, larger diameter (up to 11mm) 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 since 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. Additionally, 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.

Overall, the findings should be carefully interpreted given the use of non-functioning tablets and simulated tasks. Based on 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 center 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 rubberized 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.

Chapter 5: A 3D gesture set for common human-computer interaction commands

Introduction

The design and selection of 3D hand gestures has the potential to create a more intuitive, natural, powerful, and productive human-computer interaction than traditional input devices (Wachs 2011; Ni 2011). It also has the potential to make HCI more comfortable. The imminent release of relatively inexpensive motion capture technology is expected to lead to an explosion of 3D hand gesture input systems and languages. However, currently no basic overarching gesturing language has been designed. Most existing research evaluates the hardware and software that enable gesturing interaction (Stern 2006). The studies that have examine desktop gesturing for HCI focus on using gestures for mouse or stylus type movements, not for higher level commands (Smith 2004). In the few studies that have evaluated gesturing for interaction with desktop computers, comfort, fatigue with prolonged use, and ergonomics were not considered. This is an important concern because extreme wrist flexion and extension and asynchronous finger postures are postures known to lead to pain if repeated (Rempel 2003) and have been recommended components of gestures for common commands (Ni 2011).

Approximately 10 years ago, gesture recognition for HCI emerged for video gaming. As video game sophistication increased developers were prompted to acquire and transmit more complex commands to the game system than the ones available on traditional hand-held remotes (Leyvand 2011). By the end of 2010, the three main companies in the gesture recognition gaming space were the Kinect (Microsoft), which uses cameras and infra-red, the Wii Remote Plus (Nintendo), which uses an accelerometer, a gyroscope, and infra-red, and the PlayStation Move (Sony), which is equipped with motion sensors, a gyroscope, an accelerometer and camera (Zhang 2012; Vaughan – Nichols 2009; Sony Computer Entertainment 9/24/2009). These systems capture whole body or upper body motion and posture. Building on this technology are more precise devices with higher resolutions such as the Leap Motion Controller which are designed to capture just hand gestures (Leap Motion 2013). A competitor is the PMD-CamBoard Nano, which was released in Germany in 2012. In addition, new sensing technologies, such as the MYO, which is warn like a wrist band on the forearm samples user EMG signals to detect hand gestures (Thalmic Labs). Elliptical Technologies, uses ultrasound to detect gestures (Nuwer 2013; Elliptic Labs Technologies 2013). Such 3D hand gesture recognition systems provide the opportunity to enhance or even bypass from keyboard, mouse and touch screens. Other benefits of gesture systems are: use in a sterile non-contact environment, interaction with multiple people simultaneously, ability to secure technology and prevent vandalism, and easier manipulation of objects with three-dimensional large screens.

There is relatively little literature on the design of gesture languages for HCI. One study by de la Barré et al. (2009) tested 20 subjects for two different select command gestures. The two gestures were holding a stationary point and the second was tapping in towards the screen while pointing. The stationary method required less learning time, had less positioning error, required a smaller button activation size, and had higher satisfaction. Another study demonstrated that precision for pointing is less for hand gestures compared to using a touch screen or a mouse for pointing (Vogel 2005).

Mathematical models have been developed to evaluate the psychophysiological and technical performance of gesture control systems based on posture but the biomechanical models used were primitive (Stern 2006). Menu selection interfaces have been designed for gesturing interaction (Ni 2011; Bowman 2001); however, comfort and ergonomic design were not considered. Karam et al. (2005) developed gestures to control previous track, next track, and stop track background music on the computer. The gesture language was created by the researchers and derived from user studies. Their final selected gestures were a left to right hand wave for next piece, right to left hand wave for the previous piece and an open handed halt gesture for stopping playback. A simple gesture interface for secondary tasks of navigation and entertainment system for cars was developed and tested by Alpern et al. (2003). Ten iterative cycles of testing and think out loud were used to refine the gesture language and onscreen menu. The final gesture language was limited to ten simple gestures to limit user cognitive load including numeric gestures (1 through 5) and directional (up, down, left, and right). The interface was found to have fewer errors and was preferred over the traditional touch interface (Alpern 2003).

The development of an HCI gesture language, that is, the assignment of specific gestures to commands, needs to consider the user's expectations of computer interpretation (e.g., natural language) in order to minimize learning time and optimize usability and productivity. The gesture language should also consider the expected frequency of command use so that common commands are matched to gestures that are rapid and comfortable to form with minimal biomechanical and ergonomic risk. In addition, the gesture language should work across platforms so that it can be widely adopted. Already existing, widely used 2D touch gestures should also be considered.

The development of a gesture language should also consider cognitive load. One method of reducing user mental load is the reuse of gestures. For example, the same gesture can have two different meaning, depending on the context (Kaiser 2003). Reuse of gestures allows for a larger set of commands with fewer defined gestures. A large set of gestures would be more difficult for the user to remember and would increase the complexity of the gesture recognition system (Wu 2003). Wobbrock et al. (2009) also considered consistency and symmetry in the creation of a user-defined gesture set for touch surface interaction.

In addition to cognitive load, a gesture language needs to consider the visibility and specificity of the gesture posture. The selected gestures should be distinctive, but there will be variability in the gesture shape both within and between people when they create a specific gesture. Spatio-temporal variability is the variability that exists in duration and shape of a gesture (Keskin 2003). In addition, many devices such as the Kinect and Leap Motion, have camera viewing from one plane only. Therefore, the distinctive features of a gesture should be visible from common sensor angles (Kaiser 2003).

The ultimate design of common gesture languages for these systems is likely to follow natural language principles. However, given past experience, these languages are not likely to naturally be guided by knowledge of hand postures that are comfortable or follow ergonomic principles.

Our research team has studied hand discomfort associated with different hand gestures based on epidemiologic research, physiologic studies of hand tissues, and studies of sign language interpreters. Sign language interpreters have an extensive and unique experience forming repeated hand gestures and almost all suffer from hand or arm pain after gesturing for several hours (Feuerstein 1997; Rempel 2003). This is especially alarming when considering the possibility that computer users may be performing gesture many hours per day. Studies of sign language interpreters have identified particular hand and arm postures, that if repeated, are comfortable and others as uncomfortable or even painful. Extreme wrist flexion and asynchronous finger postures were especially uncomfortable as were wrist extension and extreme forearm rotations (Rempel 2003). Over time, these short-term uncomfortable or painful symptoms can develop into prolonged pain and impairment (Webster 1994).

The purpose of this study is to create a 3D gesture set from user defined gestures, user subjective scoring, posture risk factors, cognitive load, and system requirements. Thirty subjects were interviewed for 34 common commands. During the interviews users' natural gesture response to presented commands were collected in addition to preference, match, easiness, and effort order ranking and rating. Interviews were analyzed for gesture reduction, response time, popularity score, order, and agreement score. Results of user preference, match, easiness, and effort order in addition to gesture popularity and posture score were summed with and without weighting. Sums and expert opinion were used to define a final gesture set.

Method

In this laboratory study, 30 subjects (14 female) performed user derived gestures for 34 common computer commands. Subjects were presented with images of the commands, then performed the gestures of their choice that they thought would be the best ones to execute the command. The study was approved by the University Institutional Review Board and subjects signed a consent form.

Subjects

Eligibility criteria were age between 18 to 65 years, right hand dominate, experience with touch screen devices, and without a history of upper extremity musculoskeletal disorders in the past six months. Of the 30 subjects average age was 33(13), 80% had previous experience with Apple iOS, 53% Android OS, 17% Microsoft Kinect, and 80% Nintendo Wii.

Commands

A total of 34 commands were evaluated. The commands were selected from a list of common shortcuts used by the Microsoft OS, commands examined in Wobbrock et al., and additional commands by the research group (2009). Table 1 lists the tested commands. Commands 1–25 were rated previously by Wobbrock et al., for conceptual complexity from 1 (simple) to 5 (complex). The additional gestures, 26–34, were rated by authors.

Table 1: The 34 studied commands and conceptual complexity (1=simple, 5=complex).

Commands	Mean	SD
1. Move	1.00	0.00
2. Select Single	1.00	0.00
3. Rotate	1.33	0.58
4. Shrink	1.33	0.58
5. Delete	1.33	0.58
6. Enlarge	1.33	0.58
7. Pan	1.67	0.58
8. Close	2.00	0.00
9. Zoom In	2.00	0.00
10. Zoom Out	2.00	0.00
11. Select Group	2.33	0.58
12. Open	2.33	0.58
13. Duplicate	2.67	1.53
14. Previous	3.00	0.00
15. Next	3.00	0.00
16. Insert	3.33	0.58
17. Paste	3.33	1.15

Commands	Mean	SD
18. Minimize	3.67	0.58
19. Cut	3.67	0.58
20. Accept	4.00	1.00
21. Reject	4.00	1.00
22. Menu Access	4.33	0.58
23. Help	4.33	0.58
24. Task Switch	4.67	0.58
25. Undo	5.00	0.00
26. Gesture On	1.67	0.58
27. Gesture Off	1.67	0.58
28. Volume Up	2.67	0.58
29. Volume Down	2.67	0.58
30. Mute	2.33	0.58
31. Save	3.00	1.00
32. New	4.00	1.00
33. Find	4.33	0.58
34. Control Cursor	2.67	0.58

Commands were displayed on the monitor typically as before and after images of the command. For example, Move images are displayed in Figure 1. Once the subject understood the command and the desired output, the initial image was shown again and the subject demonstrated gestures they would make to complete the command.

Figure 1: Example before and after images for Move command.

The commands used screen shots from Apple OS X and Microsoft 8. When appropriate, mouse short-cut cues (e.g., close button on window) were hidden to force the use of a gesture rather than pointing at a button.

Workstation Setup

The subjects were provided a chair, desk, and monitor. The work surface was adjustable in height and placed 2 cm below elbow height. The monitor (50 cm diagonal) was adjustable in horizontal and vertical tilt angle and the top of the screen placed near the subject's eye level and at an arm length away. A keyboard and mouse were on the desk surface between the monitor and the subject but were not used.

Video Recording Setup

Four cameras were used to simultaneously video record the subject during the experiment (Swann Security System, SWDVK-414002, Santa Fe Springs, CA). The first camera viewed the subject's hands and arms from the right side (face not visible); the second viewed the subject's hands from above (no face but arms visible); the third viewed the interviewer's hands from the side; and the fourth viewed the screen.

Interviews

A random number generator was used to assign test order of commands. A semi-structured interview was conducted for all commands. The before and after image of commands were shown to the subject while simultaneously spoken by the researcher. Subjects were encouraged to think aloud and explain the gestures they made in response. During and after the gestures were formed the researcher asked open-ended questions about why specific gestures were selected and probed for additional gestures. Questions were non-leading, neutral and in the present tense.

Preference, Match, Easiness, and Effort Order Ranking and Rating

Immediately after all gestures were completed for a command, subjects ranked their first and second most preferred gesture. They then rated their top two preferred gestures on two questions using Likert scales (1 low – 7 high): "How would you rate 'The gesture is a good match for its intended purpose.'" and "The gesture is easy to perform." Subjects were then asked to rank order all of their gestures starting with "the gesture that requires the least amount of effort." The four ratings are: preference, match, easiness, and effort order, respectively.

Gesture reduction, response time, popularity score, and order

The subjects generated over 1300 different gestures for the 34 commands during the experiment. Only gestures that were selected by 3 or more subjects (N=84) were analyzed further.

The videotapes were reviewed by two researchers to assess response time, identification and tally of repeated gestures, and gesture order. Response time was the time in seconds from when the researcher completed the explanation of the command to the subject's first gesture response. Categorization and tally of similar gestures repeated three or more times per command was calculated and is referred to as gesture popularity. Also calculated was order of appearance of categorized gestures.

Posture Analysis

Gestures were assigned a biomechanical risk score based on the most extreme joint postures during the gesture. The scoring system (higher values represent increased risk) are combined from existing risk assessment tools and studies of physiologic and epidemiologic risk linking postures to high biomechanical loads, pain or musculoskeletal disorders (Bao 2009; Rempel 1998; Rempel 2003; Keir 1998; Hignett 2000).

Table 2: Gesture posture risk scores - higher score values represent lower risk for fatigue and MSD risk

Finger		
Extension	*State*	*Score*
Hand not fully extended	Not Full	3
Knuckles bent	Full	1
Separation of two extreme fingers	*Degree*	*Score*
Angle of separation between two most extreme fingers	0-15	3
	15-45	2
	>45	1
Wrist		
Extension/Flexion	*Degree*	*Score*
Angle of extension/flexion of the wrist from neutral	0-15	3
	15-45	2
	>45	1
Ulnar/Radial Deviation	*Degree*	*Score*
Angle of ulnar/radial deviation of the wrist from neutral	0-10	2
	10-20	1
	>20	0
Forearm	Degree	Score
Angle of forearm pronation/supination from neutral	0	3
	0-45	2
	>45	1
Shoulder	Degree	Score
External Rotation of shoulder	0	3
	30	2
	>30	1

Data Analysis

Summary measures were estimated for all command-gesture combinations for subjective ratings, posture score, and gesture popularity.

An Agreement Score was calculated using the same method as Wobbrock et al. (2009). An example of agreement score calculation for 'Accept' is shown below. A total of 60 different gestures were presented, with three specific gesture popularity totals of 19, 12, and 10 in addition to 19 gestures which were not categorized. The agreement score, which reflects the degree of consensus among participants, was calculated for both within a gesture and command.

Formula 1: Command Agreement Score for 'Accept'

$$A = \left(\frac{19}{60}\right)^2 + \left(\frac{12}{60}\right)^2 + \left(\frac{10}{60}\right)^2 + 19 * \left(\frac{1}{60}\right)^2$$

An overall Sum for command-gesture combinations was calculated by combining the six summary variables by summation: subjective preference, easiness, match, effort order, posture score, and gesture popularity. Agreement scores were not included in summation as values are identical within gestures or commands. Instead, gesture popularity was used. Before summation, the six variables were normalized to a mean value of 10, a standard deviation of 1, with high values assigned as positive traits. The normalized values were weighted then summed to achieve the Sum. The three coauthors assigned a weight to each summary variable based on an analytic hierarchy process (Bhushan 2004) and the final weighting was a Weighted Sum from the three (Table 3).

Table 3: Assigned weights for 6 variables used for Weighted Sum

Measurement	Weight
Preference	14
Easiness	8
Match	17
Effort order	9
Posture score	22
Gesture popularity	31

Selection of final Command-Gesture Set

The selection of a final command-gesture set involved using the Weighted Sum with adjustment by expert opinion. Expert opinion considered repeated gestures, cognitive load, biomechanical risk, and gesture distinctiveness and visibility. Menu interactions were not the focus of this experiment as significant changes to menus and information layout are expected in future operating systems to better accommodate gesture input (Ni 2011; Microsoft Windows 8, 2012).

Results

The 34 different commands were linked to 84 different gestures with a total of 160 gesture-command combinations. Command agreement score was calculated and plotted on the primary axis (blue line) according to Formula 1 for each command and shown in Figure 1. Values are between zero and one, with one being complete agreement. Commands are ordered on agreement score – highest to lowest. Average response time to first gesture for the command is reported in seconds on the secondary axis (orange line).

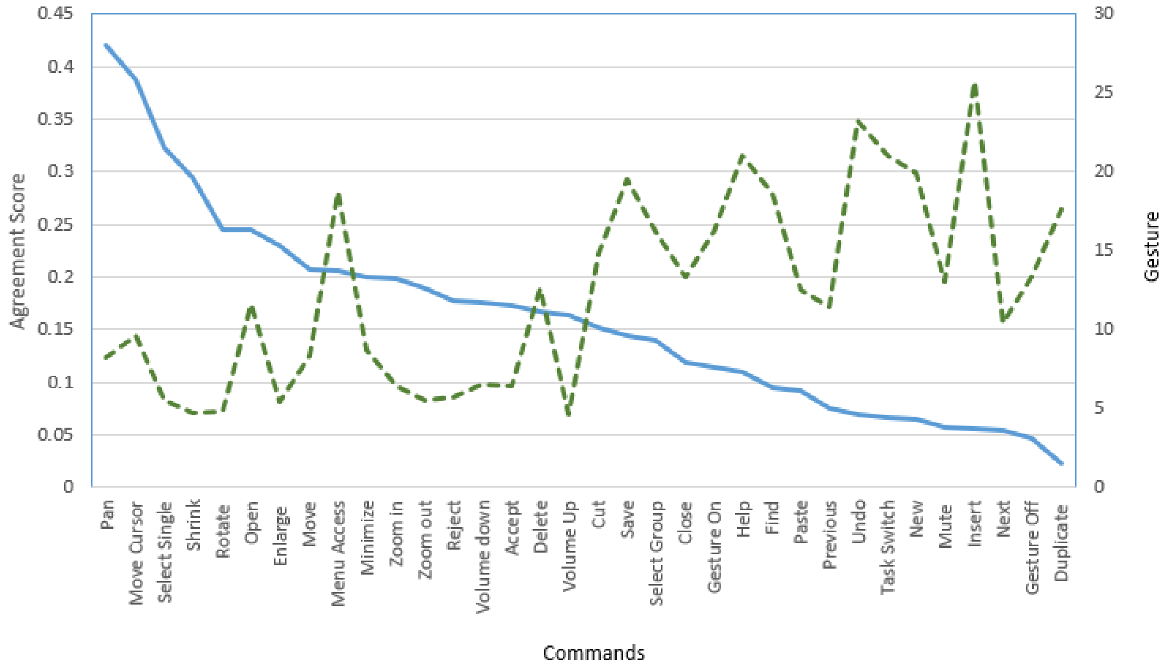


Figure 1: Agreement score (solid blue) and response time (green dash) (s) for each command.

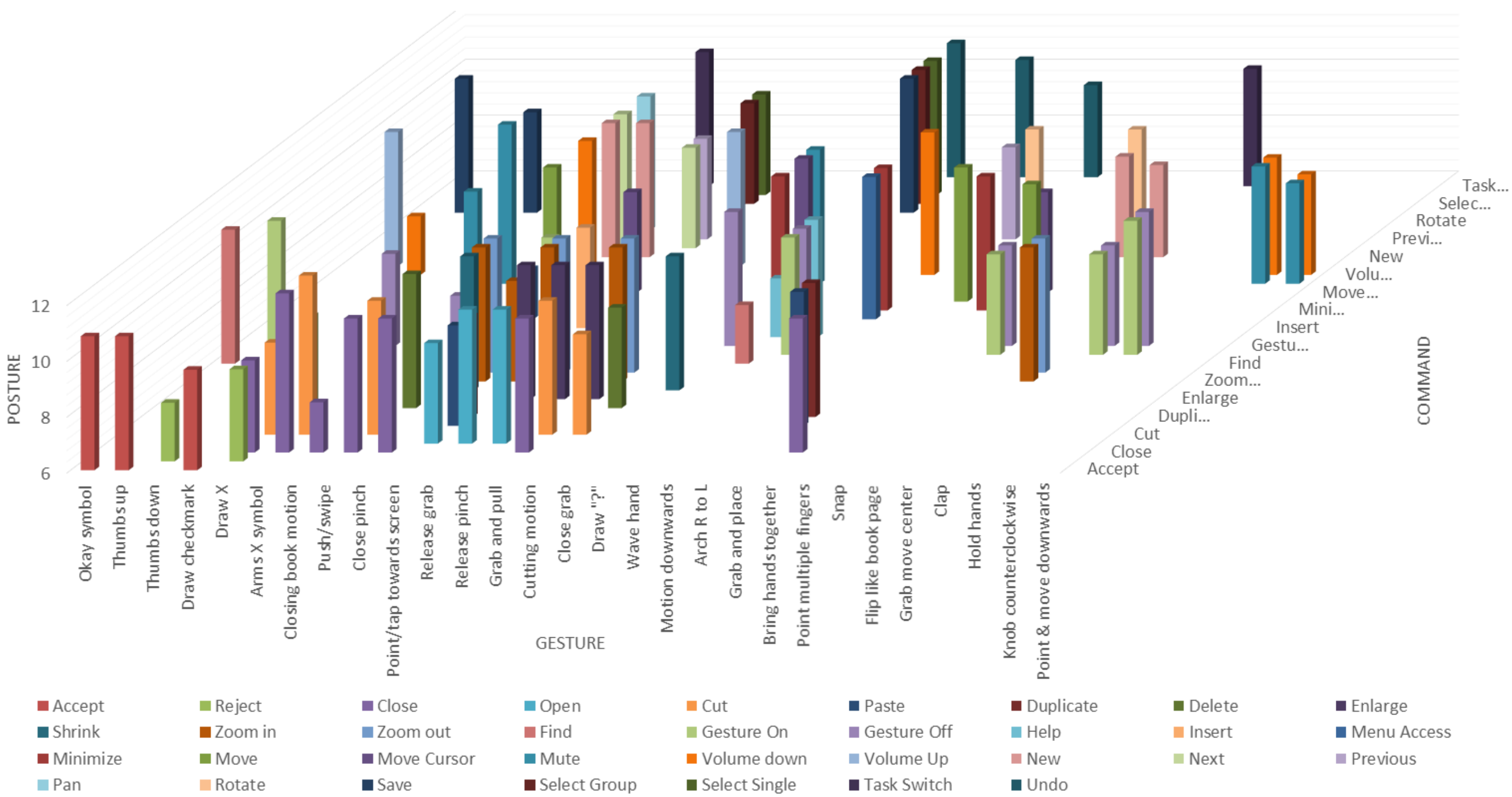


Figure 2: Posture by gesture and command

Figures 2 to 7 show posture, preference, match, effort order, easiness, and gesture popularity scores for all gestures with more than two commands. The mean score is normalized to 10 with a standard deviation of 1; higher values are better ratings. Figure 2 shows normalized posture scores by gesture and command. The lowest posture score was 7.8 for the gesture closing book motion for commands *gesture off* and *close*. The highest posture score was 11.7 for arms forming a X gesture for the commands *close*, *mute*, and *cut*.

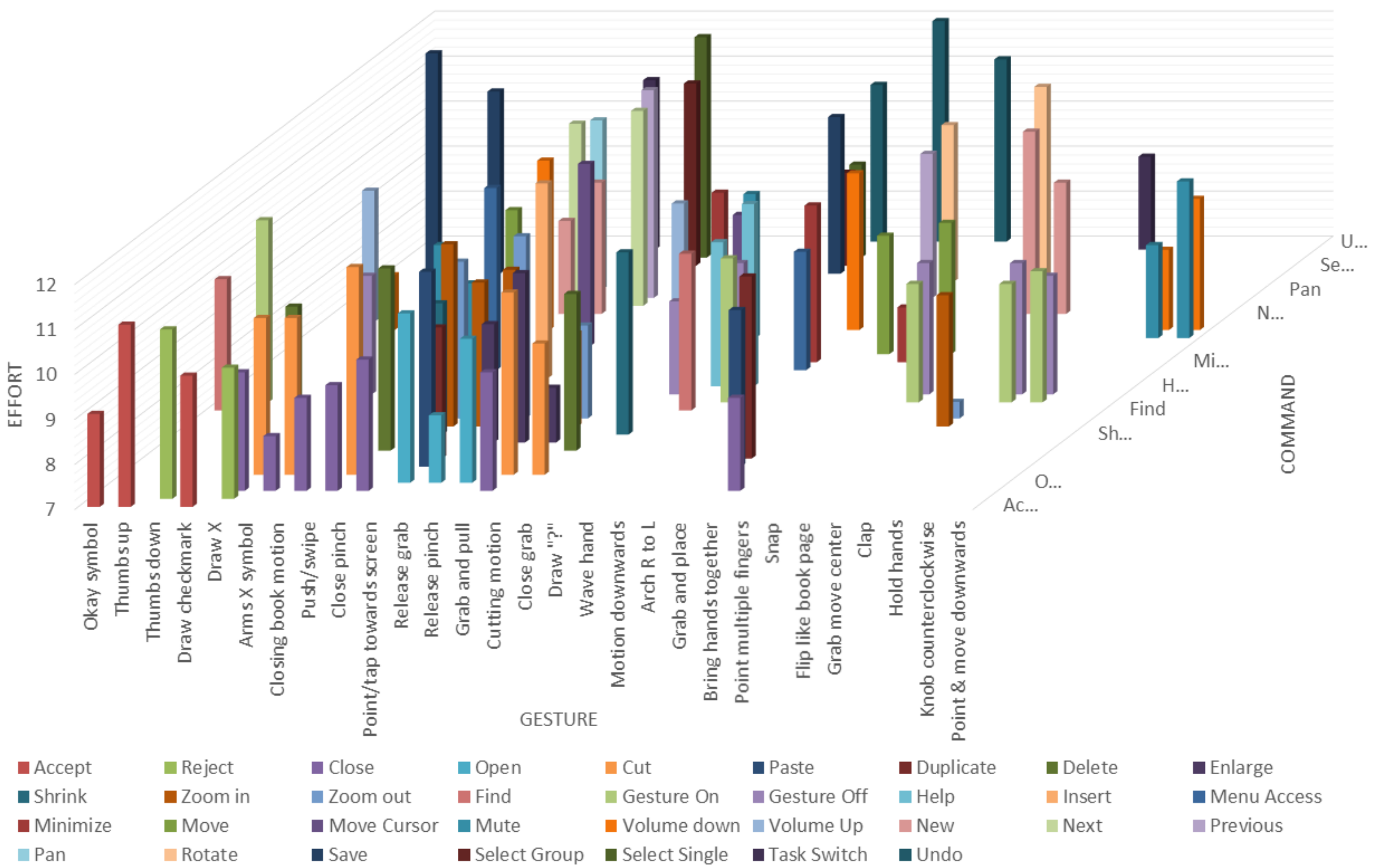


Figure 3: Effort by gesture and command

Effort scores by gesture and command are presented in Figure 3. The lowest effort score was 7.4 for the grab move center gesture for the *zoom out* command. The highest effort score was 11.9 for the gesture thumbs up for the command *save* and the point/tap towards screen gesture for the command *select single*.

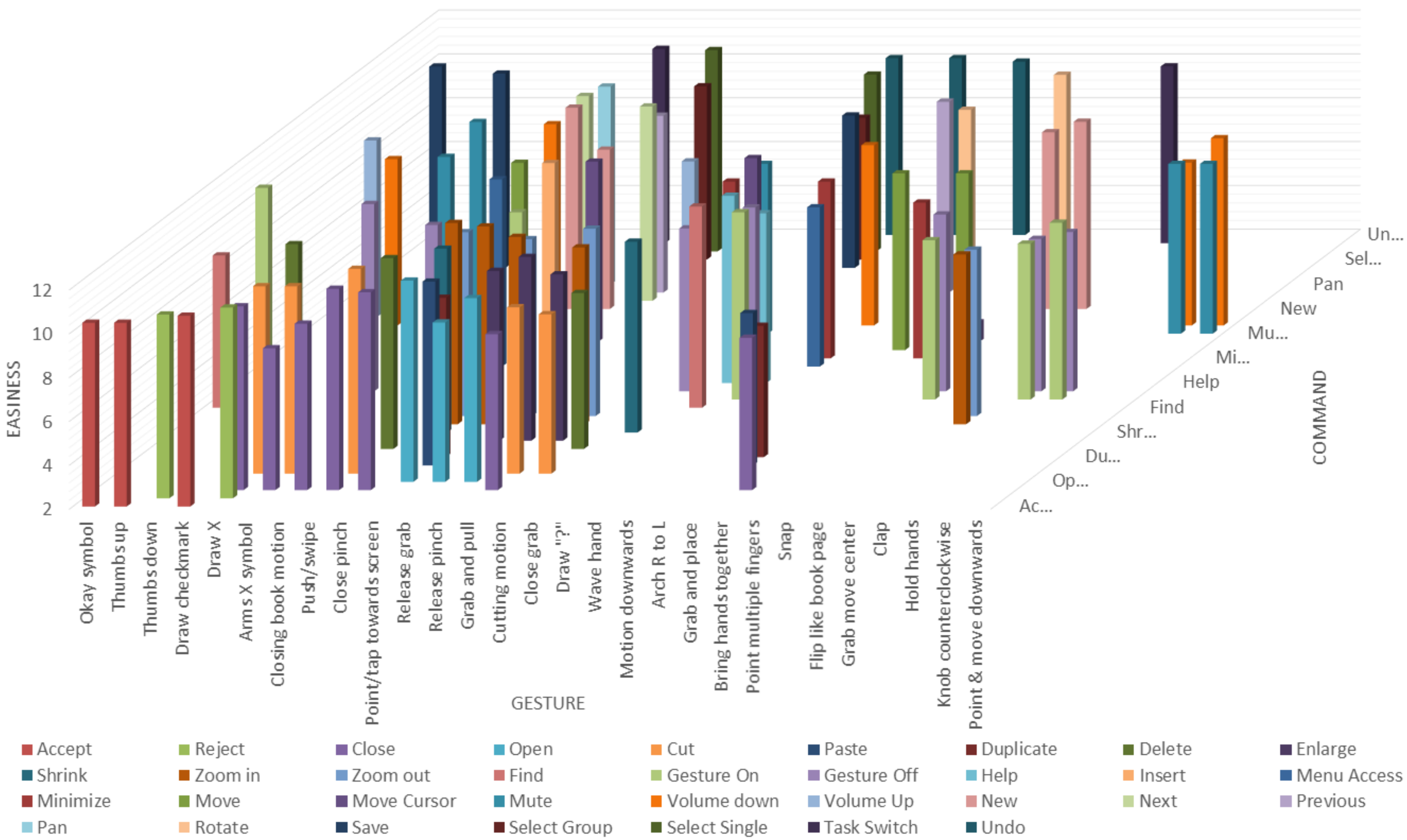


Figure 4: Easiness by gesture and command

Easiness scores by gesture and command are presented in Figure 4. The lowest easiness score was 2.9 for the point multiple fingers gesture for the *move cursor* command. The highest easiness score was 11.7 for the gesture thumbs up for the command *gesture on*, point and tap gesture for the command *insert*, and arms X symbol gesture for the command *mute*.

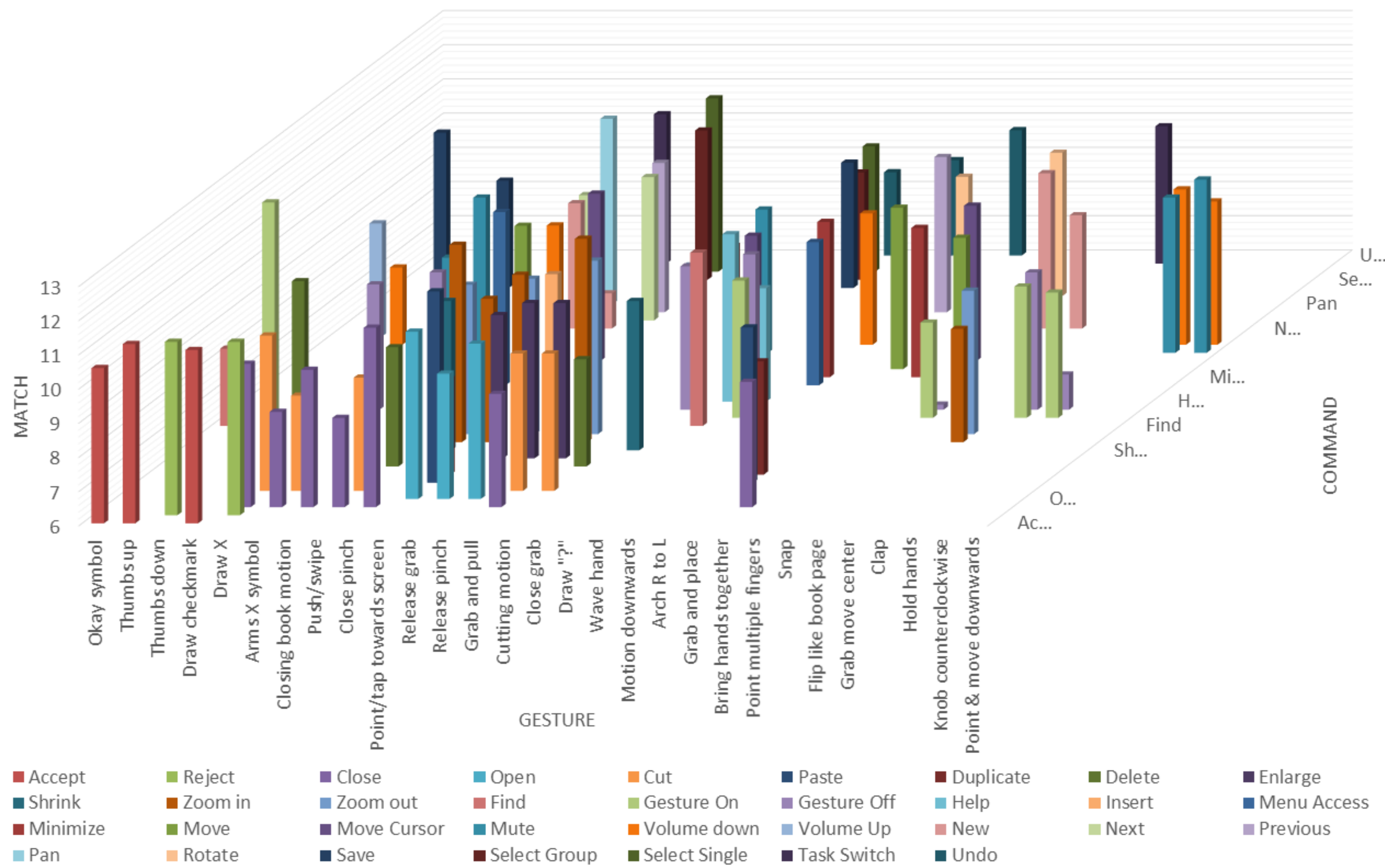


Figure 5: Match by gesture and command

Match scores by gesture and command are presented in Figure 5. The lowest match score was 6.2 for the snap gesture for the *gesture off* command. The highest match score was 12.3 for the gesture thumbs up for the command *gesture on*.

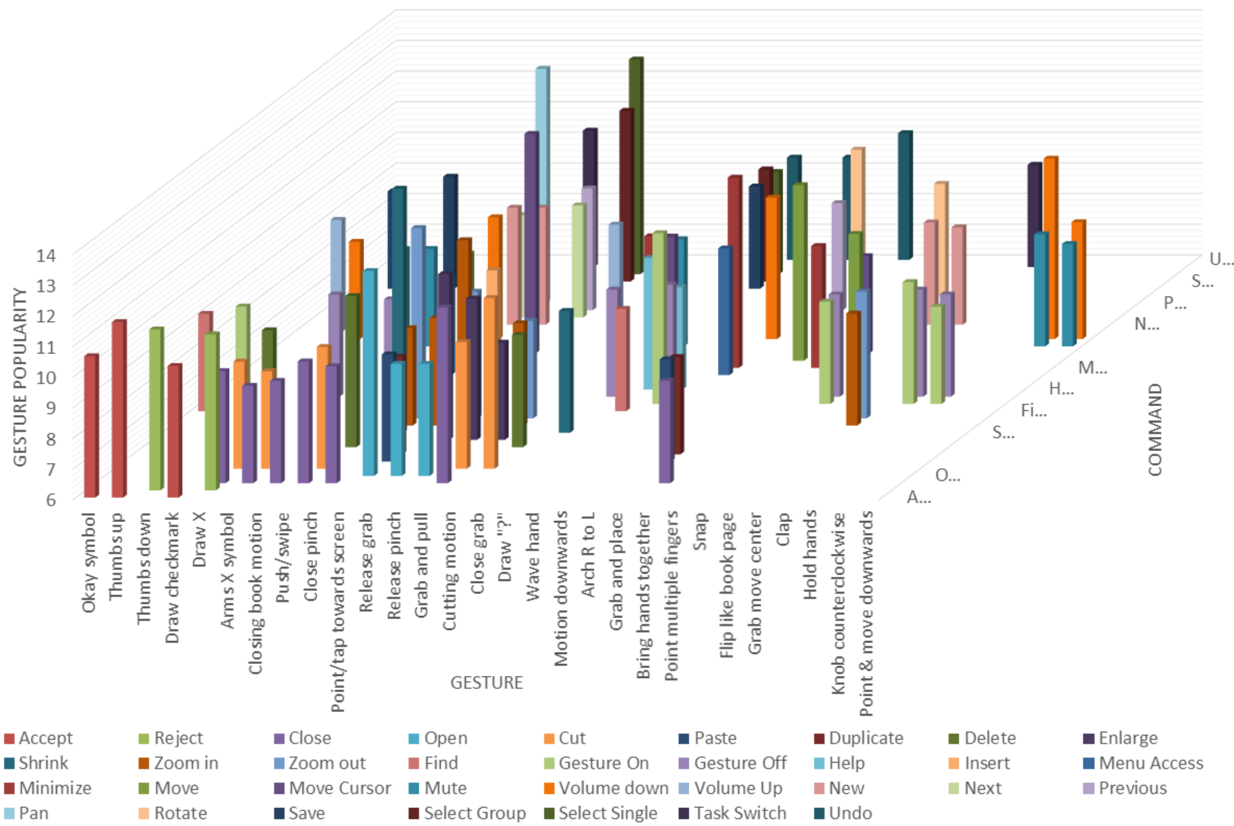


Figure 6: Gesture popularity by gesture and command

Gesture popularity by gesture and command are presented in Figure 6. The lowest gesture popularity score was 9.17 for the: thumbs up gesture for the *save* command; arms X symbol gesture for the commands *cut*, *close,* and *mute*; closing book gesture for the *gesture off* command; point/tap towards screen gesture for the *duplicate* command; grab and manipulate gesture for the *duplicate* and *enlarge* commands; close pinch gesture for the *zoom in* command; grab and pull gesture for the *zoom out* command; okay symbol gesture for the *find* command; hold hands gesture for the *gesture on* command; closing book motion gesture for the *gesture off* command; point multiple fingers gesture for the *control cursor* command; draw X gesture for the *mute* command; volume down gesture for *thumbs down* command; and flip like book page gesture for the *new* command. The highest gesture popularity score was 14.0 for the gesture close pinch for the command *shrink*.

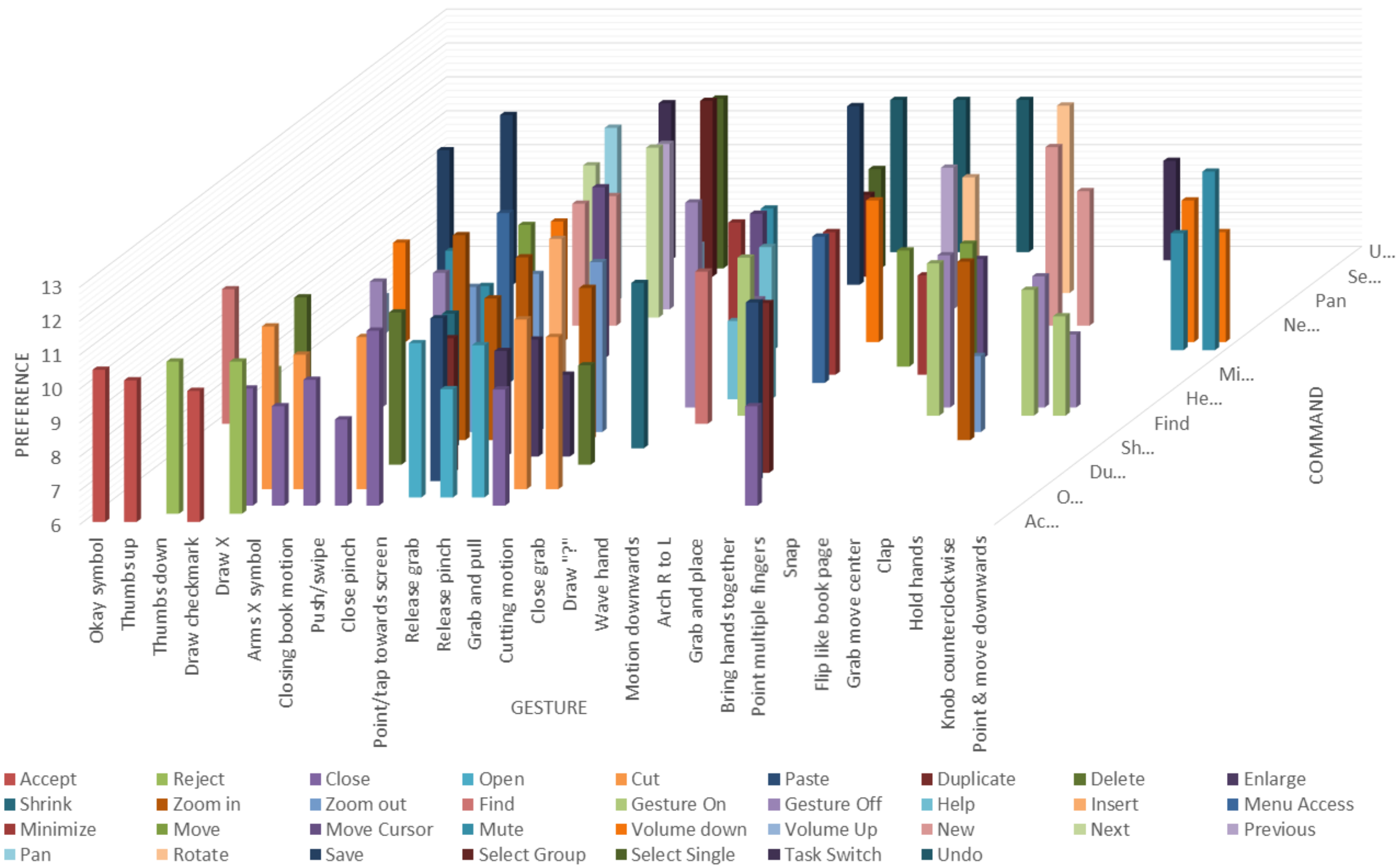


Figure 7: Preference by gesture and command

Preference score by gesture and command are presented in Figure 7. The lowest preference score was 7.1 for the thumbs up gesture for the *volume up* command. The highest preference score was 12.0 for the close pinch gesture for the *zoom in* command and the close grab gesture for the *gesture off* command.

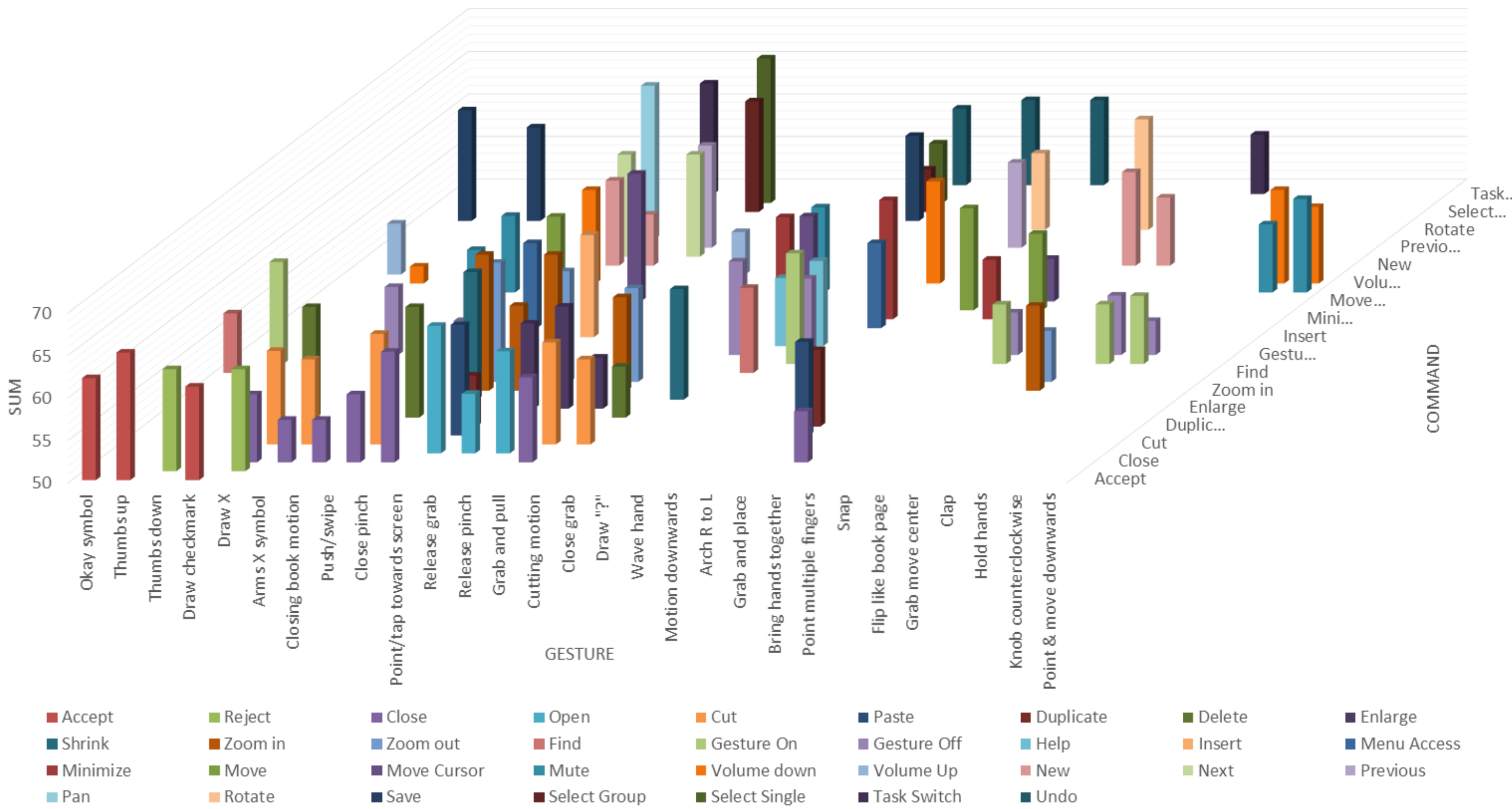


Figure 8: Sum by gesture and command

Sum scores by gesture and command are presented in Figure 8. The lowest Sum score was 52 for the thumbs down gesture for the *volume down* command. The highest Sum score was 68 for the gesture push swipe for the *pan* command.

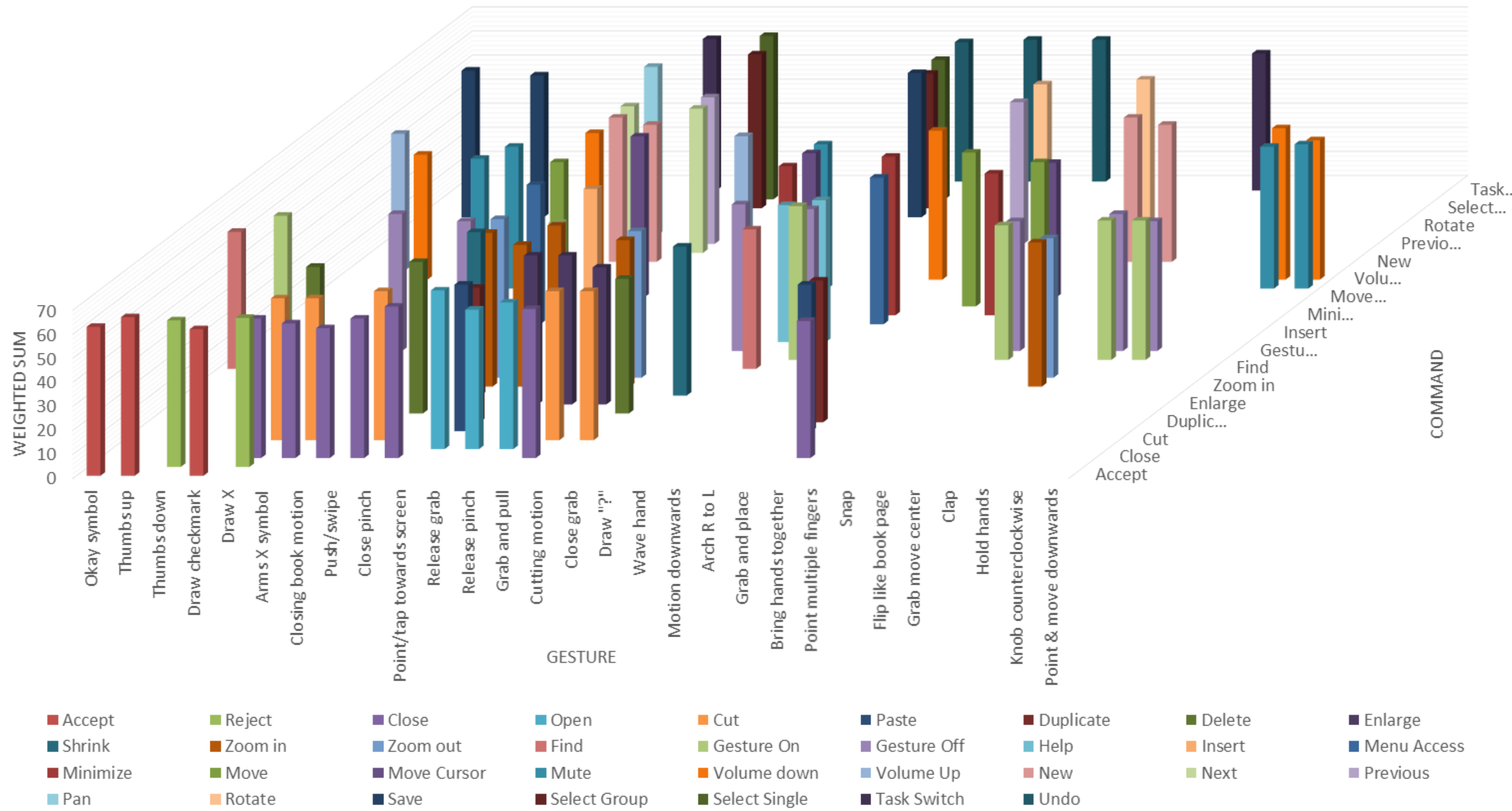
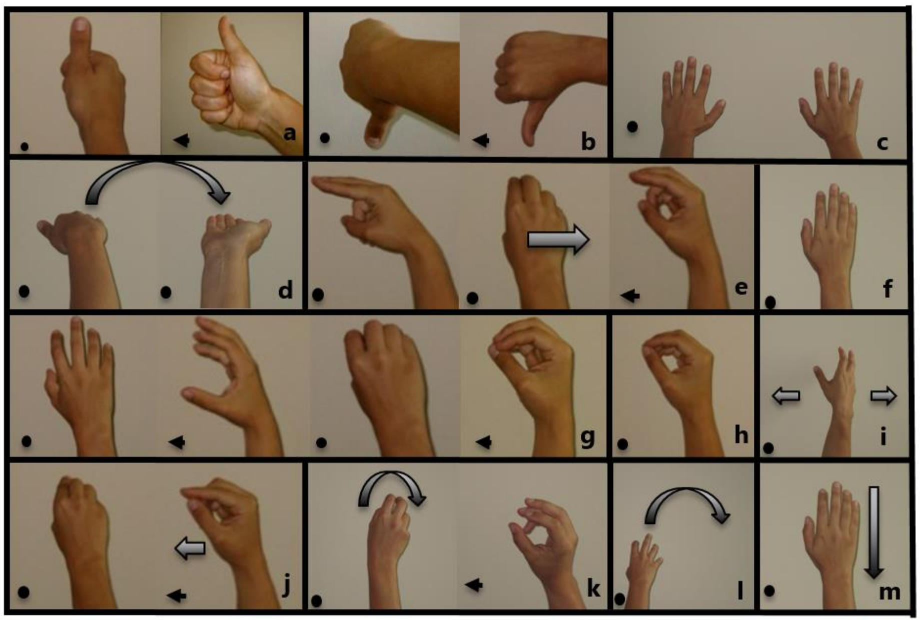


Figure 9: Weighted Sum by gesture and command

Weighted Sum by gesture and command are presented in Figure 9. The lowest Weighted Sum score was 52 for the thumbs down gesture for the *volume down* command. The highest Weighted Sum score was 71 for the gesture push swipe for the *pan* command.

A proposed gesture set for the 34 commands (13 different gestures) was created using the Sum (S) and Weighted Sum (WS) values with adjustment by expert opinion (Figure 8 and Table 4). Gesture and command agreement have a value between 0 and 1, with 1 signifying complete agreement. Sum is the simple sum of subjective preference, easiness, match, effort order, posture, and gesture popularity scores while Weighted Sum is the sum of the six categories weighted according to Table 3.



Small black arrows point towards screen.
Small black dots are arrows pointed towards screen into the paper.
Large grey arrows represent hand movement.

Figure 8: Proposed Command-Gesture Set.

Table 4: Proposed Command-Gesture Set Values

	Fig 8	Gesture	GA	CA	Pr	M	EO	E	Po	GP	S	WS
Accept	a	Thumbs up	0.43	0.17	10.2	11.2	11.1	10.4	10.8	11.7	65.0	66.0
Save	a	Thumbs up	0.43	0.18	10.0	10.5	11.9	11.2	10.8	9.2	63.0	61.0
Reject	b	Thumbs down	0.73	0.14	10.5	11.1	10.8	10.4	8.1	11.3	62.0	61.0
Gesture on	c	Hold towards screen, no movement	0.38	0.11	10.7	10.0	10.2	10.5	10.2	11.6	63.0	64.0*
Gesture off	c	Hold towards screen, no movement	0.38	0.05	9.2	10.5	9.9	10.4	10.2	9.7	59.0*	59.0*
New	d	Flip over making arch left to right	1.00	0.07	12.0	8.3	11.9	10.5	10.2	9.2	62.0	59.0
Cut	e	Cutting scissors movement two fingers	0.63	0.15	10.5	10.0	9.9	9.3	9.6	11.6	60.0*	62.0
Paste	e	Pressing down glued paper two fingers	1.00	0.09	10.6	9.7	9.6	10.4	11.1	10.5	61.0*	62.0
Insert	e	Finger scissor movement then press down	0.00	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0*	0.0*
Duplicate	e	Finger scissor movement then press down	0.00	0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0*	0.0*
Help	f	Raise hand	1.00	0.11	11.5	9.8	11.1	10.1	11.1	9.8	63.0	62.0
Enlarge	g	Grab and manipulate: open grip to scale	0.30	0.23	9.1	10.2	9.6	9.7	10.8	11.4	60.0*	62.0*
Shrink	g	Grab and manipulate: close grip to scale	0.32	0.29	10.0	10.4	9.9	10.4	10.8	14.0	65.0	68.0
Zoom in	g	Grab and manipulate: open grip to scale	0.30	0.20	11.4	10.9	10.5	10.5	10.8	12.0	66.0	67.0
Zoom out	g	Grab and manipulate: close grip to scale	0.32	0.19	10.3	10.4	10.5	10.4	10.8	12.2	64.0	66.0
Close	g	Grab and manipulate: close grip entirely	0.32	0.12	11.2	11.2	9.9	11.0	10.8	9.8	63.0	63.0
Rotate	g	Grab and manipulate: grip and rotate	1.00	0.25	10.2	10.9	10.8	10.2	10.2	12.2	64.0	65.0

Move	g	Grab and manipulate: grip, pull from screen, place, and release	0.57	0.21	9.4	10.7	9.6	10.1	10.8	11.7	62.0*	64.0
Delete	g	Grab and manipulate: grip, pull from screen, place off screen, and release	1.00	0.17	10.1	10.4	8.5	9.6	10.8	10.1	59.0*	60.0*
Find	h	Hand shaped like telescope	1.00	0.09	10.5	8.4	10.5	9.1	11.1	10.9	60.0*	61.0*
Pan	i	Pan left and right with palm facing centerline	0.16	0.42	11.1	11.4	10.8	11.0	10.8	13.6	68.0	71.0
Task switch	i	Pan left and right with palm facing centerline	0.16	0.07	10.6	10.4	10.8	10.9	10.8	10.5	63.0	63.0
Control cursor	j	Point	0.15	0.39	11.0	10.9	11.1	10.2	9.6	13.2	65.0	67.0
Select single	j	Point and tap in	0.15	0.32	11.0	11.1	11.9	11.2	9.6	13.0	67.0	68.0
Select group	j	Point and tap in with LH fist	0.15	0.14	11.2	10.4	11.1	9.9	9.6	11.6	63.0	64.0
Open	j	Point and tap in twice	0.15	0.24	10.6	10.9	10.8	11.2	9.6	12.7	65.0	66.0
Menu access	j	Point and gesture at top of screen	1.00	0.21	9.9	9.3	10.8	10.2	10.2	12.0	62.0	63.0
Volume up	k	Turn knob clockwise	0.16	0.05	10.5	9.7	11.1	11.3	10.8	9.3	62.0	61.0
Volume down	k	Turn knob counterclockwise	0.38	0.07	10.2	10.5	10.2	10.7	9.3	9.5	61.0*	63.0
Mute	k	Turn knob counterclockwise	0.38	0.07	10.5	9.7	11.1	9.9	9.3	10.1	60.0*	59.0*
Next	l	Arch left to right	0.16	0.05	10.5	9.7	11.1	11.3	10.8	9.3	62.0	61.0
Previous	l	Arch right to left	0.38	0.07	10.2	10.5	10.2	10.7	9.3	9.5	60.0*	59.0*
Undo	l	Arch right to left	0.38	0.07	10.5	9.7	11.1	9.9	9.3	10.1	60.0	59.0
Minimize	m	Pan hand down	0.38	0.2	10.2	10.5	10.5	10.1	11.1	12.2	64.0	66.0

Table 5: Correlation matrix

	Gesture Popularity	Preference	Match	Easiness	Effort order	Posture score	Gesture agreement	Command agreement	Response time
Gesture Popularity	1								
Preference	0.14	1							
Match	0.21	0.22	1						
Easiness	0.12	0.22	0.20	1					
Effort order	0.14	0.54	0.09	0.14	1				
Posture score	0.11	0.06	0.00	0.04	0.10	1			
Gesture agreement	-0.12	-0.11	0.00	-0.18	-0.22	-0.11	1		
Command agreement	0.38	0.05	0.23	0.10	0.01	0.01	0.05	1	
Response time	-0.26	-0.14	-0.27	-0.04	-0.22	-0.12	0.00	-0.59	1

A post-hoc analysis was conducted of the correlations between variables for the developed gesture-command set (Table 5). Conceptual complexity was related to command agreement score inversely (-0.38) and time to first gesture (0.57). Time to first gesture and command agreement score had a correlation value of -0.62. User subjective preference and had correlations of 0.52 for gesture order and 0.54 for effort order. Gesture order and effort order had a correlation of 0.56.

Of the 34 commands, 22 selected command-gestures were based on the highest S and 25 were based on the highest WS score. Four of the exceptions were *cut*, *paste*, *duplicate*, and *insert*. Most of the gestures recommended by subjects for these commands would not been visible to gesture systems. For example, *paste* was scored 64 S and 62 WS for motioning like pressing down glued paper across the left hand. However placement of the left hand between common sensor placement and right hand motion would have made the gesture invisible to many systems. Recommended gestures for *duplicate* and *insert* had sum values of zero. *Duplicate* and *insert* had very low agreement scores of 0.02 and 0.06. Of all the gestures presented for duplicate and insert, only 11% and 35%, respectively, had gestures that were presented three or more times. The remainder of gestures occurred two or less times and were not categorized and studied further. The highest rated gesture for *insert* was point and draw a caret however, system disambiguation between point and draw a caret and *pointing* led to the selection of the cut and paste gesture. Selection of the cut and paste gesture also limits the number of gestures that must be learned and memorized. The highest sum scores for *duplicate* were 59 with a 3 gestures combination: grab, pull towards user, and place back on screen. However, system disambiguation with the gesture grab and manipulate was a concern. In addition, selection of scissor movement used for cut paste, and insert reduced subject learning and memory requirement. If the gesture recognition system can distinguish the gesture, designers are encouraged to consider grab, pull towards user, and place back on screen for the *duplicate* command.

The highest sum for *enlarge* was an opening pinch gesture. However, because the Sum scores for *shrink*, *zoom in*, and *zoom out* were highest for the grab and manipulate gesture; grab and manipulate was still highly rated for enlarge; and a pinch gesture would add to gesture learning and memorization grab and manipulated gesture was selected for *enlarge*. If resources exist, designers may consider developing for both grab and manipulate and pinch gestures. Previously linking multiple gestures to one command has been proposed, and may be the best solution, but it increases the gestures that the system must recognize and may create some confusion for users (Wobbrock 2009).

Similar to *enlarge*, the highest *mute* sums were not selected for the proposed command-gesture set. The highest rated mute gesture was pinching of all fingers together while remaining straight, commonly known as a “shut up” gesture. However, because the selected gesture for mute was highly rated and did not add to user learning and memory it was selected. Again, designers are encouraged to include this gesture in addition to development of a gesture set if resources allow.

For *delete*, the highest rated gesture was pan with sums of 63. However, the pan gesture may be difficult to distinguish from the pan and task switch gesture. Similarly, *point*, sums of 62 S and 61WS, was scored higher. However, it would have been difficult to distinguish from the move cursor gesture. Therefore, another highly rated gesture (e.g., *grab and manipulate*) that did not increase user learning and memory was selected.

For *find* the highest rated gesture was *hand over the eyes* such as shielding one's eyes from overhead sun. However, system recognition was a concern, so the *hand shaped like telescope* gesture was selected. Again, if systems are able to interpret the *hand over the eyes* gesture, designers are encouraged to use the higher rated gesture.

The highest sums for previous were not selected. *Turning a knob counterclockwise* has sum values of 60 S and 59 WS. However, *pointing in towards the screen* gesture for previous command has values 62 S and 61 WS. *Pointing in towards the screen* was not selected because of difficultly disambiguating from *pointing to control cursor and select*. In addition, the highest sum for *volume up* and *mute* were the gesture for *turning a knob*, which formed a command-gesture combination with easy learning and memory. *Turning knob counterclockwise* for *volume down* was second highest rated.

Holding hands towards the screen with no movement had scores of 59 S and 59 WS for gesture off. However, *grabbing and closing the hand* had sum scores of 61. *Because holding hands to the screen* was more easily disambiguated from *grab and manipulate* gestures it was selected.

Discussion

A gesture set for 34 common computer commands was created based on an Overall Sum score of subject ratings of preference, easiness, match, effort, posture, and popularity. The final match of gesture to command was guided by expert opinion. Approximately half of the commands were assigned the same gesture as another command, requiring, therefore, a context based selection process.

The Overall Sum Score for each potential gesture-command were calculated with and without an expert weighting of the 6 variable ratings. However, because weighted and unweighted Overall Sum Scores were highly correlated (r=0.89), the weighted method did not alter gesture selection.

The six variables used for calculating the Overall Sum Scores were not highly correlated with the exception of *subjective preference* and *effort order* (r=0.54); therefore, they were measuring different characteristics of the gesture-command match. Gesture *response time* was correlated with the *agreement score* (r=-0.59). This suggests that, in general, the less time it takes for users to select a gesture for a command the more likely that many subjects would pick the gesture for the command. Commands that required more time for many subjects to pick the same gesture for a command, and vice versa, were *next*, *mute*, *previous*, *paste*, and *menu access*. The gestures for three of these commands (*paste*, *mute*, and *previous*) were selected by expert opinion and not because of their Overall Sum scores. This indicates that expert opinion may be most useful when the response time is long and agreement is low.

Interestingly, a number of users used a left fist to disambiguate similar right hand gestures. For example, a left fist while pointing in and out with the right hand would mean *duplicate*, while without the left fist meant *open*. Designers may want to capture the left hand gesture to allow for multiple meanings of the same right hand gesture. In addition, as previously recommended, current menu options can be used to disambiguate gestures (Alpern 2003).

Our study primarily used subjective preference, popularity, match, easiness, effort, posture, and expert opinion to create a gesture-command set. Previous studies have used subsets of these factors and, to some extent, had overlapping findings. De la Barré et al., also selected *pointing with the finger* for the *select* command (2009). However, based on our methods, *pointing in* towards screen was used instead of an extended *stationary point*. More users performed *pointing in* and it had higher subjective ratings. However, it is possible that *stationary pointing* may provide a better user experience when performed over time on a functional system are may be easier for the image analysis system to recognize. Karam et al. (2005) and Alpern et al. (2003) examined gesture sets for music control. Similar to our results, Karam et al. selected a *left to right hand wave* for *next* piece and *right to left hand wave* for the *previous* piece. Through the specifics of the gestures differed, many subjects used a left to right movement for *next* and right to left for *previous*.

Wobbrock et al. (2009) used a similar interview method to determine a touch surface (2D) gesture set. Many of the Wobbrock et al., proposed gesture-commands were similar to our set. For example, we propose *minimize* as panning downwards with an open hand while Wobbrock et al., proposed pointing and dragging the object downwards. Our *minimize* gesture is optimized for a 3D interaction space and posture. Wobbrock et al. proposed a high number of one finger pointing gestures; all but four. Our command-gesture set only includes four gestures with pointing. The differences are likely due to the increased capabilities of 3D gesture compared to touch screen and our inclusion of posture score in gesture selection. Some gestures we proposed, such as *accept* and *reject* as *thumbs up* and *thumbs down* would not have been possible for a touch screen interaction. Interestingly, Wobbrock et al., proposed use of drawing a *check mark* and *X* for *accept* and *reject* were our second highest scored gestures for the same commands. It is also interesting to note the similarities in the proposed gestures despite different study populations.

Our approach to developing a gesture-command language considered user cognitive load and system gesture recognition capabilities (expert opinion). Similar to previous studies, our gesture set attempted to limit cognitive load through consistency and symmetry in order to reduce learning and memory demands (Wobbrock 2009; Wu 2003, Alpern 2003; Kaiser 2003). Our gestures are meant to be distinguished from camera angles from one plane. The gestures are also meant to be distinctive allowing for recognition of differences in spatio-temporal variability (Keskin 2003).

Several limitations of the study should be noted. First, the subjects were male and female English speakers from Northern California. Computer users from other countries or cultures may select a different set of gesture-commands. Second, the gestures were proposed by the subjects without the aid of functional gesture recognition system. The approach was preferred because a functional system may have constrained the gestures that subjects would propose. On the other hand, the approach allowed for gestures that will never be interpretable by gesture recognition systems. Third, in order to best use subjects' time during the experiment, the ratings of preference, match and easiness were only collected for the two most preferred gestures for a command. This may have led to some gestures not being selected for commands.

In conclusion, we present a method for developing a 3D gesture language for common commands for human-computer interaction. The method considers subjective preference, easiness of forming gestures, hand biomechanics and other factors. The method led to a gesture-command language with 12 gestures assigned to 34 commands. This gesture-command language and other proposed languages should be studied with functional systems to evaluate productivity, usability and upper extremity fatigue compared to the usual method of using a mouse or touch pad for human-computer interaction.

Conclusion

Four laboratory studies measured risk factors and user preference for three different types of human computer interaction (HCI). Chapters 2 and 3 focused on keyboard key spacing of horizontal and vertical directions and effects on muscle activity level, wrist posture, productivity, and user preference. Chapter 4 examined tablet size, grip shape, and texture on muscle activity level, posture, productivity, and user preference. Chapter 5 presented a user defined 3D gesture set optimized for posture risks and cognitive load. Results added to the literature on ergonomic design of HCI, provide recommendations for HCI designers, and support changes in HCI standards.

Chapter 2 demonstrated no significant differences in gross typing speed, percent error, and subjective usability ratings between the keyboards with 17, 18 and 19 mm horizontal and 17 and 19 mm vertical key spacing. However, typing speed, percent error, and usability ratings were significantly worse for the keyboard with horizontal key spacing of 16 mm compared to the other keyboards. Evidence suggested that productivity decreased due to biomechanical factors such as fingertips striking two keys at once because the fingertips are too large or precision of finger motor control is poor for 16 mm spacing. Based on these findings, keyboard designers are encouraged to consider designing keyboards with horizontal and vertical key spacing of 17 or 18 mm to gain the benefits of smaller keyboards, e.g., smaller and lighter laptops; reduced cost to manufacture; better usability for users with smaller hands; and reduced reach to the computer mouse, while still accommodating the needs of typists with large fingers.

Chapter 3 was complementary to Chapter 2 in that there were no significant differences on the same usability and health measures with vertical spacings of 16, 17 and 18 mm. However key spacing of 15.5 mm was significantly worse than the other key spacings. Chapter 3 finds minimal differences in typing speed, percent error and usability measures between keyboards with vertical key spacing between 16 and 18 mm. However, a keyboard with vertical key spacing of 15.5 mm was associated with a significant reduction in productivity and usability. Based on these findings, keyboard designers may consider designing keyboards with a vertical key spacing of as little as 16 mm and horizontal spacing as little as 17 mm to gain the benefits of smaller keyboards, such as smaller and lighter laptops; reduced manufacturing costs; and reduced reach to the computer mouse.

Chapters 2 and 3 allow the overall footprint the alpha keys of the QWERTY keyboard to be reduced by 2.5 cm in the horizontal direction and 1 cm in the vertical direction. Additional footprint size reduction could be achieved by also reducing the same dimensions of the numeric row keys. Further footprint reduction could be achieved through the reduction of infrequently used symbol keys. Because the symbols are infrequently used, the change would have limited effect on productivity outcomes. As Chapter 4 demonstrated, smaller tablets were preferred by users and have less musculoskeletal risks. By reducing the keyboard footprint, tablet companies can create smaller and lighter devices, thereby improving the biomechanics of use while maintaining productivity. Results from Chapters 2 and 3 will likely change keyboard design standards.

Chapter 4 examined the effects of tablet size (and weight) and shape on usability, fatigue, and biomechanics. The findings support 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. Subjects reported improved usability and security from dropping 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. It appears that reducing tablet size and weight below the mid-size tablet provides no additional advantages on usability, fatigue and holding time. Addition of texture and hand grips to large tablets increased subjective security ratings. Large tablets also had less fatigue when held in portrait orientation. There were no differences in productivity between any of the design conditions. 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.

Portability of tablets has the potential to increase worker productivity, especially in field settings. Reduced size and weight of tablets has the potential to decrease the musculoskeletal risks compared to conventional, large tablet computers. Previously, there was little data on the effects of tablet design features on productivity and comfort. Already, a number of devices on market have started to explore this space. The Google Nexus is small and covered in a rubber like texture. The Microsoft Surface has a kickstand that can serve as a handle. The iPad mini has sold millions of small form factor tablets. Empirical evidence of these design changes from the original iPad had not been previously explored. Designers now have initial empirical evidence to aid in designing of tablets for mobile comfort and productivity.

Chapter 5 presents a method for developing a 3D gesture language for common commands for human-computer interaction. Specifically, 30 subjects were interviewed for their recommendations for gestures to execute 34 frequently used computer commands. The final command-gesture set was based on subject selection, an Overall Sum based on preference, easiness, match, effort, posture, and popularity, and guided by expert opinion. The method led to a gesture-command language with 12 gestures assigned to 34 commands. Since half of the commands were assigned the same gesture as another command, this language requires a context based command selection process.

Consideration of posture risks in addition to subject selection, preference, easiness, match, effort, gesture popularity, and expert opinion provides empirical data for a new technology early on in its development. The infamous QWERTY layout, which was created to slow typewriter typists down, became the standard for computer keyboards and provides an example of creation of computer input devices that are not designed for usability and comfort. By studying gesture-command language early, we hope to influence the design of 3D gesture for a variety of user needs and provide designers with empiric data to create comfortable and usable 3D gesture sets.

A limitation of Chapters 2 and 3 was the simple alpha typing task without numbers or punctuation. It is possible that increased numerical input or input using the punctuation keys could have altered the findings. Another potential limitation was the short duration of keyboard use. However, the finding that typists performed equally well on 17, 18, or 19 mm horizontal spacing, suggests that these result are likely to be stable over time. Another limitation was the study examined conventional keyboards. As onscreen and touch keyboards become available, it's possible that key spacing results would be different. With onscreen and touch keyboards, tactile feedback is not provided and users do not have individual keys to provide feedback for finger placement. However, onscreen and touch keyboards have the potential to develop algorithms that predict and correct peoples' typing, therefore increasing their typing speed. A potential limitation of the study was that while the vertical spacing between keys changed between the test conditions, the size of the keycaps remained constant. It is possible that if the key cap size was reduced in proportion to the key spacing, the error rate and productivity may not have declined at the smallest key spacing.

The findings from Chapter 4 should be interpreted carefully because the study used non-functioning tablets and simulated tasks. Productivity and usability ratings may be different if subjects were using functional tablets. Grip shape had an effect on usability and fatigue but the results may have been confounded by differences in the weights of the tablets. Another limitation 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 since subjects did not have a full selection of all possible tablets. The study examined only 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 at higher risk of fatigue and will have more difficulty with usability due to the size and weight of the tablet relative to their grip span and strength.

Several limitations of the gesture study should be noted. First, the subjects were male and female English speakers from Northern California. Computer users from other countries or cultures may select a different set of gesture-commands. Second, the gestures were proposed by subjects without a functional gesture recognition system. The approach was preferred because a functional system may have constrained the gestures that subjects would propose. On the other hand, the approach allowed for gestures that are unlikely to be interpretable by current gesture recognition systems but may be visible by future systems. Third, in order to best use subjects' time during the experiment, the ratings of preference, match and easiness were collected for only the two most preferred gestures for a command. This may have led to some gestures not being selected for commands.

Future work of Chapters 2 and 3 could include onscreen and touch keyboards with and without correction and prediction algorithms. It is possible that touch only, non-travel keyboards would have different results. Future work could also examine reduction of rarely used keys, such as symbols and the number row to further reduce overall keyboard footprint. Finally, future research could investigate the role in decreased key cap size for smaller key pitch, since there was evidence of fingertips striking two adjacent keys simultaneously which increased error rate for the smallest key pitches.

Future work of Chapter 4 could consider examining the effects of tablet size with functional tablets to assess productivity and error more realistically. A wider range of ledge and handle dimensions could be explored to identify designs that improve security with minimal increase in weight. Additionally, studies with longer duration tasks are likely to better discriminate difference in fatigue between devices. Other variables, such as radius of edges, additional tablet sizes, and changes in functional software to optimize different sizes could also be future work. Finally, studies in different postures, such as seated tablet use, could aid in design across modalities.

Future work of Chapter 5 could include evaluation of usability of gesture-command sets with functional 3D gesture sensors. Functionality of sensors would allow users to observe the results of their gestures which may alter responses. Functional sensors would also provide feedback into gesture visibility. Other future research could include evaluation of different gesture-command sets for user memory and cognitive load.

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