The Effect of Keyboard Key Spacing on Typing Speed, Error, Usability, and Biomechanics: Part 1

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Objective: In this study, we evaluated the effects of key spacing on a conventional computer keyboard on typing speed, percentage error, usability, and forearm muscle activity and wrist posture.

Background: International standards that specify the spacing between keys on a keyboard have been guided primarily by design convention because few studies have evaluated the effects of key spacing on productivity, usability, and biomechanical factors.

Method: Experienced male typists (*N* = 37) with large fingers (middle finger length ≥ 8.7 cm or finger breadth of ≥ 2.3 cm) typed on five keyboards that differed only in horizontal and vertical key spacing (19 × 19 mm, 18 × 19 mm, 17 × 19 mm, 16 × 19 mm, and 17 × 17 mm) while typing speed, percentage error, fatigue, preference, extensor carpi ulnaris and flexor carpi ulnaris muscle activity, and wrist extension and ulnar deviation were recorded.

Results: Productivity and usability ratings were significantly worse for the keyboard with spacing of 16 × 19 mm compared with the other keyboards. Differences on these measures between the other keyboards were not significant. Muscle activity tended to increase in the left forearm and decrease in the right with decreasing horizontal key spacing. There was also a trend for left wrist extension to increase and left ulnar deviation to decrease with decreasing horizontal key spacing. Reducing vertical key spacing from 19 to 17 mm had no significant effect on productivity or usability ratings.

Conclusions: The study findings support key spacing on a computer keyboard between 17 and 19 mm in both vertical and horizontal directions.

Applications: These findings may influence keyboard standards and the design of keyboards.

Keywords: key pitch, keyboard design, tool design, switch, wrist posture, electromyography

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INTRODUCTION

As laptop computers have become smaller, some laptop designers 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, Barr, Brafman, & Young, 2007). However, the key spacing on the majority of laptop and desktop keyboards follows the national and international standards of 19 mm. Minikeyboards, 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 (International Organization for Standardization [ISO]) and American (American National Standards Institute [ANSI], Human Factors and Ergonomics Society) standards (ANSI, 2007; ISO, 2008). The current ISO and ANSI 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).

The effect of key spacing on performance has been evaluated in only a few studies. In a study in Japan, Yoshitake (1995) 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 participants 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 participants 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

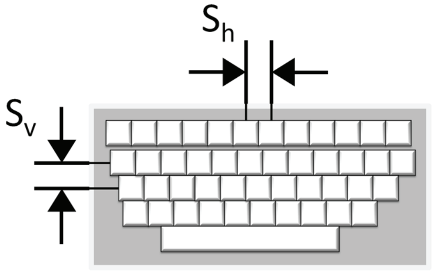

Figure 1. Horizontal (S_h) and vertical (S_v) key spacing on a conventional keyboard. From ANSI/HFES 100-2007, "Human Factors Engineering of Computer Workstations." Copyright 2007 Human Factors and Ergonomics Society. Used with permission.

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 U.S. adult male (National Institute of Bioscience and Human Technology, 1996; Pheasant, 1996). Other limitations of the study included the small study sample size (N = 8), performance based on a single-word task, and that key top sizes differed between keyboards, potentially confounding the results. A different study, carried out on numerical keypads, found greater input time and percentage error when key spacing was 21 mm compared with 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, Daniels, & Kanarick, 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). In that study, 30 users typed on each keyboard while performance, percentage error, and user preference were recorded. An analysis of a variable that combined the three outcomes revealed that the 19.0-mm horizontal and vertical key spacing was preferable to the other key spacings. However, the study had some shortcomings, such as nonrandomized keyboard order, large difference in key spacing tested, and combination of outcomes into a single metric. The authors of 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, percentage error, muscle activity, wrist posture, and usability among computer users with large fingers. On the basis of Yoshitake's (1995) study, we considered it likely that computer users with small fingers would readily adapt to keyboards with smaller key spacing; therefore, this study focused on individuals 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, percentage 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. In this article, Part 1, we primarily examine spacing in the horizontal direction for touch typists with large fingers. In Part 2, we primarily examine spacing in the vertical direction for touch typists with large and small fingers.

METHOD

In this laboratory study, 37 participants performed touch-typing tasks in five keyboard test conditions. The independent variables were the five keyboard spacings. Dependent variables were typing speed, percentage 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 participants signed a consent form.

Participants

Eligibility criteria were male gender, age between 18 to 65 years, the ability to touch type at least 30 words per minute (WPM), 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. Participants were excluded if they reported current upper-extremity musculoskeletal disorders. Participants were recruited through flyers placed on the university campus and in the community and from among participants in prior studies. A sample size of 30 was estimated with the use of a two-tailed alpha of .05, a beta of .80, and the mean and standard deviation of typing speed of large-fingered typists from Yoshitake's (1995) study.

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 participants 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 U.S. military (Greiner, 1991). The mean participant 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). Of the five keyboards, four varied in horizontal key spacing of 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 of 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.

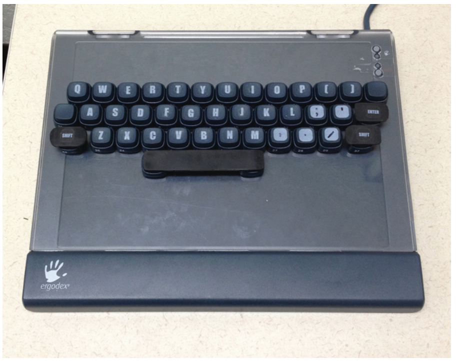

Figure 2. Keyboard with key spacing of 19 × 19 mm.

Practice Session

On the day of the study, participants first warmed up by touch-typing on the 16- by 19-mm keyboard for five 10-min sessions with 3-min breaks between sessions. Before continuing with the experiment, participants rested for 15 min.

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 participants. Typing passages were from news articles and books with grammar at the eight- or ninth-grade reading level (McLaughlin, 1969). Passages included capitalization that required shift key use but did not include numbers or punctuation. All practice sessions contained the same five passages given in the same order. The program calculated gross typing speed and percentage error. Percentage error was equal to incorrectly typed words multiplied by the average word length of five, divided by total keystrokes, and reported as a percentage. 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 five keystrokes to calculate typing speed in

WPM. WPM is a common metric for reporting productivity (Rempel, 2008; Simoneau, Marklin, & Berman, 2003).

Workstation Setup

The participants 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 two-button mouse could be placed at any location on the work surface. The monitor (20-in. diagonal) was adjustable in horizontal and vertical tilt angle and distance. Prior to the start of the experiment, chair height was adjusted so the participant's feet rested comfortably on the floor, work surface height was set to the participant's elbow height, and the keyboard was placed 18 cm from the edge of the work surface in front of the participant. Participants 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, participants 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, participants typed 3 of 15 possible passages in 5-min blocks. All participants typed all 15 passages. Productivity measurements were calculated from the average of the three trials per keyboard condition. Participants were instructed to type as fast but as accurately as possible. They took a 1-min break between blocks and a 5-min break between keyboard test conditions.

Usability and Fatigue Ratings

After each keyboard was used, usability and fatigue were assessed with the ISO keyboard questionnaire (ISO, 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 (EMG)

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 EMG (TeleMyo 2400T, Noraxon USA, 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 at anatomical landmarks (Perotto, 2005). EMG activity of both muscles was sampled from both the right and left arm at 1500 Hz. We normalized the data to the EMG activity during maximum exertion obtained by having the participant perform three 3-s maximum voluntary contractions (MVC) for each muscle (Shergill et al., 2009). The MVC values for the ECU and FCU were calculated from the highest average value of a 1,000-ms moving window across the three maximum exertions in resisted wrist ulnar deviation while the forearm was horizontal in pronation and the wrist was in a neutral posture.

Wrist Posture Measurement

We measured wrist flexion and extension and ulnar and radial deviation continuously for both wrists using two inline electrogoniometers (2D Goniometer SG-65, Noraxon USA, Scottsdale, AZ). The goniometers were secured to the dorsal surface of the hand and distal forearm and calibrated with the wrist in neutral (0° of flexion, 0° 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 with the use of repeated-measures ANOVA (RMANOVA) with the Tukey follow-up test for mean typing speed, percentage 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 with the use of Friedman's matched-group ANOVA test with Nemenyi multiple comparison test.

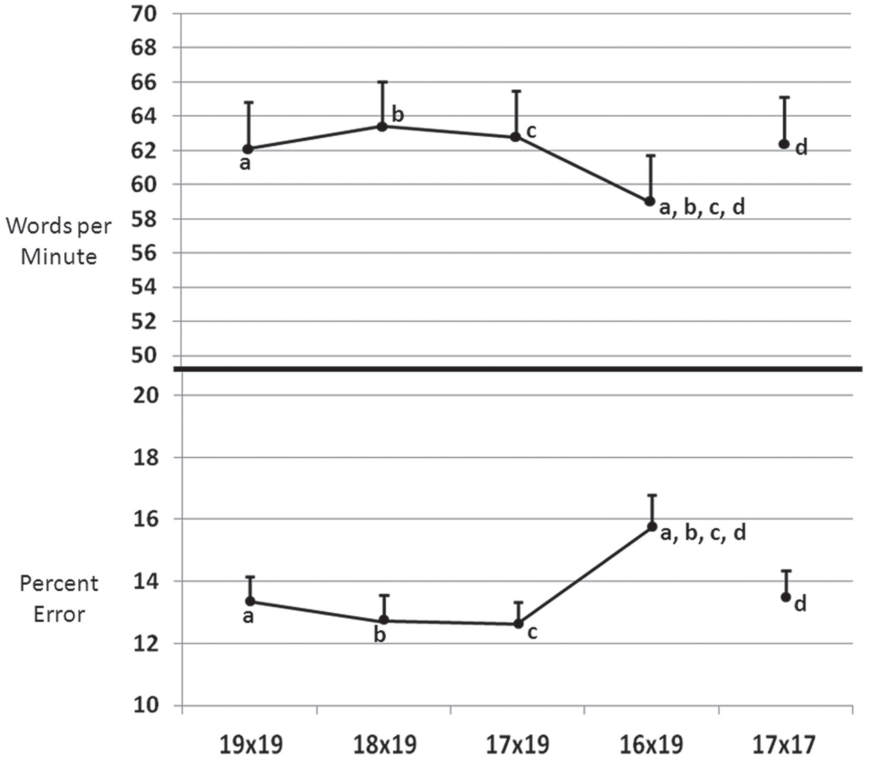

Figure 3. Mean words per minute and percentage error by keyboard (key spacing: horizontal × vertical millimeters). Significant differences between keyboards are noted by a common superscript. Error bars are SEM. $N = 37$.

RESULTS

Gross typing speed was significantly slower ($p < .001$) and percentage error was significantly higher ($p < .001$) for 16 × 19 mm compared with the other key spacings (Figure 3). There were no significant typing speed or percentage error differences between the other key spacings, including vertical spacing of 19 mm and 17 mm. There was no significant effect of trial order on typing speed or percentage 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.

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 ($p = .008$), right ECU ($p < .001$), and right FCU ($p < .001$). For the left ECU, muscle activity was significantly greater for the keyboard with spacing of 19 × 19 mm compared with those of 17 × 19 mm and 17 × 17 mm. For the right ECU, muscle activity was significantly greater for the keyboard with spacing of 19 × 19 mm than for all other keyboards. For the right FCU, muscle activity was significantly greater for 19 × 19 mm than for 17 × 19 mm and 17 × 17 mm. In addition, right FCU muscle activity was greater for 18 × 19 mm compared with 17 × 17 mm. There were no significant differences between keyboards for the left FCU ($p = .085$).

Left wrist extension was significantly greater for the keyboard with spacing of 17 × 17 mm compared with those of 19 × 19, 18 × 19, and 17 × 19 mm ($p < .001$). It was also significantly greater for the keyboard with spacing of 16 × 19 mm than for those of 19 × 19 mm and 18 × 19 mm, and it was significantly greater for 17 × 19 mm than for 19 × 19 mm. Right wrist extension

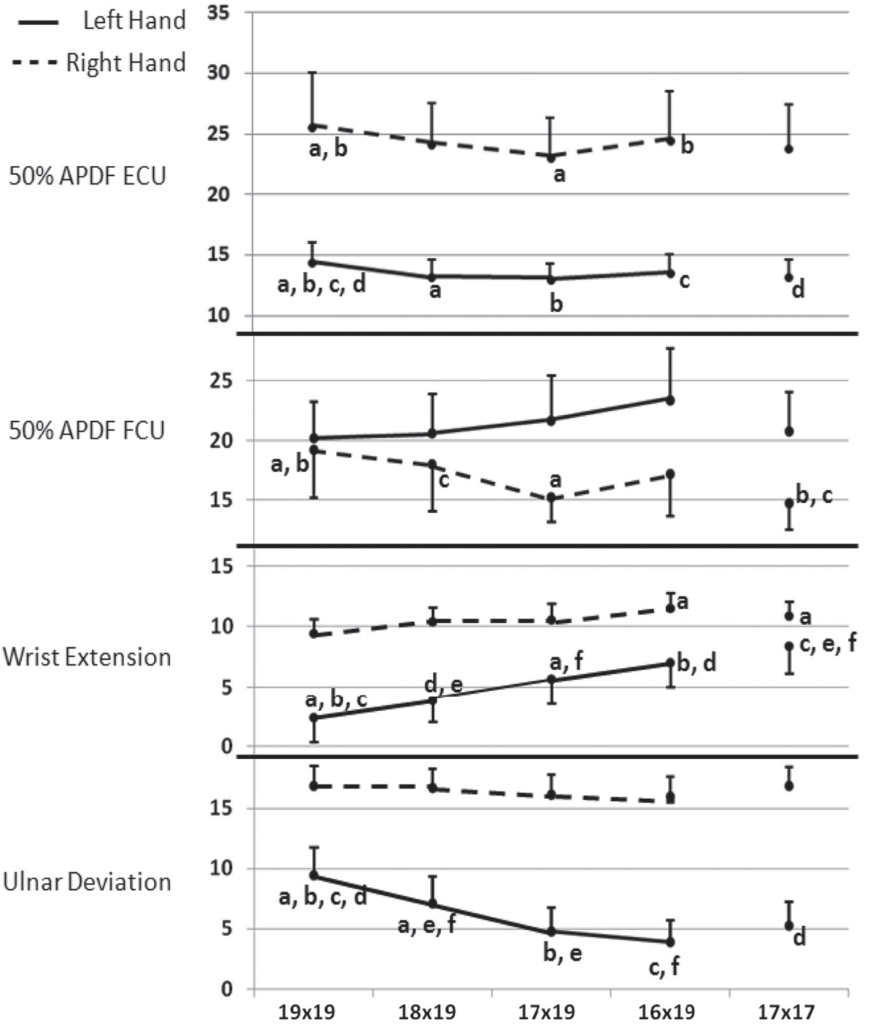

Figure 4. Muscle activity, wrist extension, and ulnar deviation during typing by keyboard (key spacing: horizontal × vertical millimeters). Significant differences between keyboards are noted by a common superscript. Error bars are SEM. $N = 35$. APDF = amplitude probability density functions; ECU = extensor carpi ulnaris; FCU = flexor carpi ulnaris.

was significantly greater for 16 × 19 mm than for 17 × 17 mm ($p < .001$). Left wrist ulnar deviation was significantly greater for 19 × 19 mm when compared with all other keyboards ($p < .001$). It was also significantly greater for 18 × 19 mm compared with 17 × 19 mm and 16 × 19 mm. For right ulnar deviation, no significant differences between keyboards were observed ($p = .14$). 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, key spacing of 16 × 19 mm received the worst ratings compared with the other keyboards, whereas the differences between the other keyboards were not large. Specifically, for force required to activate keys and keying rhythm, spacing of 16 × 19 mm was rated significantly worse compared with all other keyboards ($p < .001$). For fatigue in hands or wrists, spacing of 16 × 19 mm was rated worse compared with 19 × 19 mm and 17 × 19 mm ($p = .001$). Fatigue in arms was rated significantly worse for the key spacing of 16 × 19 mm

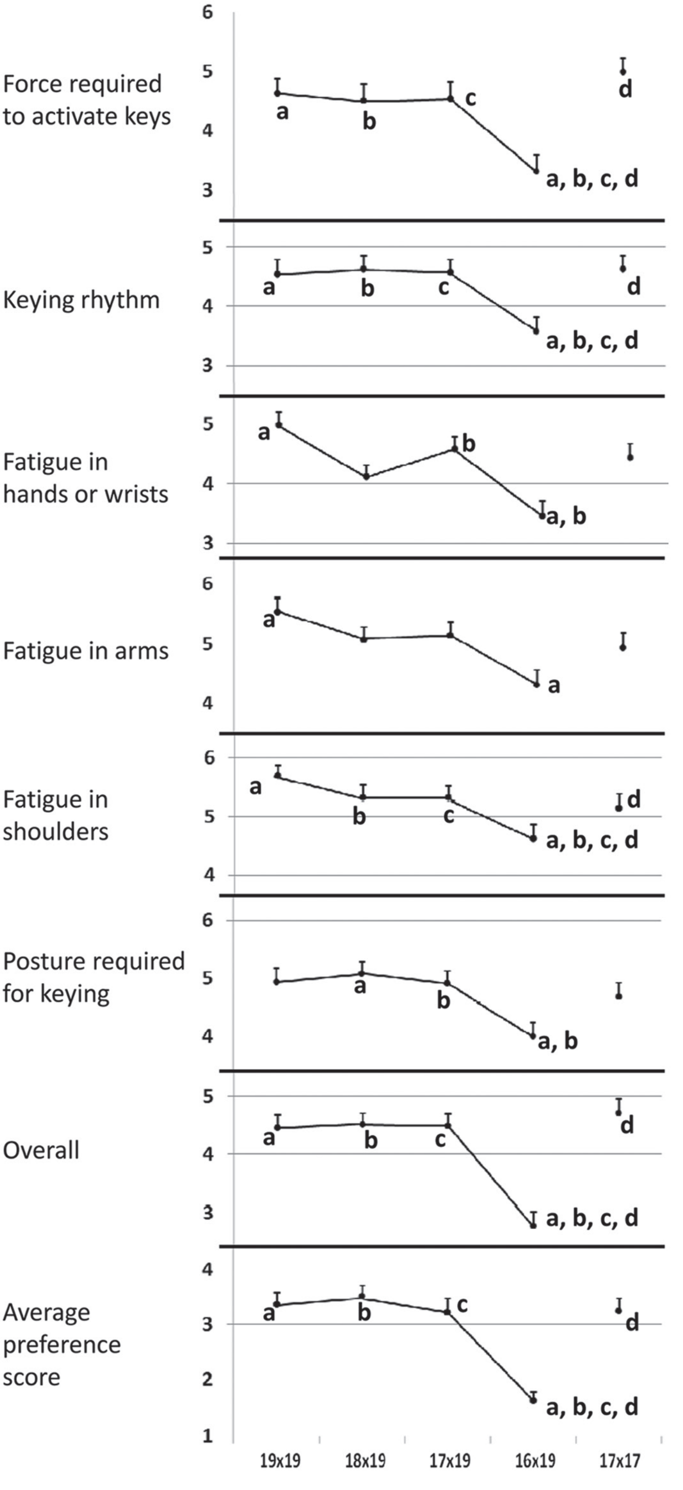

Figure 5. Subjective usability ratings of keyboards (1 = *poor characteristic* and 7 = *good characteristic*). Significant differences between keyboards are noted by a common superscript (Friedman's test and Nemenyi follow-up). For preference, keyboards were rank ordered from 1 = *least favorite* to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

compared with 19 × 19 mm (p = .005). For fatigue in shoulders, spacing of 16 × 19 mm was rated significantly worse than 19 × 19, 18 × 19, and 17 × 17 mm ($p < .001$). Posture required for keying was rated significantly worse for spacing of 16 × 19 mm compared with 18 × 19 mm and 17 × 19 mm ($p < .001$). Overall, participants least preferred spacing of 16 × 19 mm in comparison to the other keyboards ($p < .001$). There were no significant differences in preference between the other keyboards.

DISCUSSION

No significant differences in gross typing speed, percentage error, and subjective usability ratings were measured between the keyboards with 17-, 18-, and 19-mm horizontal key spacing. However, typing speed, percentage error, and usability ratings were significantly worse for the keyboard with horizontal key spacing of 16 mm compared with 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 participants 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 did not specifically report typing error rates for large-fingered participants, the combined data across all finger sizes showed a trend of increasing errors at horizontal and vertical key spacing of 16 mm.

Typically, during typing on a conventional keyboard, percentage error decreases with decreasing typing speed. However, typing speed decreased and percentage error increased with the horizontal 16-mm key spacing. This finding suggests that decreased horizontal key spacing, not changes in typing speed, was the cause of increased error. Increased error may be attributable 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 because of 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 with all other spacings. Since the actual mean key activation forces were the same for all keyboards, this perception may be attributable to fingers' touching each other with the horizontal 16-mm key spacing. There was a nonsignificant increase in forearm muscle activity levels for the horizontal 16-mm spacing compared with spacings of both 17 × 19 mm and 17 × 17 mm, which may be attributable to the interference of adjacent fingers, such as crowding on the 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 = .33) between increasing finger width and increasing error and decreasing productivity and an opposite relationship with finger length (r = –.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 small, only 2% to 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, Armstrong, Rempel, and Woolley (2002) reported significant differences in forearm muscle activity of 1% to 2% between keyboard conditions from 2 hr of recorded EMG signals. Ergonomic modifications for meatpacking jobs have resulted in reductions of 2% to 5% in forearm muscle effort (Cook, Ludewig, Rosecrance, Zimmermann, & Gerleman, 1999). Therefore, although the observed differences are small, these small differences may be important for tasks performed 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 et al., 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 with use of 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 with 17-, 18-, and 19-mm horizontal spacing suggests that these results are likely to be stable over time. Authors of studies evaluating other characteristics of keyboards (e.g., stiffness or auditory feedback) have observed stable performance across multiple days of testing (Gerard et al., 2002; Gerard, Armstrong, Martin, & Rempel, 1999). 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 attributable to smaller key spacing and not to a lack of familiarity with small key spacing. Another limitation of the study is that it did not include typists with small fingers and did not include females. Participants 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, we find that there is little difference in typing speed, percentage error, and usability measures between keyboards with horizontal key spacing between 17 mm 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% to 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 mm or 17 mm, respectively. This finding may be mitigated by the observed simultaneous reduction in ulnar deviation. On the basis of these findings, keyboard designers are encouraged to consider designing keyboards with horizontal and vertical key spacing of 17 mm 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.

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KEY POINTS

- For typists with large fingers, typing speed, error, and usability ratings are the same when the center-to-center horizontal key spacing on a keyboard is 17.0 mm, 18.0 mm, or the current standard of 19.0 mm.
- For typists with large fingers, typing speed, error, and usability ratings are the same when the vertical key spacing is 17.0 mm or 19.0 mm.
- For typists with large fingers, typing speed, error, and usability are reduced when the horizontal key spacing is 16.0 mm in comparison to key spacing of 17.0, 18.0, or 19.0 mm.

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