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The Effect of Keyboard Key Spacing on Typing Speed, Error, Usability, and Biomechanics, Part 2: Vertical Spacing

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Objective: The objective was to evaluate the effects of vertical key spacing on a conventional computer keyboard on typing speed, percentage error, usability, forearm muscle activity, and wrist posture for both females with small fingers and males with large fingers.

Background: Part 1 evaluated primarily horizontal key spacing and found that for male typists with large fingers, productivity and usability were similar for spacings of 17, 18, and 19 mm but were reduced for spacings of 16 mm. Few other key spacing studies are available, and the international standards that specify the spacing between keys on a keyboard have been mainly guided by design convention.

Method: Experienced female typists (n = 26) with small fingers (middle finger length ≤ 7.71 cm or finger breadth of ≤ 1.93 cm) and male typists (n = 26) with large fingers (middle finger length ≥ 8.37 cm or finger breadth of ≥ 2.24 cm) typed on five keyboards that differed primarily in vertical key spacing (17 × 18, 17 × 17, 17 × 16, 17 × 15.5, and 18 × 16 mm) while typing speed, error, fatigue, preference, forearm muscle activity, and wrist posture were recorded.

Results: Productivity and usability ratings were significantly worse for the keyboard with 15.5 mm vertical spacing compared to the other keyboards for both groups. There were few significant differences on usability ratings between the other keyboards. Reducing vertical key spacing, from 18 to 17 to 16 mm, had no significant effect on productivity or usability.

Conclusions: The findings support the design of keyboards with vertical key spacings of 16, 17, or 18 mm.

Applications: These findings may influence keyboard design and standards.

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

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INTRODUCTION

This study complements "The Effect of Keyboard Key Spacing on Typing Speed, Error, Usability, and Biomechanics: Part 1" (Pereira et al., 2013), which evaluated the effects of keyboard spacing, primarily in the horizontal direction, on male typists with large hands. As previously discussed, international and national standards (International Organization for Standardization, 2008; Human Factors and Ergonomics Society, 2007) recommend key spacings of 19 × 19 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, Barr, Brafman, & Young, 2007).

In Part 1, we primarily evaluated the effects of horizontal key spacing (19 × 19, 18 × 19, 17 × 19, 16 × 19, and 17 × 17 mm [horizontal × vertical]) on typing speed, percentage error, usability, forearm muscle activity, and wrist posture (Pereira et al., 2013). The conventions for horizontal and vertical spacing are illustrated in Figure 1. Participants were experienced male typists (n = 37) with large fingers (75th 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 16 × 19 mm key spacing compared with 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 participants with large fingers (average middle finger length and proximal interphalangeal [PIP] joint width of 8.48 cm and 2.24 cm, respectively) the performance was

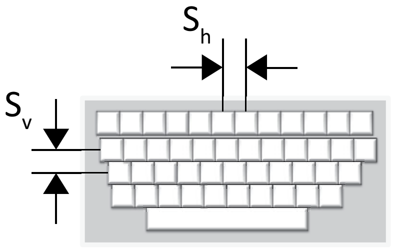

Figure 1. Horizontal (S_h) and vertical (S_v) key spacing on a conventional keyboard.

Source. Human Factors and Ergonomics Society (2007). Used with permission.

lower when the key spacing was 16.0 mm or less. However, for participants 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 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. Changes in key spacing in the vertical direction require changes in wrist and extrinsic finger extensor/flexor as well as intrinsic finger flexor/extensor motor control (Dennerlein, Mote, & Rempel, 1998; Repp, 2005). Changes in key spacing in the horizontal direction require 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 participants with small fingers was not influenced by key spacing, could not be confirmed.

The primary purpose of this study, Part 2, was to determine whether reducing vertical key spacing would modify typing speed, percentage 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, percentage 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.

METHOD

Detailed methods can be found in Part 1 (Pereira et al., 2013), but a summary of methods including differences from Part 1 is presented here. In this laboratory study, 26 female participants with small fingers and 26 male participants 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, percentage 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 participants signed a consent form.

Participants

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 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 (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 participant population hand anthropometry measures and the corresponding population percentiles are summarized in Table 1. The mean female and male participant 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	*M* cm (*SD*)	Range cm	% (Range)	*M* 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)

Note. DIP = distal interphalangeal joint; PIP = proximal interphalangeal joint.

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.

Setup and Typing Tasks

Participants warmed up for 50 min on the 17 × 16 keyboard, and during that time the chair and work surface height were adjusted to the most comfortable configuration. After the warm-up session, participants were not permitted to adjust the setup. They then completed three 5-min typing tasks with each keyboard. A random number generator assigned keyboard test order. For each keyboard test condition, participants typed 3 of 15 possible passages in 5-min blocks. Participants were instructed to type as fast but as accurately as possible.

Objective Outcome Measures

Gross typing speed and percentage error were calculated from the typing tests. Surface electromyography of the extensor carpi ulnaris and flexor carpi ulnaris 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, participants completed a usability and fatigue questionnaire. At the end of the study, participants 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 with Tukey's 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 ($p < .001$ and $p = .006$, respectively) and error rate was significantly higher ($p < .001$) for the 15.5 mm vertical key spacing compared to the other vertical key spacings (Figures 2 and 3). There were no significant

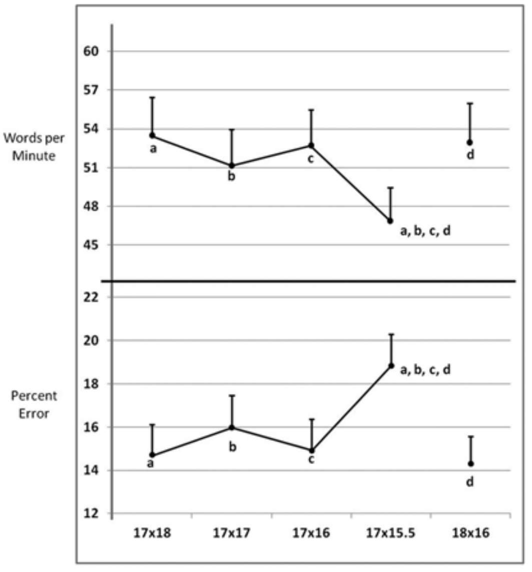

Figure 2. Females with small fingers: productivity and error. Mean words per minute and percentage error by keyboard (key spacing: horizontal × vertical mm). Significant differences between keyboards are noted by a common superscript. $n = 26$. Error bars are *SEM*.

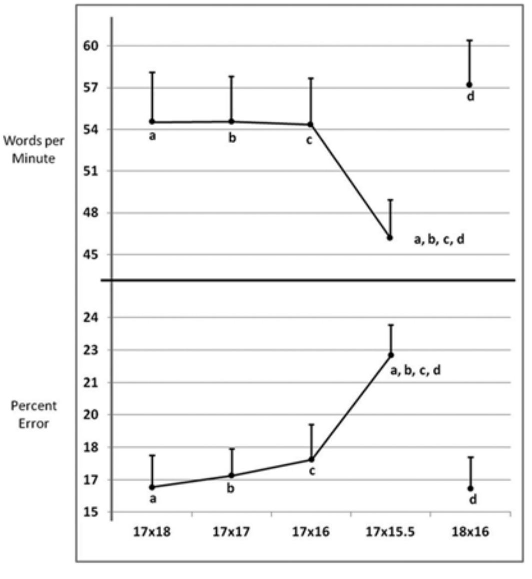

Figure 3. Males with large fingers: productivity and error. Mean words per minute and percentage error by keyboard (key spacing: horizontal × vertical mm). Significant differences between keyboards are noted by a common superscript. $n = 26$. Error bars are *SEM*.

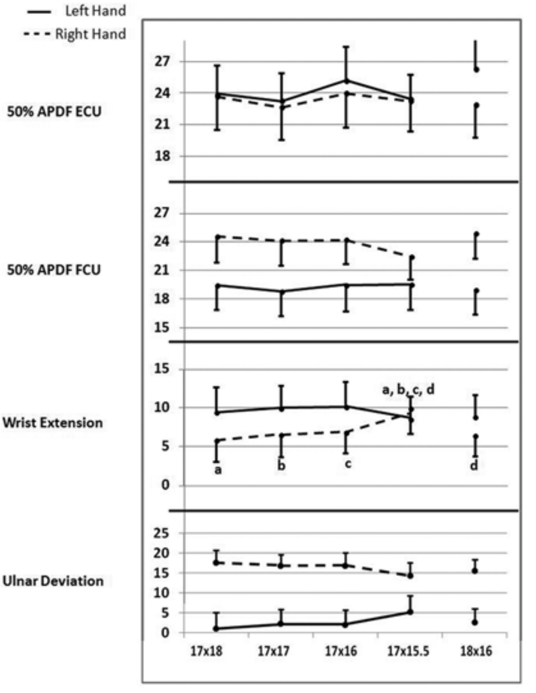

Figure 4. Females with small fingers: median muscle activity and mean wrist extension and ulnar deviation during typing by keyboard (key spacing: horizontal × vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are *SEM*.

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 percentage error, indicating no learning effect.

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 17 × 15.5 compared to the other keyboards ($p = .004$). Mean left wrist extension in males with large fingers was significantly greater for 17 × 15.5 compared to 17 × 17 keyboards ($p = .04$). 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.

Subjective comfort and usability ratings are summarized in Figures 6 and 7. Across all

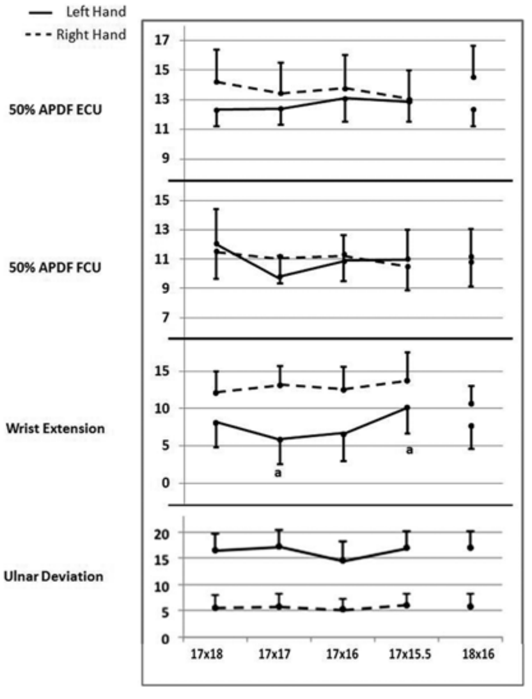

Figure 5. Males with large fingers: median muscle activity and mean wrist extension and ulnar deviation during typing by keyboard (key spacing: horizontal × vertical mm). Significant differences between keyboards are noted by a common superscript. Error bars are *SEM*.

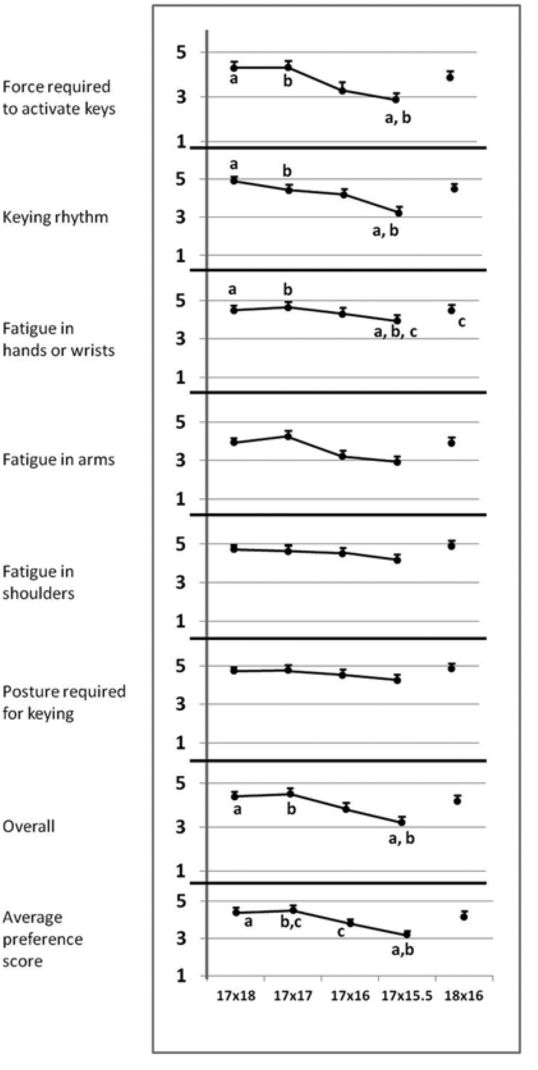

Figure 6. Female with small fingers: mean subjective usability ratings of keyboards (1 = *poor characteristic* and 7 = *good characteristic*). Significant differences between keyboards are noted by a common superscript. For preference, keyboards were rank ordered from 1 (*least favorite*) to 5 (*most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

subjective ratings, among both females with small fingers and males with large fingers, 17 × 15.5 received the worst ratings, compared to the other keyboards. The differences in ratings between keyboards other than 17 × 15.5 were not large. Male participants, when judging *force required to activate keys* and *keying rhythm*, rated 17 × 15.5 significantly worse compared to all other keyboards ($p < .001$). On the same outcome, females rated 17 × 15.5 significantly worse than 17 × 18 or 17 × 17 ($p < .001$). For *fatigue in hands or wrists*, males reported 17 × 15.5 to be worse compared to 17 × 18, 17 × 17, or 17 × 16 ($p < .001$), whereas female participants reported that 17 × 15.5 was worse than 17 × 18, 17 × 17, or 18 × 16 ($p < .001$).

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 17 × 15.5 significantly more fatiguing than 18 × 16 ($p = .005$). For p*osture required for keying*, males rated 17 × 15.5 significantly worse than all other keyboards ($p < .001$). For *overall* ratings, female participants rated 17 × 15.5 significantly lower than 17 × 18 or 17 × 17 ($p < .001$) and male

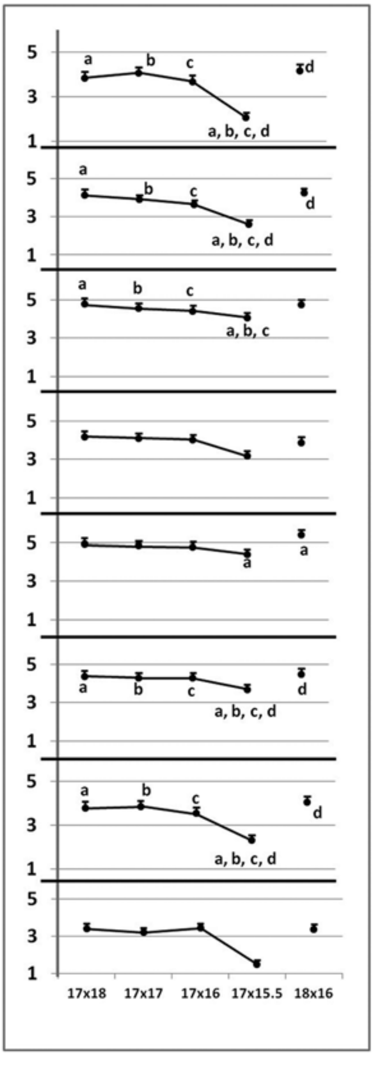

Figure 7. Males with large fingers: mean subjective usability ratings of keyboards (1 = *poor characteristic* and 7 = *good characteristic*). Significant differences between keyboards are noted by a common superscript. For preference, keyboards were rank ordered from 1 (*least favorite*) to 5 (*most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

participants rated 17 × 15.5 significantly lower compared to all other keyboards ($p < .001$). Females least *preferred* the 17 × 15.5 keyboard compared to the 17 × 18 and 17 × 17 keyboard and *preferred* the 17 × 17 keyboard over the 17 × 16 ($p = .001$). Male participants least *preferred* the 17 × 15.5 compared to all other keyboards ($p = .005$).

DISCUSSION

There were no significant differences in gross typing speed, percentage error, and subjective usability ratings among 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, percentage 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., 17 × 16 vs. 18 × 16 mm).

Yoshitake (1995) found no significant differences in performance for participants ($n = 18$) who typed on keyboards with five different key spacings 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 limit 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, percentage error, and subjective usability ratings between keyboards with different horizontal spacings, 17 × 19, 18 × 19, and 19 × 19 mm, but the outcome measures were significantly worse with the smallest horizontal key spacing, 16 × 19 mm (Pereira et al., 2013). The current study is complementary in that there were no differences on these measures with keyboards of different vertical spacings, 17 × 16, 17 × 17, and 17 × 18 mm; however, a vertical spacing of 17 × 15.5 mm was significantly worse. These findings also match the findings in Part 1 that compared two keyboards with different vertical key spacing, 17 × 19 versus 17 × 17. Combining the two studies provides evidence that horizontal spacing may be as low as 17 mm, whereas vertical spacing may be as low as 16 mm. Although the typical 19 × 19 keyboard was not directly compared in Part 2, in Part 1 the 17 × 17 keyboard was not significantly different from the 19 × 19 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 participant this effect was a result of the smaller key spacings, and not 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 cm 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 (Keir & Wells, 2002).

The biomechanical or motor control basis for the slight difference in vertical and horizontal minimal key spacing (e.g., 16 vs. 17 mm) is 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 metacarpophalangeal and PIP joints (Kuo, Lee, Jindrich, & Dennerlein, 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 is that although the vertical spacing between keys changed between the test conditions, the size of the keycaps remained constant. It is possible that if the keycap size had been 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 (International Organization for Standardization, 2008).

In conclusion, this study finds minimal differences in typing speed, percentage 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 study, Part 1, 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.

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KEY POINTS

- Typing speed, error, usability ratings, and biomechanical measures were similar when the center-to-center vertical key spacing on a keyboard was 16.0, 17.0, or 18.0 mm for both females with small fingers and males with large fingers.
- Typing speed, error, usability, and wrist extension were worse when the vertical key spacing was 15.5 mm compared to key spacings of 16.0, 17.0, or 18.0 mm for both females with small fingers and males with large fingers.

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