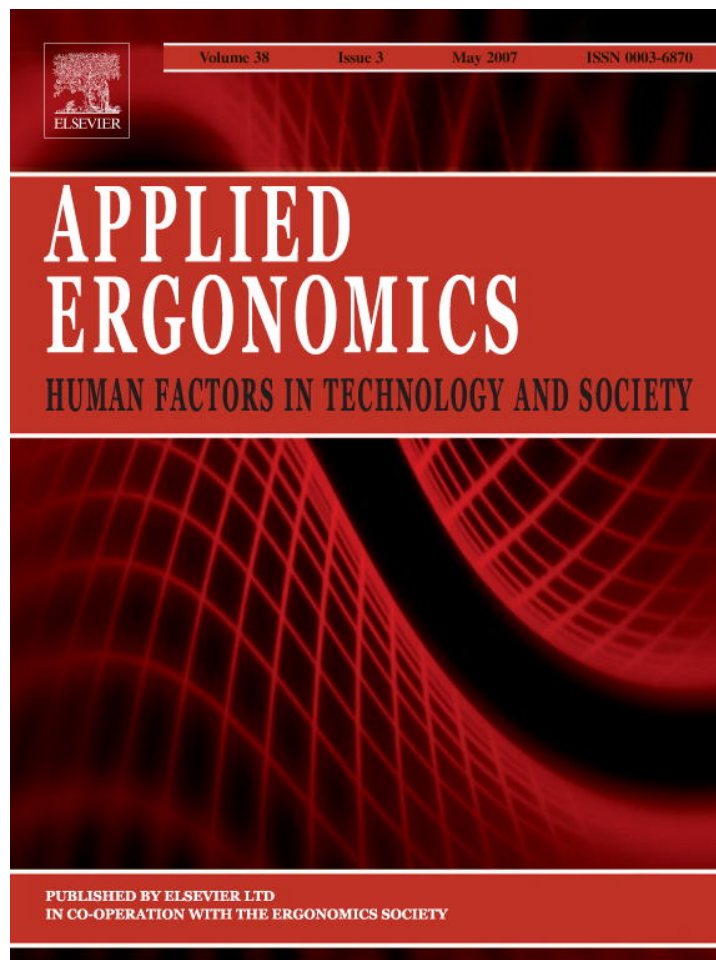


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# The effect of six keyboard designs on wrist and forearm postures

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## Abstract

There is increasing evidence that alternative geometry keyboards may prevent or reduce arm pain or disorders, and presumably the mechanism is by reducing awkward arm postures. However, the effect of alternative keyboards, especially the new designs, on wrist and arm postures are not well known. In this laboratory study, the wrist and forearm postures of 100 subjects were measured with a motion analysis system while they typed on 6 different keyboard configurations. There were significant differences in wrist extension, ulnar deviation, and forearm pronation between keyboards. When considering all 6 wrists and forearm postures together, the keyboard with an opening angle of 12°, a gable angle of 14°, and a slope of 0° appears to provide the most neutral posture among the keyboards tested. Subjects most preferred this keyboard or a similar keyboard with a gable angle of 8° and they least preferred the keyboard on a conventional laptop computer. These findings may assist in recommendations regarding the selection of keyboards for computer usage. © 2006 Elsevier Ltd. All rights reserved.

**Keywords:** Keyboard; Design; Posture

## 1. Introduction

Long hours of computer use are associated with elevated rates of musculoskeletal disorders in the arms and neck (Gerr et al., 2004). The evidence linking awkward wrist and forearm postures during keyboard use to elevated risk for arm disorders is mixed (Gerr et al., 2004). However, during the past 50 years, a number of alternative geometry keyboard designs have been proposed to reduce awkward wrist and forearm postures during typing (Kroemer, 1972; Zipp et al., 1983; Nakaseko et al., 1985; Honan et al., 1995). Only recently has there been evidence, from prospective intervention trials, that alternative geometry keyboard designs may reduce or prevent hand and arm pain and disorders (Tittiranonda et al., 1999; Moore and Swanson, 2003). Generally, these designs involve splitting

the keyboard into two halves and modifying the relationship of the two halves so that there is a reduction of ulnar deviation, wrist extension, or forearm pronation. For some designs, the two halves are fixed relative to each other, while for other designs, the two halves are adjustable (Marklin et al., 1999).

The presumed benefits of the alternative keyboard designs are reduced ulnar deviation, wrist extension, or forearm pronation and the associated reduction in muscle, tendon and nerve pressures and loads (Rempel et al., 1999). The effects of alternative keyboard designs on these postures have been investigated in a number of laboratory studies. The earliest studies measured wrist postures using manual goniometers (Nakaseko et al., 1985), while recent studies use motion analysis systems or electronic goniometers to measure wrist and forearm postures (Honan et al., 1995; Zecevic et al., 2000).

The purpose of this study was to evaluate the differences in wrist and forearm postures while subjects typed on 6 different keyboards. The null hypothesis was that there were no differences in wrist extension, wrist ulnar deviation, or forearm pronation between keyboard conditions.

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A secondary null hypothesis was that there were no differences in typing speed between keyboard conditions. Subjective feedback regarding the keyboards was also collected from participants during the study.

## 2. Methods

This was a full factorial, laboratory study in which 100 subjects performed a touch-typing task on 6 keyboard test conditions while wrist and forearm postures were measured in both upper extremities. The study was approved by the University of California at San Francisco Committee on Human Research.

### 2.1. Keyboard test conditions

The six keyboard designs evaluated and the naming conventions were (1) a conventional keyboard (CONV) (Dell Model No. SK-8110), (2) a conventional laptop (LAP) (Dell Latitude C800, Model No. PP01X), (3) a fixed split keyboard with 6° split but no gable (CURVE) (Microsoft Comfort Curve Keyboard 2000), (4) a fixed split keyboard with 12° split and 8° gable (ELITE) (Microsoft Natural Elite), (5) a fixed split keyboard with 12° split and 14° gable and 0° slope (ERGO) (Microsoft Natural Ergonomic Keyboard 4000), and (6) a fixed split keyboard with 12° split and 14° gable and -7° slope (REVERGO) (Microsoft Natural Ergonomic Keyboard 4000 with reverse slope attachment). The keyboard configuration angles and dimensions are listed in Table 1.

### 2.2. Subjects

Subjects were recruited from flyers placed on the university campus and at a local temporary employment agency. Inclusion criteria were the ability to touch type 40 words per minute and at least 1 week of experience using a split keyboard. Subjects were excluded if they reported current head, neck, back or arm injuries or difficulty performing a typing task for an entire day. Subjects who

did not have experience with a split keyboard were allowed to participate if they performed an intensive typing task for 4 h on a split keyboard (CURVE) several days prior to the study.

Subjects completed a demographic questionnaire. The subject's height without shoes and weight were measured, as were the right arm length (elbow to end of middle finger), hand length (palm side, distal wrist crease to end of middle finger), index finger length, and small finger length (dorsal side from metacarpophalangeal joint to tip of finger).

### 2.3. Practice session

On the day of the study, subjects warmed up by typing on the three alternative keyboards (ELITE, ERGO, REVERGO) for 10–20 min. Subjects were instructed to avoid resting their wrists, forearms, or elbows on the keyboard, work surface, or chair while typing. A program (Typing Workshop Deluxe, ValuSoft Inc., Waconia, MN) presented text on the screen, which was typed by subjects. The program was used in the practice and test sessions to calculate typing speed. Subjects who were unable to type at least 40 words/min during the last 5 min on keyboard ELITE during the practice session were eliminated from the study.

### 2.4. Workstation setup

The chair (Leap, Steelcase, Grand Rapids, MI) was secured to the floor and the back rest was adjusted to an inclination angle of 115°. The arm supports were removed from the chair. The chair pan height was adjusted so that the subject's feet were flat on the floor with their knees flexed 90° or less. The seat pan depth and back support height were adjusted to fit the subject's anthropometry. The monitor was adjusted so that the center of the monitor was 15° below the horizon from the eyes and approximately 60 cm from the eyes. After this setup, subjects could make small adjustments to the chair for comfort, but once the experiment began, subjects were not allowed to adjust the chair. After all workstation adjustments were made, the sitting elbow height (from floor to bottom of elbow) and seat pan height were recorded. The keyboard support surface height was adjusted to elbow height.

### 2.5. Data collection and marker placement

Subjects wore short-sleeve shirts to expose their arms. To record forearm and wrist posture, four lightweight plastic plates (32 × 35 × 5 mm, 16 g) were mounted to the dorsum of both hands and forearms using double-sided tape (each with infrared light emitting diodes (IREDS): 2 IREDS on the hand plate and 3 IREDS on the forearm plate). The IREDS were permanently attached to the plate and oriented toward a camera bank. IREDS on the hand plate were 4 cm apart.

Table 1  
Design dimensions and angles of 6 keyboard configurations tested

	Keyboard configuration					
	CONV	LAP	CURVE	ELITE	ERGO	REVERGO
Split angle (deg.)	0	0	6	12	12	12
Gable angle (deg.)	0	0	0	8	14°	14
Slope (deg.)	0	0	0	0	0	-7
Height (mm) <sup>a</sup>	30	35	20	41	36	49
Horizontal (mm) <sup>b</sup>	67	166	87	132	151	149
D to K (mm) <sup>c</sup>	95	94	106	144	138	138

<sup>a</sup>Height measured from the table surface to the top center of the "D" key.

<sup>b</sup>Horizontal distance from the front edge of the keyboard closest to the user to the center of the "D" key.

<sup>c</sup>Distance between the centers of the "D" and "K" keys.

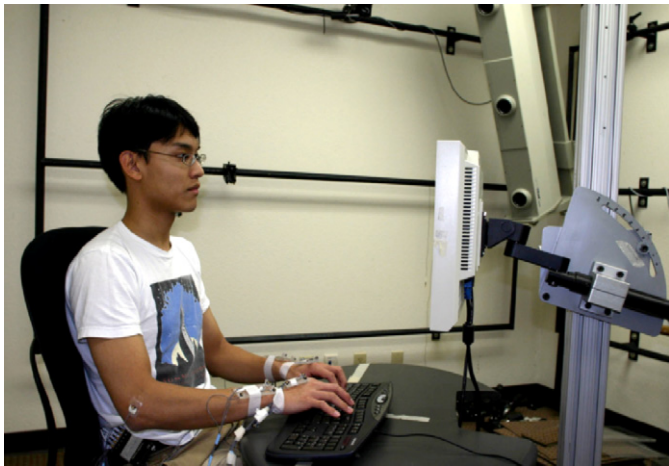


Fig. 1. Subject typing during experiment while forearm and wrist postures are recorded by camera banks in corners of the room. Note the 3D IRED markers on the elbow and on blocks on the distal forearm and the back of the hands.

Before the plates were attached, the subject's forearm was placed in a neutral posture (elbow at side, forearm in  $0^\circ$  supination/pronation, wrist in  $0^\circ$  extension and  $0^\circ$  ulnar deviation, and fingers straight). A line was drawn from the third metacarpal on the dorsal side of the hand to the lateral epicondyle. The forearm plate IREDs were located 2.0 cm from the line toward the ulnar head, 2.0 cm from the line toward the radius, and 2.0 cm from the line toward the ulnar head and 7.8 cm along the line toward the lateral epicondyle. The IREDs on the plate on the dorsum of the hand were aligned with the third metacarpal. An IRED was also attached to the lateral epicondyle (Fig. 1). The marker placement was modified from that used by Zecevic et al. (2000). Other studies have used electrogoniometers placed across the wrist to measure wrist posture during typing (Honan et al., 1995; Marklin et al., 1999; Simoneau et al., 2003; McLoone et al., 2005).

The 3-space coordinates of each IRED marker were recorded using 2 Optotrak 3020 sensor banks (Northern Digital, Ontario, Canada). Marker positions were recorded continuously at 10 Hz.

## 2.6. Posture calculations

The three IREDs on the forearm plate were used to form a local coordinate system, the origin of which lay above and between the styloid processes of the ulna and radius. The  $X$ -axis was directed proximally toward the lateral epicondyle and the  $Y$ -axis was directed toward the styloid process of the radius. The  $Z$ -axis was formed by the cross-product of  $X$  and  $Y$ . The 2 IREDs on the hand plate hand markers aligned with the third metacarpal were used to create a vector directed distally. The projection onto the  $XY$  plane of this vector was used to calculate ulnar deviation angles. The projection of the same vector onto the  $XZ$  plane was used to calculate wrist extension angles. Forearm pronation was determined by calculating the

rotation of the wrist-based coordinate system inside a global, workstation-based coordinate system. A reference posture of  $0^\circ$  flexion,  $0^\circ$  deviation and  $45^\circ$  pronation was collected by having the subject place their palms onto a trapezoidal block located on the table in place of the keyboard. Data for this reference posture were recorded for 10 s and used for subsequent posture calculations.

## 2.7. Testing protocol

Keyboard condition test order was randomized using a random number generator. For each test condition, the keyboard was secured to the work surface using double-sided carpet tape so that the home row was 16.0 cm from the front edge of the keyboard support surface; therefore, the keyboard distance to the subject was the same across all keyboards. The subject typed text from a passage displayed on the screen (the text passages were extracted from short stories by contemporary authors that included all the letters of the alphabet, numbers and punctuation). Approximately 5 min into the typing task, unannounced to the subject, posture data were recorded with the motion tracking system. After 5 min of data recording, the typing test was stopped and the subject's net typing speed was recorded. Typing speed was the gross typing speed minus errors. Subjects completed the comfort questionnaire for the keyboard (modified from ISO 9241). The next keyboard condition was tested after a 3 min pause.

After testing on all 6 keyboards, the subjects were asked to rank order the keyboards by categories (ease of use, accuracy, speed, comfort, overall) from 'best' (1) to 'least favorable' (6). The subjects were also asked to select their first choice among the keyboards.

## 2.8. Statistical analysis

Differences in postures between the 6 keyboard conditions were evaluated using repeated measures ANOVA. Significant findings were followed-up with the Tukey test for multiple comparisons. Differences in subjective ranking of keyboards were evaluated using Friedman's chi-square test and significant findings were followed-up with the Tukey test.

## 3. Results

A total of 105 subjects participated in the study and data for subjective evaluation of keyboards were available for all subjects. Due to hardware problems, posture data were available for only 100 subjects. The mean age of the 105 participants was 30.9 (SD  $\pm$  12.6) years, with 38 males (36%) and 67 females (64%); 56% were between 20 and 29 years old. Most participants, 58 (55%), were from the temporary hiring agency and the others, 47 (45%), were from the university staff and students. Most participants, 68%, had greater than 1 week experience typing on a split keyboard. Participants' handedness was 98 (93%)

right-handed and 7 (7%) left-handed. The subjects' mean heights and weights were 168.1 cm ( $\pm 10.6$ ) and 71.3 kg ( $\pm 17.0$ ). The mean measured right arm, hand, index, and small finger lengths were 43.4 cm ( $\pm 2.7$ ), 18.4 cm ( $\pm 1.3$ ), 7.4 cm ( $\pm 0.7$ ), and 6.0 cm ( $\pm 0.7$ ), respectively. The mean seat pan height was 41.9 cm ( $\pm 5.2$ ) and the sitting elbow height was 66.4 cm ( $\pm 6.0$ ).

Mean typing speeds by keyboard are presented in Table 2. Based on the repeated measures ANOVA, the typing speeds were significantly different across keyboard configurations. The follow-up test of pairwise comparisons was performed with the Tukey test to adjust for multiple comparisons. All 15 pairwise comparisons were significant, except between 4 keyboard pairs: LAP:ERGO, LAP:REVERGO, ERGO:REVERGO, and CURVE:ELITE.

Mean wrist and forearm postures by keyboard are presented in Table 2 and Figs. 2–4. Based on the repeated measures ANOVA, there were significant differences in all postures measured between keyboard configurations. The follow-up test of pairwise comparisons was performed with the Tukey test to adjust for multiple comparisons. For right wrist extension, all pairwise comparisons were significant except between keyboard pair CURVE:ELITE. For left extension, all pairwise comparisons were significant except between keyboard pair LAP:ERGO. For right ulnar deviation, all pair-wise comparisons were significant except between keyboard pair CONV:CURVE. For left ulnar deviation, all pairwise comparisons were significant except between keyboard pairs CONV:CURVE, CONV:REVERGO, and ELITE:ERGO. For left and right pronation, all pairwise comparisons were significant except between keyboard pair LAP:CURVE.

Subjective ratings of keyboards are presented in Table 3; lower scores are better ratings. Based on the Friedman test, there were significant differences in ratings for all categories except 'speed'. The follow-up test of pairwise comparisons was performed with the Tukey test. For 'ease of use', all pairwise comparisons were significant except between keyboard pairs CONV:LAP, CONV:REVERGO, LAP:CURVE, LAP:ELITE, CURVE:REVERGO, ELITE:ERGO, and ELITE:REVERGO. For 'accuracy', there were significant differences between all keyboard pairs except

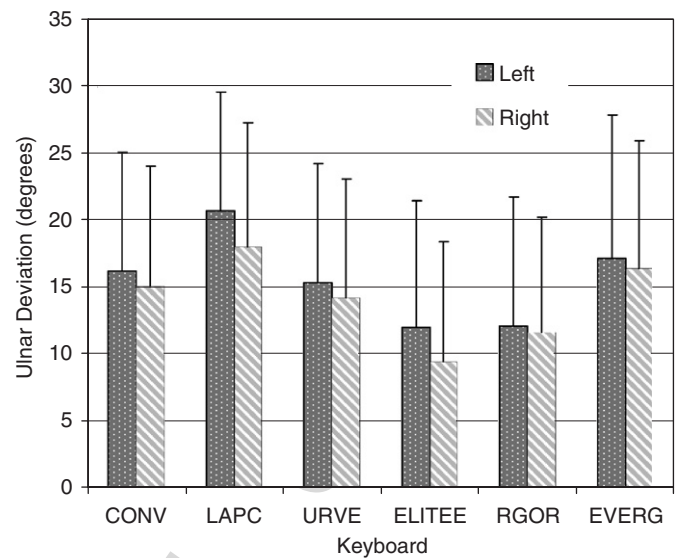


Fig. 2. Mean left and right ulnar deviation while typing on 6 keyboard configurations ( $N = 100$ ).

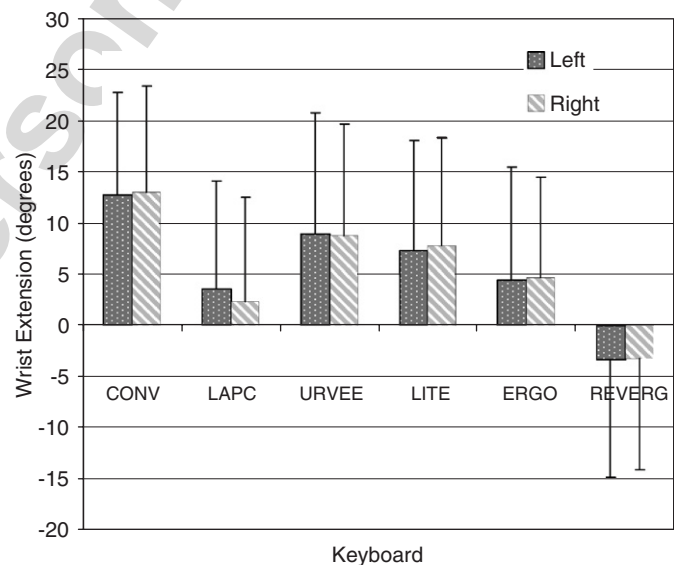


Fig. 3. Mean left and right wrist extension while typing on 6 keyboard configurations ( $N = 100$ ). A negative value is wrist flexion.

Table 2

Mean typing speed in words per minute (SD) and wrist and forearm postures in degrees (SD) ( $N = 100$ )

	Keyboard configuration						<i>p</i> -Value <sup>a</sup>
	CONV	LAP	CURVE	ELITE	ERGO	REVERGO	
Typing speed (wpm)	51.9 (16)	46.8 (15) <sup>a</sup>	50.4 (16) <sup>b</sup>	50.0 (16) <sup>b</sup>	47.9 (16) <sup>a</sup>	46.8 (16) <sup>a</sup>	$p < 0.0001$
Right wrist extension	13.1 (11.0)	2.4 (9.8)	8.8 (10.6) <sup>a</sup>	7.9 (10.3) <sup>a</sup>	4.8 (10.1)	-3.1 (10.9)	$p < 0.0001$
Left wrist extension	12.8 (11.6)	3.6 (11.0) <sup>a</sup>	9.0 (10.9)	7.4 (10.0)	4.6 (10.5) <sup>a</sup>	-3.2 (11.9)	$p < 0.0001$
Right ulnar deviation	15.2 (9.5) <sup>a</sup>	18.1 (8.5)	14.3 (8.9) <sup>a</sup>	9.5 (8.9)	11.8 (9.3)	16.5 (8.9)	$p < 0.0001$
Left ulnar deviation	16.3 (10.7) <sup>a,b</sup>	20.8 (9.7)	15.4 (9.4) <sup>a</sup>	12.1 (8.8) <sup>c</sup>	12.2 (8.9) <sup>c</sup>	17.2 (8.9) <sup>b</sup>	$p < 0.0001$
Right pronation	66.9 (10.8)	65.8 (10.5) <sup>a</sup>	65.5 (10.3) <sup>a</sup>	61.2 (10.1)	59.3 (9.9)	56.9 (9.7)	$p < 0.0001$
Left pronation	67.2 (10.2)	66.0 (10.1) <sup>a</sup>	66.3 (9.7) <sup>a</sup>	62.5 (9.8)	59.3 (9.6)	57.8 (9.6)	$p < 0.0001$

<sup>a</sup>Repeated measures ANOVA.

<sup>b</sup>Within a row, values between keyboard configurations are significantly different, based on the Tukey test, except those with the same superscript.

CONV:LAP, CONV:ERGO, CONV:REVERGO, LAP:CURVE, LAP:ELITE, CURVE:REVERGO, ELITE:ERGO, and ELITE:REVERGO. For ‘comfort’, there were significant differences between all keyboard pairs except CONV:LAP, CONV:ELITE, LAP:CURVE, LAP:ELITE, LAP:ERGO, CURVE:REVERGO, and ELITE:REVERGO. For ‘overall’, there were significant differences between all keyboard pairs except CONV:LAP, CONV:REVERGO, LAP:CURVE, LAP:ELITE, LAP:ERGO, CURVE:REVERGO, ELITE:ERGO, and ELITE:REVERGO. When asked to choose the most preferred keyboard, subjects selected the ELITE or the ERGO/REVERGO keyboard while the least preferred was the LAP keyboard. Limiting the question to just males ( $N = 38$ ) made little change to the preference order. When this question was limited to subjects who had little prior experience with a split keyboard ( $N = 34$ ), the highest preference was for the

ERGO/REVERGO keyboard and, again, the LAP keyboard was the least preferred.

#### 4. Discussion

When using a computer, wrist and forearm postures are influenced by a number of factors, including task, chair, workstation, and keyboard design. This study found that when all factors except keyboard are held constant, wrist and forearm postures are strongly influenced by keyboard design. For wrist extension, the most neutral angles were achieved on keyboards LAP, ERGO, and REVERGO. Keyboards CONV and CURVE were the only keyboards without a built in wrist support, and this may explain the larger wrist extension observed with these keyboards. For ulnar deviation, the most neutral angles were achieved on keyboards ELITE and ERGO while the greatest ulnar deviation was observed with keyboard LAP. For forearm pronation, the most neutral angles (least pronation) were observed on keyboard REVERGO while the greatest pronation was observed on keyboard CONV.

Keyboard CURVE is similar in design to the conventional keyboard except that it has an opening angle of  $6^\circ$ . Interestingly, this opening angle had no significant effect on ulnar deviation but did reduce extension and pronation. Keyboard ERGO is similar to keyboard ELITE except that the gable angle is steeper and is increased from  $8$  to  $14^\circ$ ; plus it has a more prominent wrist support. As might be expected, these design differences caused a reduction in pronation and extension. Keyboard REVERGO, which is keyboard ERGO tilted from a  $0^\circ$  slope to a negative  $7^\circ$  slope, moved the wrist from slight extension to flexion, but also decreased pronation even further than keyboard ERGO. However, keyboard REVERGO was associated with a mean increase in ulnar deviation of  $4.9^\circ$ . Tilting a conventional keyboard from a  $0^\circ$  slope to a negative slope will increase ulnar deviation. In a study by Simoneau et al. (2003), tilting a conventional keyboard from  $0^\circ$  to a

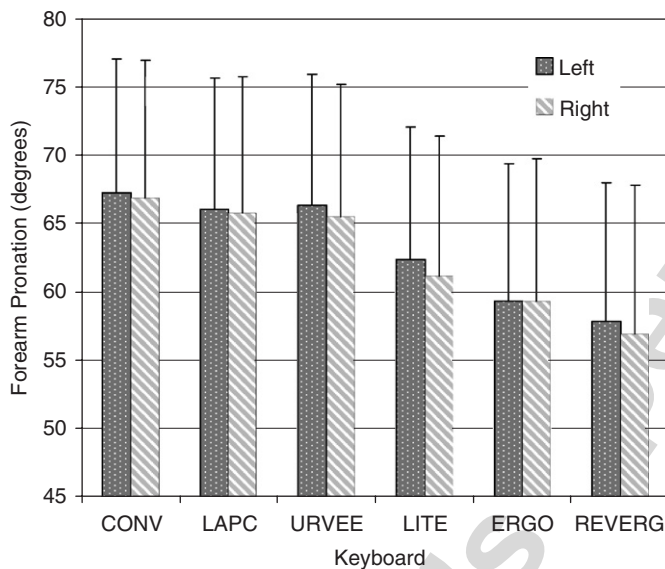


Fig. 4. Mean left and right forearm pronation while typing on 6 keyboard configurations ( $N = 100$ ).

Table 3

Mean rank order rating of keyboard configurations by ease of use, accuracy, speed, comfort, and overall characteristics

	Keyboard configuration						<i>p</i> -Value <sup>a</sup>
	CONV	LAP	CURVE	ELITE	ERGO	REVERGO	
Ease of use	3.0 (1.8)	4.3 (1.6)	3.0 (1.4)	2.8 (1.5)	3.6 (1.4)	4.2 (1.8)	$p < 0.05$
Accuracy	2.7 (1.7)	4.1 (1.7)	3.1 (1.5)	2.8 (1.5)	3.7 (1.3)	4.4 (1.5)	$p < 0.05$
Speed	2.7 (1.7)	4.0 (1.7)	2.9 (1.4)	2.8 (1.5)	3.7 (1.3)	4.5 (1.6)	NS
Comfort	3.6 (1.8)	4.5 (1.6)	2.9 (1.3)	2.7 (1.5)	3.2 (1.5)	3.9 (1.8)	$p < 0.05$
Overall	3.2 (1.7)	4.3 (1.6)	2.9 (1.4)	2.7 (1.5)	3.6 (1.5)	4.1 (1.8)	$p < 0.05$
Preference (%)	14.3	2.9	21.9	30.2	15.2	15.2	
Preference subset A (%) <sup>b</sup>	10.5	5.3	21.1	26.3	15.8	21.1	
Preference subset B (%) <sup>c</sup>	16.7	5.9	23.5	23.5	11.8	17.6	

Ratings are from 1 (best) to 6 (worst). Subjects were also asked which keyboard they would prefer ( $N = 105$ ).

<sup>a</sup>Friedman's test for ratings.

<sup>b</sup>Subset A is male subjects ( $N = 38$ ).

<sup>c</sup>Subset B is subjects with little prior experience with split keyboards ( $N = 34$ ).

negative 7.5° slope led to a mean increase in ulnar deviation of 1.6°.

There are no prior studies of wrist or forearm postures on keyboard ERGO/REVERGO. However, there are prior studies comparing postures on a conventional keyboard to keyboard CURVE (McLoone et al., 2005) and ELITE (Honan et al., 1995; Marklin et al., 1999; Zecevic et al., 2000). The mean values of joint postures differ between these studies and the differences are likely due to differences in workstation setup (e.g., keyboard height, chair location, presence of wrist support). However, the changes in postures between keyboards are very similar to those observed in this study. For example, Zecevic et al. (2000) observed a 5° reduction in pronation when subjects used keyboard ELITE compared to the conventional keyboard while we observed a mean reduction of 5.2°. McLoone et al. (2005) observed a reduction of 2.2° in ulnar deviation when subjects used keyboard CURVE compared to the conventional keyboard while we observed a mean reduction of 0.9°.

There were differences in typing speeds between keyboards, as might be expected given the limited exposure subjects had to some of the keyboards (Table 2). The fastest typing speed was observed on the conventional keyboard; the typing speeds for keyboards CURVE and ELITE were just below that of the conventional keyboard. Keyboards LAP, ERGO, and REVERGO were associated with the lowest typing speeds. McLoone et al. (2005) observed a 1.2 wpm drop in typing speed between a conventional keyboard and keyboard CURVE, a value similar to the 1.5 wpm drop that we observed. Typically, typing productivity on an alternative keyboard recovers to the usual after 2 days of use (Swanson et al., 1997).

The subjective rankings of keyboards by subjects should be interpreted with caution because the exposure to the keyboards was so brief. Subjects are likely to select keyboard designs with which they are most familiar. Indeed, in a similarly designed study conducted 10 years ago, comparing the keyboard ELITE configuration to a conventional configuration, subjects overwhelmingly preferred the conventional keyboard (Honan et al., 1995). In the current study, the subject preference was evenly split between keyboard ELITE (30.2%) and keyboard ERGO/REVERGO (30.4%).

One of the limitations of the study was the relatively brief exposure of subjects to the alternative keyboards prior to testing. Most subjects (68%) had more than a week's experience with keyboard ELITE prior to the study. However, the only exposure subjects had to keyboards CURVE, ERGO, and REVERGO was during the warm-up period prior to testing. Interestingly, the keyboard preferences for those with less experience with alternative keyboards were not very different from those with more experience (Table 3).

This is the largest study to date evaluating the effects of alternative keyboard designs on wrist and forearm postures. From the standpoint of forearm and wrist

postures, depending on the posture being measured, keyboard LAP, keyboard ELITE, and keyboard ERGO/REVERGO provided the most neutral postures among the keyboards tested. When considering all 6 wrists and forearm postures together, keyboard ERGO appears to provide the most neutral posture among the keyboards tested. Computer users with hand and arm pain may be advised to try alternative keyboards, but it is important that they understand the goals for altering the keyboard height and slope when adjusting their workstation (e.g., neutral postures, comfort, reduced shoulder load). Computer users should also understand that it may take several weeks or months (Tittiranonda et al., 1999) before they notice a change in their hand or forearm comfort after switching to an alternative geometry keyboard.

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