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Design and evaluation of a curved computer keyboard

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Conventional, straight keyboards remain the most popular design among keyboards sold and used with personal computers despite the biomechanical benefits offered by alternative keyboard designs. Some typists indicate that the daunting medical device-like appearance of these alternative 'ergonomic' keyboards is the reason for not purchasing an alternative keyboard design. The purpose of this research was to create a new computer keyboard that promoted more neutral postures in the wrist while maintaining the approachability and typing performance of a straight keyboard. The design process created a curved alphanumeric keyboard, designed to reduce ulnar deviation, and a built-in, padded wrist-rest to reduce wrist extension. Typing performance, wrist postures and perceptions of fatigue when using the new curved keyboard were compared to those when using a straight keyboard design. The curved keyboard reduced ulnar deviation by $2.2^\circ \pm 0.7$ ($p < 0.01$). Relative to the straight keyboard without a built-in wrist-rest, the prototype curved keyboard with the built-in padded wrist-rest reduced wrist extension by $6.3^\circ \pm 1.2$ ($p < 0.01$). There were no differences in typing speed or accuracy between keyboards. Perceived fatigue ratings were significantly lower in the hands, forearms and shoulders with the curved keyboard. The new curved keyboard achieved its design goal of reducing discomfort and promoting more neutral wrist postures while not compromising users' preferences and typing performance.

Keywords: wrist posture; ergonomics; performance; comfort; productivity

1. Introduction

Alternative keyboards such as adjustable split and split-fixed designs have been on the market for over two decades; yet, widespread sales and use have not exceeded those of conventional, straight keyboard designs. Alternative keyboards were introduced in the 1990s with designs based on the findings of several investigators (Kroemer 1972, Buesen 1984, Nakaseko *et al*. 1985, Ilg 1987). A review article by Rempel (2008) provides a summary of the published research on split keyboards between 1926 and 2007. Fixed-split keyboards (Figure 1) reduce awkward postures (Honan *et al*. 1995, Rempel *et al*. 1995, Honan *et al*. 1996, Marklin *et al*. 1999, Zecevic *et al*. 2000), muscle strain (Strasser *et al*. 2004) and overall pain and discomfort as well as improving the functional status of participants with pre-existing hand and wrist pain (Tittiranonda 1997, Tittiranonda *et al*. 1999). Further, research has shown the benefit of the fixed-split keyboard design in reducing the incidence of new cases of carpal tunnel syndrome and other symptoms (Moore and Swanson 2003). Yet, straight keyboards are still popular designs among those keyboards shipped with new personal computers and sold separately in retail stores.

Many keyboard users have invested time to learn how to touch type: striking keys without looking and using all or almost all 10 digits. During this relatively extensive training process, users have memorised both cognitively and physically where the keys are positioned and located. Fixed-split keyboards, by their nature, physically change the location of keys in space, such that new users must relearn where keys are located. This retraining may take only a few minutes or a matter of weeks depending on the typist's skill and motivation (Morelli *et al*. 1995, Tittiranonda 1997). In some cases, typists on more extreme alternative keyboard designs may never reach the typing speeds and error rates they experienced with straight keyboards (Chen *et al*. 1994, Swanson *et al*. 1997).

Despite the reported ergonomic benefits of alternative keyboards and the relatively short learning curve for some typists, many computer users prefer to purchase and use straight keyboards instead. Internal research at Microsoft identified that, among the general population of typists, fixed-split keyboards are

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often perceived as an orthotic or medical device, used more often by people with pain and less approachable for use by otherwise less motivated healthy typists.

As a result of the demonstrated benefits from alternative keyboards and the challenges associated with their perceived poor approachability, a design team was formed to create a new alternative keyboard. The goal was to design a keyboard that not only provided the ergonomic benefit of reducing awkward wrist postures, but that would also have an approachable design that would appeal to the masses of straight keyboard users.

A series of iterative-evaluative, user-centred experiments were conducted to attempt to incorporate further ergonomic advantages into the straight keyboard layout. The research team articulated metrics for success based on a user experience framework of performance, comfort and desirability. The metrics for success included determining whether there were any differences in typing performance, wrist–forearm postures, perceived comfort and subjective preference between a straight keyboard and new curved keyboard prototypes developed during this iterative-evaluative product design process. Representative users were invited into laboratory settings to evaluate a series of models and prototypes to provide their impressions and preferences and thus assist with the evolution of the new curved keyboard design. The series of three experiments presented in this paper exemplified a user-centred product design process.

Figure 1. Fixed-split keyboard (Microsoft Natural Keyboard (Elite version)).

2. Method

2.1. Experiment 1

2.1.1. Experimental design and protocol

The first experiment was an iterative-evaluative product design research study of preferred keyboard opening angle. A conventional, straight keyboard with 0° opening angle and three curved keyboards with centre opening angles of 8°, 10° and 13° were evaluated by representative users for their visual and tactile preferences. Figure 2 shows a curved keyboard model with the 10° opening angle. As shown in the figure, the gap created in the middle of each keyboard created by the opening angle was filled by increasing the size of the key caps. All keyboards had a 0° slope (i.e. key surfaces were flat/parallel to the table surface) by default and were mechanically operational but not electrically functional.

To simulate using each keyboard, participants sat in an adjustable workstation. In this workstation, participants adjusted the chair so that their feet rested flat on the floor and their thighs were parallel to the floor and then they adjusted the table so that the home row of the keyboard was positioned at elbow height.

The experiment consisted of having the participants simulate typing a standard text passage on each keyboard prototype. When participants formed an opinion of the experience (between 2 and 5 min), they gave feedback on the quality of their experience with each prototype. Keyboard prototype order was counter-balanced and, after testing all keyboards, the participants were asked to rank the keyboards from most ('first') to least ('fourth') preferred and the reasons for their preferences.

2.1.2. Participants

Seven participants (three males, four females) external to Microsoft were brought into a usability laboratory to test the four keyboards. The average age of the participants was 49 (range 18–62) years and all

(a) (b)

Figure 2. (a) The straight keyboard and (b) one of the curved keyboard models (10° split angle shown) tested in Experiment 1.

participants were straight keyboard users. Participants were not screened for their typing ability. Four participants reported that they used a computer $\geq$4 d per week and the other three participants that they used a computer 7 d per week. The participants were recruited from a database of people in the Seattle metropolitan area who were willing to be considered for usability research at Microsoft. All participants gave their consent to participate and received a Microsoft hardware or software gratuity in exchange for their participation. Studies followed Microsoft's standard organisational procedures for usability testing with human subjects.

2.1.3. *Measurements*

For both this study and the second one described below, participants were instructed to 'think aloud' or otherwise encouraged to express their positive, neutral and negative impressions of the keyboard prototypes and keycap designs. Participants' impressions and rank order preferences were summarised and tallied.

2.1.4. *Results*

Most of the participants appreciated the three new curved keyboards. In terms of preferences, five of the seven participants preferred a split keyboard design over the straight keyboard. The prototypes with the opening angles of 8°, 10° and 13° received average rank order preferences of 2.3, 2.1 and 2.0 respectively on a ranking scale from 1 (most preferred) to 4 (least preferred). The straight keyboard had a generally lower average rank order preference of 3.0. Some participants found the new curved keyboards easy to get used to and were able to perceive the benefits of the split in the centre of the keyboard. Two participants said that the curved keyboards were 'easy to use' and had 'easy to access keys'. Three other participants offered similar comments that the curved keyboards were 'natural, comfortable and felt good with the split angle'. However, the straight keyboard was appreciated by two participants for its 'familiarity' and for 'easy to use, predictable key locations'. The 'stretch' keys in the middle were generally well perceived; however, a few participants expressed some concerns about the non-uniform key size.

2.2. *Experiment 2*

2.2.1. *Experimental design and protocol*

The second experiment was an iterative-evaluative product design research study of preferred keyboard geometry and key cap design.

To evaluate keyboard geometry, five keyboard designs were assessed for usability including three different curved keyboards with opening angles of 10°, 13° and 16° (Figure 2), a conventional, straight keyboard (a benchmark, Figure 2) and a fixed-split keyboard (a second benchmark) with a opening angle of 25° and lateral inclination angle of 8° (Figure 1). The new curved keyboards and the straight keyboard had 0° lateral inclination angle and all keyboards had a 0° slope (i.e. keys were flat/parallel to the table surface). The two benchmark keyboards were chosen to bracket the range of keyboard geometries currently commercially available. The expectation was that, on average, participants would give a higher rating to one or more of the curved keyboards compared to the straight keyboard representing one extreme and to the fixed-split keyboard representing the other extreme. As in the first experiment, all models were mechanically operational but not electrically functional. Participants simulated typing a standard text passage on each keyboard (for between 2 and 5 min) until they were able to provide judgement about the quality of their experience with each prototype and to make a decision about their preference for each design relative to the other designs. Keyboard order was counter balanced.

In addition to the above keyboard layout designs, the participants evaluated five key cap designs on the 10° opening angle curved keyboard. These key cap designs represented variations on how to fill the space between the keys created by the opening angle. Should the keys remain unchanged and the space be filled with solid plastic or should the keys be enlarged to fill this space? As shown in Figure 3, model P filled the opening area with stepped keycaps, each key on either side elongated to fill the gap half way. Models Q and S had irregularly sized keys with an obvious centre line. Model R used identical sized keys with a 'baseball cap' key design. With this design, the keys had a secondary lower surface to fill extra space in the middle of the keyboard. Finally, model T filled the opening area with a triangular island of plastic surrounded by irregular sized keys. Model P had the 'B' key cross the centreline to allow for the opening in the keyboard and no separating space or island between the keys. Models Q and S had a symmetrical opening between the middle of the keyboard with the centre keys elongated to minimise the gap in the middle of the keyboard. Model S also used the stepped keycap design, whereas model Q used a more conventional gradual slope on the key sides. These designs were printed full-size on paper and affixed to a foam core poster board for presentation to participants. Again, key cap designs were presented in counter-balanced order. A Friedman's test for ordinal, ranked data was used to determine whether

Figure 3. The non-electrically functional prototype curved keyboard models with the five alternative centre keycap designs assessed in Experiment 2.

there were differences in the rankings of the opening angles and keycap designs.

To simulate using each keyboard, participants sat in an adjustable workstation and adjusted the chair so their feet rested flat on the floor and their thighs were parallel to the floor and then they adjusted the table so that the home row of a straight keyboard was positioned at elbow height. The experiment consisted of having the participants simulate typing a standard text passage on each keyboard prototype. When participants formed an opinion of the experience (within 2–5 min), they gave feedback on the quality of their experience.

The participants were then asked to orient a 2-D paper model of a split keyboard into a position that they felt was the most comfortable for their hands. The paper model was a printed layout of a full-sized keyboard pasted on to heavy cardstock paper and then cut into two pieces representing two halves of a split keyboard between the numbers '6' and '7' in the numeric row and the 'T' and 'Y', 'G' and 'H' and 'B' and 'N' keys in the rows consisting of letters. Participants were instructed to keep the '6' and '7' keys on the two halves touching as they selected their optimum opening angle, while keeping the paper model flat on the desk in front of them (that is, with 0° slope and lateral inclination angles). The paper orientation was traced to record each participant's self-selected opening angle.

2.2.2. *Participants*

The second experiment brought 20 participants (10 men, 10 women) into a laboratory to represent a wider cross section of ages and body sizes. The average age of participants was 34 (range 22–50) years. A total of 18 participants were right-hand dominant, two participants were left-hand dominant and all were conventional, straight keyboard users. As measured from the distal crease of the wrist to tip of middle finger, the average hand size was 17.5 (range 16.0–18.7) cm for the female participants and 19.7 (range 18.1–21.2) cm for the male participants. All reported that they were touch typists (that is, used all 10 digits and typed without looking at the keyboard) and did not have any hand or visual disability that would impact performance while typing on a keyboard. They reportedly used a computer 6 h per day on average (range 2.5–11.0 h). In this experiment, the participants did not know that Microsoft was sponsoring the research and received a monetary gratuity for their participation.

2.2.3. *Measurements*

After using all five of the keyboards, participants were asked to rank the keyboards from most ('first') to least ('fifth') preferred and they were asked to place each of the prototype keyboards along a 21-point scale with the benchmark, straight keyboard at the centre 'zero' point and with '+10' being the best possible keyboard and '−10' being the worst possible keyboard. The straight keyboard was chosen as the scale mid-point as all participants used a straight keyboard as their primary keyboard. It was left up to the individual participant to decide the meanings of 'best' and 'worst' possible keyboard.

For the new key cap designs, in addition to noting and counting the open-ended, positive and negative comments, the participants were asked to rank the key designs from most ('1' for first) to least ('5' for fifth) preferred.

2.2.4. *Results*

2.2.4.1. Participants' preferences for opening angles. In Experiment 2, the keyboard models with 10° and 13° opening angles were generally more preferred over the fixed-split keyboard and the 16° opening angle keyboard prototype but not the conventional, straight keyboard (0°). The average rank order preferences from 1 (most preferred) to 5 (least preferred) were 2.7 and 2.5 for the 10° and 13° opening angles, respectively, 2.8 for the conventional, straight keyboard (benchmark) and 3.6 and 3.5 for the 16° opening angle and the fixed-split keyboard, respectively. These differences in rankings were not statistically significant but approached significance ($p = 0.07$).

Based on the ratings utilising the 21-point scale (worst possible keyboard –10 to best possible keyboard + 10), there were significant differences in ratings between keyboards ($p = 0.02$). The mean (SD) ratings for the curved keyboards with 10° and 13° opening angles were 1.9 (5.6) and 1.7 (4.9) respectively compared to the conventional, straight keyboard (representing 0 on the 21-point scale). The fixed-split keyboard and the curved keyboard with the 16° opening angle were not rated as favourably and had average scores of −2.1 (6.8) and −1.3 (6.7) respectively. The curved keyboard with the 10° opening angle was rated significantly higher than the fixed-split and curved keyboard with the 16° opening angle, and the curved keyboard with the 13° opening angle was rated significantly higher than the fixed-split keyboard with the 16° opening angle. Based on the positive and negative comments provided for each keyboard, both the 16° angle keyboard and the fixed-split keyboard were talked about in a neutral way with an equal ratio (1 to 1) of positive and negative open-ended comments. By contrast, the 10° and 13° models were talked about more positively with a higher 3 to 1 ratio of positive to negative open-ended comments. For this group of standard keyboard users, the increase in opening angle to 16° and the layout of the fixed-split keyboard were deemed too radical.

2.2.4.2. Participants' self-selected preference for opening angle. When participants were asked to orient the 2-D paper model keyboard halves into the position that they felt was the most comfortable, the average self-selected opening angle for the group was 12.3° (SD 6.1°). This value was consistent with the ranking results of the keyboards presented in section 5.1, where the intermediate keyboard angles of 10° and 13° were selected over the straight (0°) and the more extreme 16° opening angles.

2.2.4.3. Participants' preferences for key cap design. With regard to the preferences for the various key cap designs to accommodate the opening angle, most (83%) participants preferred either models P (stepped keys) or Q (irregular shaped keys) for their first choice. Models S, P and Q had the highest average (SD) rank order preferences of 2.6 (0.8), 2.5 (1.7) and 2.4 (1.4) respectively. There were no significant differences between these three designs but they were all rated significantly better ($p = 0.03$) than models R (identical sized keys) and T (centre filled with small plastic triangular region).

The participants' reasons for choosing model P included: 'looked most proportional'; 'most proportionately laid out'; 'more integrated/together'; 'liked flow'. They also liked the key size: 'centre key sizes are the same (or close) – difference won't increase the error rate'; 'visual curve and shape of centre keys look like rest of keys'; 'key shape similar to straight – would be able to use blend'; 'others look like pre-occupied with compensating for the middle'. Their reasons for choosing models Q and S included the symmetry, subtle, gradual look and less noticeable key treatment: 'gradual'; 'symmetry, no dead space in the middle, no odd shaped keys'; 'treatment not as noticeable'; 'smoother/symmetrical'. Models R and T had lower average (SD) ranks of 3.2 (1.2) and 4.1 (1.3) respectively with no differences in ranking between these two keycap designs. Model T had the lowest rating since participants felt the keys did not aesthetically fill the centre area of the keyboard.

2.3. Experiment 3

The two previous experiments used non-electrically functional keyboard prototypes. The purpose of Experiment 3 was to evaluate the new curved keyboard with an integrated wrist-rest using a fully functional prototype of the preferred design embodiments against a straight keyboard with and without a built-in wrist-rest. As a result of the first two experiments, the preferred design embodiments included an opening angle of 12° and stepped key design in the centre area of the curved keyboard. The objectives were to determine what effect, if any, the preferred keyboard embodiments had on wrist and forearm postures and whether the same positive subjective impressions would also be found when subjects used a fully functional prototype.

2.3.1. Participants

A total of 26 straight keyboard users (14 males and 12 females) participated in this experiment. Participants were recruited from the Industrial Engineering Department and the Environmental and Occupational Health Science Department at the University of Washington. The mean age of the participants was 31 (range 31–51) years and all participants reported that they were touch typists who could type 40 words per min or higher. The participants were not aware of who was sponsoring the study and were paid \$15/h in cash for their participation. The study took place at the University of Washington, had the approval of the University Human Subjects Committee and all participants gave informed consent.

2.3.2. Experimental protocol

The experiment consisted of having participants type standardised text for 15 min on three different keyboards. As shown in Figure 4, the three keyboards used were a Dell OEM standard keyboard without a wrist-rest (P/N 04N454; Dell Computer, Round Rock, TX, USA), a conventional, straight keyboard with a built in wrist-rest (Optical Desktop Elite 1.0; Microsoft Corporation, Redmond, WA, USA) and a fully functional prototype of the new curved keyboard design, which was based on the preferred design embodiments identified in the two earlier user-centred experiments.

The design embodiments incorporated into the new curved keyboard included a built-in, padded wrist-rest, an alphanumeric keyboard layout with a opening angle of 12° and covering the central split between the two distinct halves of the alphanumeric portion of the keyboard with slightly larger, staggered keys in the centre of the keyboard.

The test workstation where participants typed was set up according to the ANSI/HFS 100–1988 standard to match the participant's stature (ANSI/HFS 1988). Participants adjusted the chair so that their feet rested flat and firmly on the floor, their thighs were parallel to the seat pan and the chair backrest firmly supported their back. Then, when comfortably resting their upper arms at their sides and forming roughly a 90° angle at the elbow, the table height for the keyboards was adjusted to be 2.5 cm below elbow height. This ensured that participants were comfortably seated, their shoulders were relaxed and their wrists were in a relatively neutral flexion/extension position when typing. Participants were allowed to make slight adjustments for comfort.

2.3.3. Measurements

2.3.3.1. Posture measurement. Bi-axial electrogoniometers (Model XM-65; Biometrics Ltd., Newport, Gwent, UK) were applied to the right and left wrists and forearms of participants and calibrated as prescribed by Johnson *et al*. (2002). Calibration consisted of having participants assume a typing posture with their upper arms resting at their side, forearms parallel to the work surface and hands fully pronated. This was to minimise any offset errors associated with forearm pronation. As prescribed by the American Academy of Orthopedic Surgeons (Greene and Heckman 1994), the neutral flexion/extension position of the wrist was defined at the position where the horizontal plane formed by the back of the hand was in line with the plane formed by the back of the forearm. The neutral radial/ulnar position was defined as the position where the third metacarpal was in line with the long axis of the forearm.

2.3.3.2. Typing performance. A program called Typing Workshop Deluxe (version 6.0; Valusoft, Inc., Waconia, MN, USA) was used to measure typing speed and accuracy. In addition, a second program written in Labview (version 6.1; National Instruments, Austin, TX, USA) measured minute to minute changes in typing speed. Simple alphanumeric text from chapters of a novel was used for the typing test. In order to become familiar with the operation of the Typing Workshop program, participants were allowed 5 min practice with the program using a conventional, straight keyboard different from the conventional, straight keyboards used in the study. Prior to the start of the typing task, participants were asked to balance

Figure 4. The functional keyboards tested in Experiment 3 for typing performance, comfort and users' preferences. (a), a conventional, straight keyboard; (b), a conventional, straight keyboard with built-in wrist-rest; (c), the new curved keyboard.

speed and accuracy when typing. Thus, all experimental procedures could be completed within 2 h, the typing task consisted of having the participant type on each keyboard for two 7.5 min blocks (total of 15 min). The two 7.5 min blocks were chosen so that perceived fatigue measurements (see section 2.3.3.3) could be collected at the beginning, middle and end of each typing session.

2.3.3.3. Perceived fatigue. Perceived fatigue levels with each keyboard were measured using the BORG CR-10 scale (Borg 1982) administered before and after each of the two 7.5 min typing blocks (at the beginning, middle and end of each 15 min typing session). The participant was asked to identify the level of perceived fatigue in the right and left hands, wrists, forearms, shoulders and neck. Other than the time taken to fill out the Borg CR-10 scale ratings ($\sim$1 min), there was no rest between the two 7.5 min typing blocks.

2.3.4. Data analysis

During the experiment, the angle data from the electrogoniometers were collected at 100 Hz and stored on a portable logger (ME6000-T8; Mega Electronics, Kupio, Finland). After data collection, the data were downloaded and analysed using an analysis program written in Labview. Within each 7.5 min block of typing, the first and last 45 s were discarded; thus, 6 min records were used for the goniometer analysis. The 10th percentile, mean and 90th percentile angles from the two 6 min blocks were calculated for each participant and group means and standard errors were calculated and presented for each keyboard. With the typing data minute-by-minute typing speeds, mean typing speeds and typing accuracy were tabulated for each keyboard and group mean values were calculated.

The BORG CR-10 scale data were evaluated based on relative change across the beginning, middle and end measurements with each keyboard. Calculating relative changes involved setting the beginning measurement to zero by subtracting the beginning Borg scale rating from beginning, middle and end measurements in that particular session. Thus, a change in Borg scale ratings relative to a beginning value of zero was calculated. This reduced any additive effects of time that randomisation may not have counterbalanced.

Data were then analysed using repeated measures ANOVA using the statistical program JMP (version 5.1; SAS Institute, Cary, NC, USA). All values are presented as mean $\pm$ SE. Differences were considered to be significant when p-values were less than 0.05.

2.3.5. *Results*

2.3.5.1. Wrist posture. Due to equipment failure with one participant, complete data were collected from 25 of the 26 participants. When the wrist extension data were compared between keyboards and hands, there was a significant difference in mean extension angles between keyboards ($p < 0.01$) and between hands ($p = 0.04$) and a trend suggesting a potential hand by keyboard interaction ($p = 0.052$). The statistical results for the 10th and 90th percentile data paralleled the results for the mean wrist extension data. As shown in Figure 5, the curved keyboard with the built-in wrist-rest reduced mean wrist extension angles by $6.3 \pm 1.2°$ (mean $\pm$ SE) when compared to the conventional, straight keyboard without a wrist-rest. However, there was no significant difference in wrist extension between this curved keyboard and the straight keyboard with a built-in wrist-rest. When comparing hands, when averaged across all keyboards, participants worked with $3.6 \pm 1.6°$ more extension in the right hand.

In the radial and ulnar plane, there were also significant differences in mean ulnar deviation angles between keyboards ($p < 0.01$) and between hands ($p < 0.01$), but there was no hand by keyboard interaction ($p = 0.54$). Again, the statistical results for the 10th and 90th percentile data paralleled the results for the mean ulnar deviation data. The curved keyboard reduced mean ulnar deviation angles by $2.2 \pm 0.7°$ compared to the conventional, straight keyboards (with or without wrist-rests) (Figure 5). When comparing hands, participants worked with $8.7 \pm 1.3°$ more ulnar deviation in the left hand.

2.3.5.2. Typing performance. As shown in Figure 6, data gathered from the typing performance program revealed that the differences in typing speed between the three keyboards were not significant ($p = 0.08$). The mean (SE) typing speeds with the straight keyboard, straight keyboard with wrist-rest and curved keyboard were 51.8 ($\pm$3.2), 51.5 ($\pm$3.2) and 50.6 ($\pm$3.2) words per min respectively. In addition, there were no differences in typing accuracy ($p = 0.77$) between keyboards, the mean (SE) accuracy with the straight keyboard, straight keyboard with wrist-rest and curved keyboard being 93.5 ($\pm$0.6)%, 93.2 ($\pm$0.7)% and 93.1 ($\pm$0.6)% respectively.

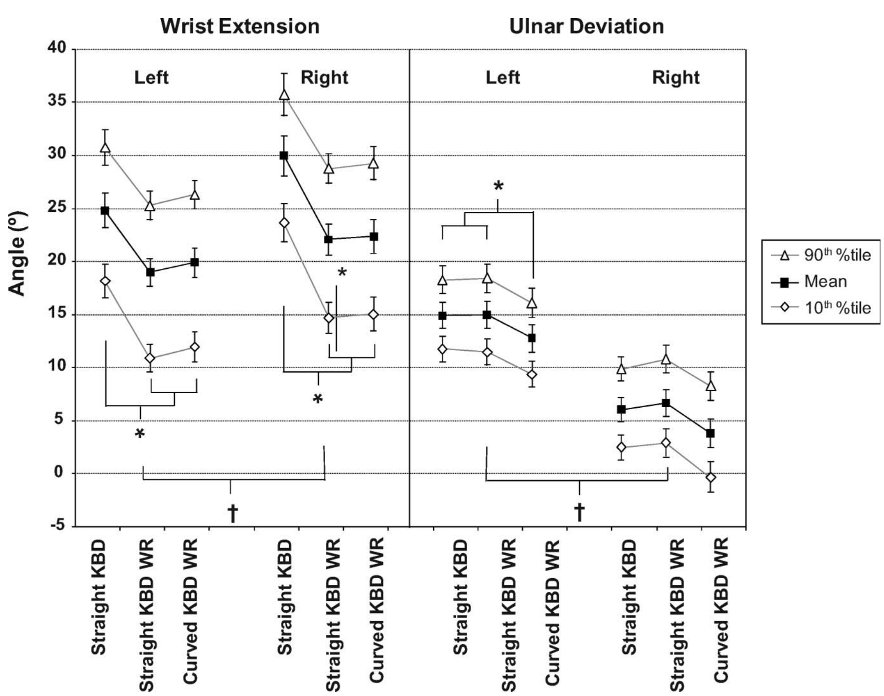

Figure 5. 10th percentile (%tile), mean and 90th %tile ($\pm$SE) wrist extension and ulnar deviation angles by keyboard (KBD) and plotted with regard to hand. Significant differences between keyboards (*) and hands (†) are indicated on the figure (n = 25). WR = wrist-rest.

2.3.5.3. Perceived fatigue. Perceived fatigue as measured by changes in Borg CR-10 ratings with regard to time were analysed for each body part and the mean values for the changes in ratings are plotted in Figure 7. No differences in perceived fatigue ratings were observed between right and left sides. As a result, the perceived fatigue data presented in Figure 7, with the exception of the neck, were based on the average changes combining the results from the right and left sides. Perceived fatigue changed and increased with regard to time with all keyboards ($p < 0.001$). As shown in Figure 7, the curved keyboard with the built-in wrist-rest consistently had the lowest changes/increases in perceived fatigue and the straight keyboard without a wrist-rest consistently had the highest changes/increases. The only differences in perceived fatigue ratings that were significant were in the forearm ($p = 0.004$), with the curved keyboard having smaller changes in perceived fatigue relative to the straight keyboard without a wrist-rest. The differences in perceived fatigue ratings in the shoulders between keyboards approached significance ($p = 0.054$) with the keyboards with the built-in wrist-rests having smaller changes in perceived fatigue.

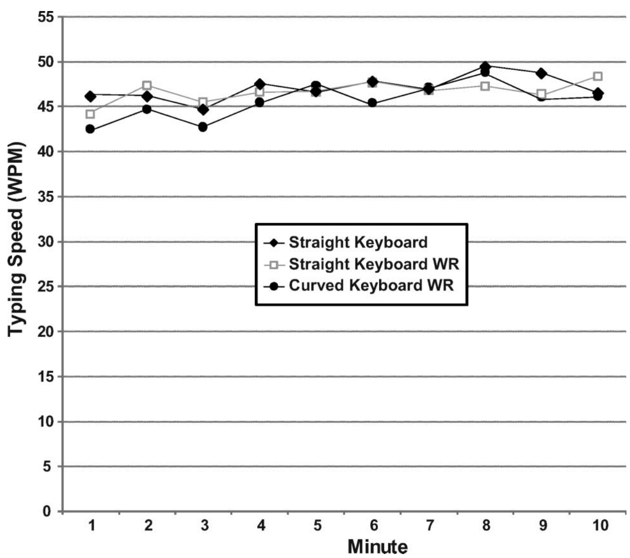

Figure 6. Mean, minute-by-minute typing speed in words per minute (WPM) by keyboard. Standard error bars are omitted for clarity (n = 26). WR = wrist-rest.

3. Discussion

The intent behind the design of the new curved keyboard was to promote a more neutral posture when typing, while at the same time not affecting speed and accuracy and eliminating the perceived 'medical device' look of the various alternative ergonomic keyboard designs. The major differences between the new curved keyboard (Figure 4) and the fixed-split keyboard (Figure 1) are the flat profile and the unbroken appearance of the alphanumeric section of the curved keyboard. The fixed-split keyboard has a noticeably visible 25° opening angle between keyboard halves compared to the subtle 12° opening created by the shape and curve of the keys on the new curved keyboard. In addition, the fixed-split keyboard has an 8° lateral inclination (i.e. gable) angle between key halves to reduce forearm pronation compared to no lateral inclination on the new curved keyboard.

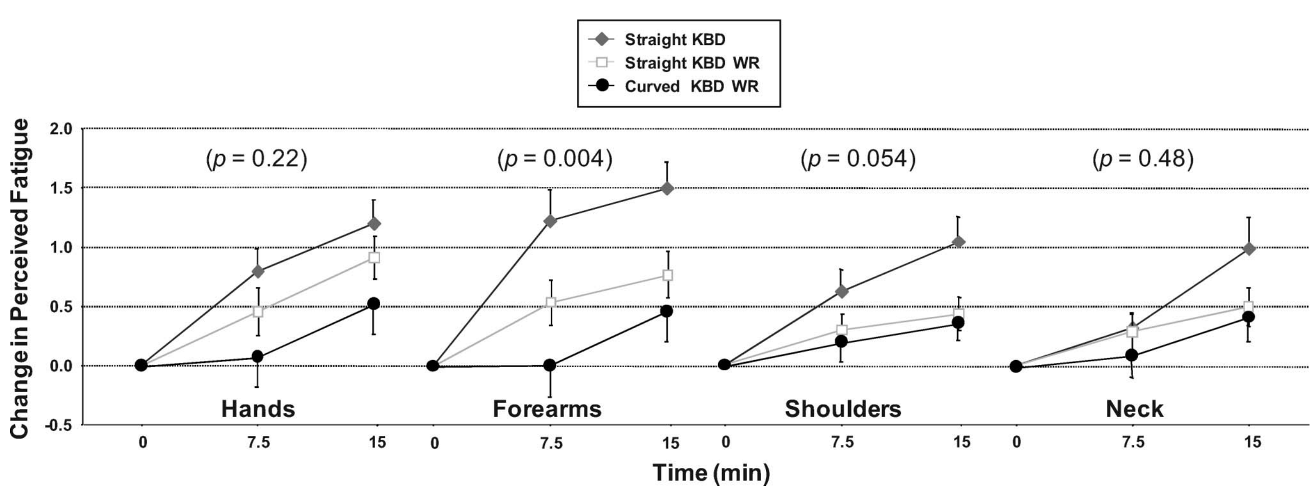

Figure 7. Mean (±SE) change in the Borg CR-10 perceived fatigue ratings in the hand, forearm, shoulder and neck for each keyboard (KBD) and plotted with regard to time (n = 26). p-Values in the figure indicate the significance levels of the differences between keyboards. WR = wrist-rest.

Figure 8. Microsoft Optical Desktop Pro Keyboard with comfort curve design.

The study results indicated that, compared to the conventional, straight keyboards (with and without a wrist-rest), the curved keyboard design (incorporating a wrist-rest) reduced ulnar deviation by 2.2°. Rempel *et al.* (2007) reported a reduction of 0.9° in ulnar deviation when comparing use of this new curved keyboard with the conventional, straight keyboard, although their measured difference in ulnar deviation did not reach statistical significance.

Although the primary interest was determining whether the curved keyboard reduced ulnar deviation, it is worth noting that the built-in wrist-rest had a fairly substantial effect on wrist extension; on average, wrist extension was reduced by 6.3° compared to a conventional, straight keyboard without a wrist-rest. However, when compared to a conventional, straight keyboard with a wrist-rest, no significant difference in extension was observed between the straight and curved keyboards. Compared to a straight keyboard without palm rest, Albin (1997) reported an 8.4° decrease in wrist extension when typists used a straight keyboard with a palm rest and Rempel *et al.* (2007) observed an average reduction in wrist extension of 4.2° when comparing use of this new curved keyboard with the conventional, straight keyboard without a wrist-rest. The sources for the small differences in ulnar deviation and extension measured in the present study and in Rempel *et al.*'s (2007) study are not known. These may not be significant or could be due to systematic measurement differences between equipment (electrogoniometry vs. video-based joint markers) or differences in the characteristics of the participants used in the two studies.

The perceived fatigue measures appear to corroborate the postural measures. The more neutral postures in the wrist may explain the lower perceived fatigue ratings in the hand and forearm with the curved keyboard. The short-term changes in perceived fatigue with the curved keyboard were less than the perceived changes measured with the straight keyboards. This appears to indicate that the participants were able to readily adapt to using the curved keyboard. In addition, perceived fatigue levels in the shoulders were lower with the keyboards with built-in wrist-rests. This result suggests that wrist-rests bear some of the load of the arms and reduce discomfort in the shoulder region. Since posture and/or electromyography were not measured in the upper arm and shoulder, objective data are not available to confirm this hypothesis.

Finally, there were no differences in typing performance and typing accuracy between the conventional, straight keyboards and the curved keyboard.

One potential limitation of this study was that no prior verification was made of whether the participants in Experiment 3 were touch typists before their inclusion in the study. However, the group mean (SE) typing speed was 51.3 ($\pm$3.2) words per min, indicating that it was likely that the majority of them were touch typists. In addition, another limitation in Experiment 3 was the short duration of the typing exposure and measuring changes in perceived fatigue over such a short period of time. Small changes in perceived fatigue were measured using the visual analogue form of the Borg CR-10 scale, but one could question whether the same results would be found over a longer duration of exposure. This could be a goal to test in future studies.

4. Conclusions

While reducing awkward wrist–forearm postures, the relatively extreme geometries of some ergonomic keyboards can be perceived as barriers or are real barriers to adoption by some computer keyboard users. Using a series of usability experiments, a new ergonomic keyboard design was developed that was shown to promote more neutral wrist postures, not to adversely affect typing performance and to lower perceptions of fatigue among a sample of straight keyboard users. Two iterative experiments, using a representative sample of straight, conventional keyboard users, identified a 12° opening angle as the preferred choice when presented with an array of possible opening angles (the acceptable range being 10–13°). In addition, across the five keycap designs tested, a 'stepped' presentation of keys spanning the opening was the preferred design. This 'stepped' key design more closely resembled current straight keyboard designs than the other keycap designs tested and, as a result, was perceived as more familiar and approachable by the participants. The third experiment used a fully functional prototype of the curved keyboard to confirm quantitatively the final design's effect on wrist postures, typing performance and perceived fatigue across a sample of representative typists. The 12° opening angle and curve in the keys in the alphanumeric section of the keyboard reduced ulnar deviation and, relative to a straight keyboard without a built-in wrist-rest, the curved keyboard's built-in wrist-rest reduced wrist extension. Typists liked the new keyboard design relative to a conventional, straight keyboard. As a result, the design goals of creating a keyboard that promoted more neutral postures, was perceived as less fatiguing and did not adversely affect typing speed and accuracy was achieved. In Autumn 2004, the curved keyboard was released and marketed as the Microsoft Optical Desktop Pro with the comfort curve design (shown in Figure 8) and since then additional keyboards have been introduced with the curved keyboard design.

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