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User-centered design and evaluation of a next generation fixed-split ergonomic keyboard

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Abstract. *Objective:* Research has shown that fixed-split, ergonomic keyboards lessen the pain and functional status in symptomatic individuals as well as reduce the likelihood of developing musculoskeletal disorders in asymptomatic typists over extended use. The goal of this study was to evaluate design features to determine whether the current fixed-split ergonomic keyboard design could be improved.
Participants: Thirty-nine, adult-aged, fixed-split ergonomic keyboard users were recruited to participate in one of three studies.
Methods: First utilizing non-functional models and later a functional prototype, three studies evaluated keyboard design features including: 1) keyboard lateral inclination, 2) wrist rest height, 3) keyboard slope, and 4) curved "gull-wing" key layouts.
Results: The findings indicated that keyboard lateral inclination could be increased from 8° to 14°; wrist rest height could be increased up to 10 mm from current setting; positive, flat, and negative slope settings were equally preferred and facilitated greater postural variation; and participants preferred a new gull-wing key layout. The design changes reduced forearm pronation and wrist extension while not adversely affecting typing performance.
Conclusions: This research demonstrated how iterative-evaluative, user-centered research methods can be utilized to improve a product's design such as a fixed-split ergonomic keyboard.

Keywords: Computers, text entry, design process, wrist posture, forearm posture, performance

1. Introduction

Fixed-split ergonomic keyboards were introduced in the mid-1990s with the design based on the findings of several investigators [3,6,8,14]. As shown in Fig. 1, the notable design characteristics of a fixed-split keyboard included separating and opening the alphanumeric section into two dedicated halves for the left and right hands (i.e., opening angle), tenting the left and right alphanumeric halves to form a peak or tent in the middle of the keyboard (i.e., lateral inclination), providing a built in wrist rest, and user-adjustable legs on the underside for flat (0°) and positive slopes. Because the left and right hands address the keyboard at roughly equal and opposite angles, splitting the keyboard into left and right halves was intended to reduce ulnar deviation. The tenting of the two alphanumeric sections was intended to reduce forearm pronation. Finally, the purpose of the built-in wrist rest was to reduce wrist extension. These design enhancements improved wrist postures and were thought to reduce the exposure to known risk factors which can lead to upper-extremity musculoskeletal disorders [5,9,11,17,18]. Additionally, fixed-split ergonomic keyboards have been shown to reduce muscle strain [16], improve the health of those persons with hand pain [17], and reduce the incidence of new musculoskeletal disorders among an asymptomatic population after extended use [12].

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Fig. 1. Picture showing the design characteristics contained in most fixed-split ergonomic keyboards including: 1) the splitting of the alphanumeric sections of the keyboard into two halves creating an opening angle, 2) tenting the keyboard halves so the keys slope up forming a peak in the middle (i.e., lateral inclination), 3) flip down legs on underside (out of view) for slope, and 4) the built-in wrist rest to provide wrist support. Microsoft Natural Keyboard shown in photo.

While variations of the fixed-split keyboard have evolved over the years, the original keyboard geometry has remained relatively unchanged. The purpose of this research was to determine whether the design of the current fixed-split keyboard could be improved. For example, could non-neutral postures be further reduced by exploring more dramatic design geometries? Could reach distances to the keys on the periphery of the keyboard be further reduced by altering horizontal and vertical planer key surface geometries? Do further design innovations remain unrealized?

Basic research evaluated the fundamental design of the fixed-split keyboards to identify opportunities for design evolution and improvement. An experiment was conducted at the University of California's Ergonomics Lab to evaluate alternative lateral inclination angles, opening angles, and spacing of the keyboard halves. The results suggested that a steeper lateral inclination angle of 12° was preferred by touch typists, while further reducing wrist pronation, compared to the lateral inclination angle of 8° on the commercially available, fixed-split keyboards at the time [1]. A second experiment measured finger-tip trajectory angles at which fingers contacted the keyboard keys. The preliminary results of this study suggested that fingers strike the keys in the central portion of the keyboard primarily straight up and down; whereas keys on the periphery were struck with more oblique angles [2]. In addition, motion analysis studies conducted in Microsoft's usability labs identified more extreme finger and wrist postures when typists reached for keys on the lateral edges of the fixed-split keyboard (e.g. Backspace key).

As a result of the new findings, research goals were identified that questioned basic assumptions about the design of fixed-split keyboards. The goals of the research included determining whether upper-extremity postures could be improved by 1) increasing the lateral inclination of the keyboard (Fig. 2), 2) increasing the wrist rest height, 3) adding a negative slope adjustment, and 4) evaluating two new key layouts (Figs 2 and 3), given typing performance and subjective preference. The new key layouts had a secondary goal of reducing the overall thickness of the keyboard and thus maintaining approachability for users and fit on desks and in keyboard trays. None of these design embodiments existed in commercially-available, fixed-split keyboards at the time of this research. Another project goal was to create an innovative keyboard design that differentiated itself from other commercially available keyboards.

The research was conducted in two phases. The first iterative-evaluative design phase utilized a series of non-functional models in two usability studies (experiment #1 and experiment #2). The second phase (experiment #3) used a fully-functional prototype to evaluate and confirm the most highly rated design embodiments identified in the two earlier usability experiments.

A cross-functional team consisting of ergonomists, industrial designers, model makers, mechanical engineers, business planners and university researchers explored opportunities to improve the design of the fixed-split keyboard. Representative users were invited into the lab to evaluate a series of models and prototypes to provide their impressions and preferences and thus assist with the evolution of the new keyboard design.

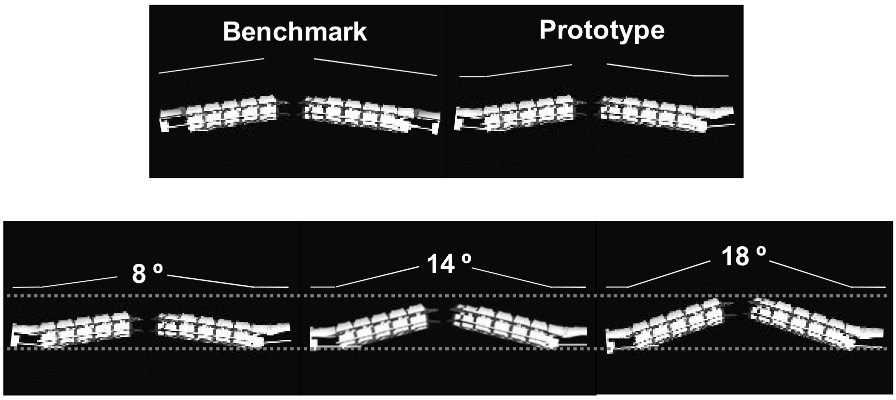

Fig. 2. CAD representation of showing a front elevation representation of the benchmark ergonomic keyboard (top- left) and prototype gull-wing design (top-right). Bottom of figure, CAD representation of the 8°, 14° and 18° lateral inclinations.

Fig. 3. Left, the model used in Experiment 1 with the straight alignment of the peripheral keys positioned upward (but not inward). Right, the model used in Experiments 1 and 2 with the "gull-wing" design with peripheral keys positioned upward and inward The "gull-wing" design was introduced to better match finger strike angles of fingers typing on peripheral keys and to make the peripheral keys easier to reach.

The series of three experiments presented in this paper illustrate a user-centered product design process.

2. Methods (Phase I)

2.1. Participants

All participants were recruited through Microsoft's Central Usability database and volunteered to participate in usability research. To be eligible, participants had to use a fixed-split ergonomic keyboard – any brand or manufacturer – as their primary keyboard for work and/or personal use, self-reported personal computer of at least 10 hours per week, and not be Microsoft employees. The participants were not screened for past or present hand-related injury or pain. They gave their consent to participate and received a Microsoft software gratuity (value: $20 to $600) in exchange for their participation. Studies followed Microsoft's standard organizational procedures for usability testing with human subjects.

In the first usability experiment, thirteen fixed-split keyboard users (7 men, 6 women) with an average age of 38 years (range 18 to 56 years) who were all right hand dominant participated in the study. Three of the thirteen participants had previously used a fixed-split keyboard yet used primarily a straight keyboard at the time of the experiment. In the second experiment, recruiting criteria was tightened to ensure only current fixed-split keyboard users attended. In the first experiment, hand size was not measured. In the second experiment, a different set of thirteen fixed-split keyboard users (7 men, 6 women) with an average age of 47 years (range 25 to 60 years) who were also all right hand dominant participated in the study. The second group had six "large" hands (defined as hand length of 50th percentile adult U.S. male or larger: $\geqslant$ 189 mm); four "medium" hands (between 50th percentile U.S. adult male and 50th percentile U.S. adult female: 174 to 189 mm); and three "small" hands (50th percentile adult U.S. female or smaller: $\leqslant$ 174 mm)] [15].

2.2. Experimental set-up

For both experiments, the usability lab consisted of a height adjustable table and chair with a one-way viewing mirror to an observation room. The workstation was set up according to the participant's stature and comfort level. Participants adjusted the chair to have their feet flat on the floor and thighs parallel to the floor. Then, the table was adjusted so the home row of the keyboard was elbow height. A computer display was present and the top of screen was positioned at eye level roughly arms length away; however, since the keyboard models were not functional, the display was for reference only.

2.3. Lateral inclination angles and key layouts

The keyboard models with new lateral inclinations and key layouts were machined, solid-block, high-density foam with key caps glued to their surface and thus were not mechanically or electrically functional. Each keyboard was flat (slope of 0°) and had a built in wrist rest. The wrist rest height was in line with the base height of the first row of keys of the keyboard.

In the first experiment, models of keyboards with three lateral inclination angles: 8° (current, benchmark), 10°, and 12° were presented randomly. And, across the three lateral inclinations, two different types of key layouts were presented. First, participants were presented models with keys in a straight row alignment with raised peripheral keys that were moved upward in vertical plane to match the plane of keyboard case-top (Fig. 2, top-right; Fig. 3, left). Then, they were shown three models that repositioned peripheral keys vertically upward and horizontally inward in a "gull-wing" design where the same peripheral keys were repositioned in both vertical and horizontal planes (Fig. 2, top-right; Fig. 3, right). Both of the new key layouts repositioned the key cap surfaces on the right side (i.e., =,], ", ?, Backspace, \, Enter, Shift, and Ctrl) and on the left side (i.e., ∼, Tab, Caps Lock, Shift, and Ctrl). Given the asymmetry of the keys on each side of the opening angle, two columns of peripheral key surfaces were repositioned on the right side whereas only one column was repositioned on left side. If they had not already mentioned it, participants were asked if they noticed a difference between the two key layouts. Then, the two key layout arrangements were pointed out and placed in front of the participants. They were asked to rank the first and second choice for key layout as well as rate acceptability.

The second experiment evaluated three additional lateral inclination angles (while confirming presentation of "gull-wing" key layout with its upward and inward peripheral keys). In this second study, a different set of participants evaluated the same 8°, 10°, and 12° lateral inclination models and additional models with lateral inclinations of 14°, 16°, and 18°. All models evaluated had the gull-wing design, which was identified as the preferred key layout in the first experiment.

For both experiments, participants were asked to simulate typing at each keyboard model for approximately 5 minutes or until they were certain of their evaluation. They were instructed to verbally express any thoughts and/or feelings that they had about the model when typing. At the end of the testing, the models were placed in front of the participants and they were asked to rank order their preference for key layout (experiment #1) and lateral inclination angles (experiment # 1 and experiment #2) as well as whether they thought each respective model was acceptable or not.

2.4. Wrist rest heights

Many conventional and fixed-split keyboards presently available have wrist rests to provide a gradual transition from the front edge of the keyboard to the desk surface. This portion of the experiment was designed to evaluate an array of wrist rest heights to determine whether there was an optimal or preferred height. A mechanically-functional, straight keyboard in the neutral (0°) slope position was retrofitted so different height wrist rests could be installed for the heights of interest from 0 to 28 mm (Microsoft Wireless MultiMedia Keyboard v1, Redmond, WA). In the first experiment, thirteen participants evaluated five wrist rest heights: 0 mm (current wrist rest/benchmark) and 7 mm, 14 mm, 21 mm, and 28 mm taller than the benchmark. In the second experiment, a different group of thirteen participants repeated the testing with a refinement of the wrist rest heights which included the 0 mm, 7 mm, 10 mm, and 14 mm. Identical to the lateral inclination testing, participants were asked to simulate typing a standard text passage as well as their name, home address, favorite movie, and any other words of their choosing on each keyboard (about 3 to 5 minutes at each keyboard) and verbally express any thoughts and/or feelings they had about the model when typing. After testing each wrist rest height, participants were asked to rate each height's acceptability and rank order the wrist rest heights from most to least preferred.

Table 1
Tallies (modes for each angle in **bold**) and means of participants' rank order preferences and the acceptability proportions for the lateral inclination angles tested ($n = 13$)

	Lateral inclination angle					
Rank	8°	10°	12°	14°	16°	18°
1st	0	1	1	**5**	**4**	2
2nd	1	1	2	**5**	3	1
3rd	1	3	2	1	2	**4**
4th	0	3	**6**	2	2	0
5th	3	**5**	1	0	2	2
6th	**8**	0	1	0	0	**4**
Average Rank*	5.2	3.8	3.5	2.0	2.6	3.8
% Acceptable	77%	85%	92%	100%	77%	46%

*Average rank is calculated where "1" is counted for each first place rank, "2" for each second place rank, and so on to "6" for each last, sixth place rank and these values are summed and then divided by number of participants. Lower average ranks are "better."

2.5. Keyboard slopes

For the keyboard slope testing in the first experiment, the thirteen participants randomly evaluated a keyboard prototype with negative ($-7°$); neutral (0°) and positive slope (7°) settings. The prototype was built using a mechanically-functional, fixed-split keyboard (Microsoft Wireless Natural MultiMedia Keyboard v1.0, Redmond, WA) with rear lift-legs installed on the front underside of the keyboard to offer a new negative slope setting. Identical to the other testing, participants were asked to simulate typing at each keyboard for about three to five minutes and verbally express any thoughts and/or feelings they had about each slope condition when typing. At the end of the testing, the participants were then asked to rate the acceptability of each slope setting and then rank the first, second, and third most preferred slopes. Keyboard slope was not evaluated in the second experiment.

3. Results (Phase I)

3.1. Lateral inclination angles and key layouts

In the first experiment, all lateral inclination angles tested were deemed acceptable (70% or more of the participants stating they would buy a keyboard with the lateral inclination they just tested). The 12° lateral inclination was most preferred, followed by 10°, and the 8° lateral inclination was the least preferred. The 8° lateral inclination is the current tenting angle on most commercially available, fixed-split keyboards. Because the optimum, upper limit lateral inclination angle may not have been identified, in experiment #2 in addition to the 8°, 10° and 12° lateral inclinations, additional lateral inclinations of 14°, 16° and 18° were also tested. As shown in Table 1, participants again showed a preference for steeper lateral inclination angles with 14° being the most preferred, followed by 16° as the second choice, and 12° as the third choice. The lateral inclination angles of 8° and 10° were also acceptable, but 18° was deemed unacceptable.

Participants understood and appreciated the postural benefits of a steeper lateral inclination angle. They said that the acceptable models felt good with their wrists in a comfortable or natural posture and that their hands felt more relaxed. The results indicated that it was acceptable to increase lateral inclination angles and build a new keyboard with a lateral inclination angle between 12° and 16°.

Participants liked the new gull-wing design with the peripheral keys turned upwards and inwards. They preferred it to models with the peripherals keys only turned upward. With the new gull-wing key layout, participants stated that they felt the peripheral keys were easier to reach and that the keys seemed right where they belonged, matching the contour of the fingers of the hand.

Table 2
Tallies (modes for each height in **bold**) and means of participants' rank order preferences and the acceptability proportions for the wrist-rest heights tested ($n = 13$)

	Wrist rest height			
Rank	0 mm	7 mm	10 mm	14 mm
1st	3	4	**5**	1
2nd	1	**5**	4	2
3rd	**5**	2	3	3
4th	4	1	1	**7**
Average Rank*	2.8	2.0	2.0	3.2
% Acceptable	62%	92%	77%	38%

*Lower average ranks are "better."

3.2. Wrist rest heights

In the first experiment, the wrist rest heights of 0 mm and 7 mm had acceptability ratings of 100%, while the 14 mm height was rated marginally acceptable (69%), and the 21 mm and 28 mm wrist rest heights were just too tall (acceptability ratings of only 8%). Because the first set of wrist rest height gradations were so large, to more precisely determine the preferred height, the second experiment evaluated wrist rest heights of 0 mm, 7 mm, 10 mm, and 14 mm. As shown in Table 2, participants rated the wrist rest heights of 7 mm and 10 mm as most favorable, the 0 mm height acceptable, and the 14 mm height unacceptable. With the higher wrist rests, the participants stated that the wrist rests put their wrists in a flatter angle, their wrists felt more relaxed, and their fingers were more comfortable on the keys. Participants indicated that the two tallest wrist rest heights physically interfered with the use of space bar. The results indicated that it was acceptable to increase wrist rest heights up to 10 mm.

3.3. Keyboard slopes

In experiment #1, participants were evenly split on preference for the three keyboard slopes: one-third each preferred the negative, flat, and positive slopes. For those participants who liked the negative slope, they said their wrists might not get as tired during prolonged periods of typing. As a result, it appeared that providing a keyboard which could be configured into any of the three slope settings would be desirable.

4. Methods (Phase II)

4.1. Keyboards

A functional prototype was specially constructed with a 14° lateral inclination angle, gull-wing key surfaces, legs in front and back to offer 3 keyboard slopes (negative $-7°$; flat 0°; positive $+7°$), and had removable wrist rests so the keyboard could be configured to have wrist rest heights of 0 mm, 7 mm, and 10 mm. Besides testing and evaluating the new keyboard features, the prototype was also compared to a benchmark, fixed-split keyboard with 8° lateral inclination and benchmark keycap surfaces (Microsoft Wireless Natural MultiMedia Keyboard v1.0, Redmond, WA) and a conventional, straight keyboard (P/N 04N454; Dell Computer, Round Rock, TX). The brand logos were removed or hidden on each keyboard. Each participant evaluated every test condition.

4.2. Participants

A separate group of thirteen current fixed-split ergonomic keyboard users (8 males, 5 females) – different from the users in the prior usability experiments – participated in this study. The group had four "large" hands, six "medium" hands, and three "small" hands. As with the previous two experiments, participants were recruited through Microsoft's Central Usability database and received a Microsoft software gratuity in exchange for their participation. The mean age of the participants was 37 years old (range 23 to 54 years) and all participants were touch typists with a self-reported typing speed of at least 40 words per minute. All procedures were approved by the University of Washington's Human Subject Committee.

4.3. Experimental set-up

The workstation was set up according to the participant's stature and comfort preferences. Participants adjusted the chair so their thighs were parallel to the seat pan, feet flat and firmly supported by the floor, and chair back rest adjusted to firmly support the back. After the participants were comfortable with their chair settings, participants were instructed to comfortably rest their upper arms at their sides, form roughly a 90 degree angle at the elbow, and the table height was adjusted to be 2.5 centimeters below elbow height. This ensured that participants were comfortably seated with their shoulders relaxed and typed with their wrists in a relatively neutral flexion/extension position. After the initial setting, participants were allowed to make slight adjustments for comfort.

4.4. Wrist and forearm postures

As shown in Fig. 4, a combined goniometer and inclinometer system was used to measure wrist and forearm posture respectively. Bi-axial electrogoniometers (SG-65; Biometrics, Gwent, UK) were used to measure wrist flexion/extension and radial/ulnar deviation. A small, customized, light-weight (11 grams) inclinometer (FAS-G; Microstrain, Inc; Williston, VT) was attached to the distal end-block of the electrogoniometer to measure forearm pronation. When rotated through 360° of movement, the maximum error in angle measurement of the inclinometers was no greater than 2.3° [7]. Participants were prepared for instrumentation by cleaning the back of the hand, wrist and forearm with alcohol. After the alcohol dried, a line was drawn from the third metacarpal on the back of the hand down the centerline of the long axis of the forearm. Using double-sided tape, the combined goniometer and inclinometer systems were then placed on the lines, with the flexible wire between the goniometer end-blocks centered over the wrist crease. The instrumentation was then connected to a portable 8-channel logger (ME-6000-P8; Mega Electronics; Kupio Finland) and the subsequent data were collected and stored at 100 Hz in the compact flash memory card of the logger.

Fig. 4. Side and top view of laboratory set-up showing participant instrumented with combined goniometer/ inclinometer systems while working with the new prototype keyboard.

To calibrate the goniometers, participants pronated their hands and forearms to 90° (hands parallel to the work surface) and were asked to position their hands and wrists in a neutral flexion/extension and radial/ulnar deviation position three times. Neutral wrist and forearm (pronation) postures were defined using the methods prescribed by the American Academy of Orthopedic Surgeons [4]. Neutral radial/ulnar deviation was the position where the third metacarpal was in line with the long axis of the forearm. Neutral flexion/extension was the position where the plane formed by the back of the hand was in line with the dorsal surface of the forearm. Neutral hand/forearm pronation (0°) was the position where the hand was upright (thumb pointing up) and in the handshake position, 90° pronation was the position where the hand was flat and parallel to the work surface. To calibrate the inclinometers, the participants were asked to move their hands from flat and parallel to the work surface (90° pronation) to the handshake position (0° pronation) three times. The average of the three calibration positions determined the neutral postures for the wrists and forearms.

4.5. Typing performance

The testing of the various keyboard configurations was randomized. When the first keyboard configuration was tested, participants were asked to place the keyboard in front of them in the position that felt most comfortable for typing. Then, the horizontal and vertical location of the keyboard spacebar was marked on the table and all subsequent keyboards were placed so the space bar was in the same location. As shown in Fig. 4, the prototype tested was a fully functional keyboard. The prototype could accommodate wrists rests of different heights (0 mm, 7 mm, and 10 mm) and the legs could be adjusted to put the prototype in negative ($-7°$), flat (0°) or positive slope settings (7°).

To measure typing performance, a program called Typing Tutor Deluxe was used (Version 6.0; COKeM International Ltd.; Plymouth, MN, USA). Using simple English text from a novel, the typing program displayed the text participants were supposed to type, and a second window immediately below, displayed the actual text typed by the participants underlining mistyped words. Prior to the actual keyboard testing, participants spent two minutes typing using a conventional, straight keyboard in order to become familiar with the display and operation of the typing program. Since adapting to a new keyboard can take anywhere from a few minutes to days depending on the design [13], a choice was made to not allow any practice with the various keyboard designs and randomized keyboard order. Each keyboard configuration was tested for a period of five minutes and over that five minute period the typing software automatically calculated the average typing speed in words per minute and typing accuracy, defined as the percentage of words correctly typed. During the actual keyboard testing, participants were asked to balance typing speed and accuracy.

4.6. Subjective keyboard preferences

In addition, after using each keyboard configuration, participants answered a series of 7-point Likert questions ($1 =$ Strongly Disagree and $7 =$ strongly agree) assessing desirability (see Table 4). Participants were asked to rank the keyboards from most preferred to least preferred and to give their reasons for their rankings.

4.7. Data analysis

The goniometer and inclinometer data were analyzed using an interactive data analysis program written in Labview. Mean radial/ulnar, flexion/extension and pronation/supination angles were calculated for each keyboard configuration tested. The typing speed, typing accuracy, and desirability data were also tabulated

Table 3
Mean $\pm$ SE posture ($n = 11$) and performance measures ($n = 13$) for the various keyboard configurations tested. For the performance measures, typing speed was measured in words per minute (wpm) and accuracy was the percentage of words correctly typed. Lateral inclination angle was tested with 0 mm wrist rest and the zero slope setting. Wrist rest height was tested with the 14° lateral inclination prototype keyboard and the zero slope setting. Slope was tested with the 14° lateral inclination prototype keyboard and the 0 mm wrist rest height

		Posture			Performance	
Variable	Condition	Extension	Ulnar deviation	Pronation	Speed (wpm)	Accuracy (%)
Lateral Inclination Angle	8 degrees (Benchmark Ergonomic Keyboard)	30.6 ± 3.0	4.0 ± 1.4	$56.9^{a} \pm 1.5$	46.5 ± 5.3	$92.0\% \pm 1.5$
	14 degrees (Prototype)	30.6 ± 2.8	3.4 ± 1.2	$52.0^{b} \pm 1.4$	41.8 ± 4.3	$84.4\% \pm 3.4$
Wrist Rest Height (using prototype)	0 mm (Benchmark)	$30.6^{a} \pm 2.8$	$3.4^{a} \pm 1.2$	$52.0^{a} \pm 1.4$	41.8 ± 4.3	$84.4\%^{a} \pm 3.4$
	+7 mm	$26.1^{b} \pm 3.2$	$4.5^{a} \pm 1.2$	$49.4^{b} \pm 1.4$	44.6 ± 4.7	$88.4\% \pm 2.6$
	+10 mm	$19.8^{c} \pm 2.9$	$7.1^{b} \pm 1.1$	$48.1^{b} \pm 1.7$	43.3 ± 5.0	$90.0\%^{b} \pm 2.2$
Slope (using prototype)	Negative (−7°)	$19.8^{a} \pm 2.9$	$8.7^{a} \pm 1.6$	$47.8^{a} \pm 1.5$	45.1 ± 5.1	$88.8\% \pm 2.4$
	Flat (0°)	$30.6^{b} \pm 2.8$	$3.4^{b} \pm 1.2$	$52.0^{b} \pm 1.4$	41.8 ± 4.3	$84.4\% \pm 3.4$
	Positive (+7°)	$34.8^{c} \pm 3.3$	$2.4^{b} \pm 1.3$	$51.4^{b} \pm 1.8$	44.4 ± 5.0	$87.2\% \pm 4.9$
Keyboard	Conventional Keyboard (0° Lateral Inclination, No Wrist Rest, 0° Slope)	$32.1^{a} \pm 3.7$	$10.9^{a} \pm 1.9$	$65.2^{a} \pm 2.0$	47.6 ± 5.9	$85.6\% \pm 4.5$
	Benchmark Ergonomic Keyboard (8° Lateral Inclination, 0 mm Wrist Rest, 0° Slope)	$30.6^{a} \pm 3.0$	$4.0^{b} \pm 1.4$	$56.9^{b} \pm 1.5$	46.5 ± 5.3	$92.0\% \pm 1.5$
	Prototype (14° Lateral inclination, Gull-Wing Key Layout, 7 mm Wrist Rest, 0° Slope)	$26.1^{b} \pm 3.2$	$4.5^{b} \pm 1.2$	$49.4^{c} \pm 1.4$	44.5 ± 4.7	$88.4\% \pm 2.6$

*For a given variable, values in the same column with the different superscripts are significantly different ($p < 0.05$).

for each keyboard configuration. With the exception of the Likert scale data which were analyzed using Friedman's test, all data were analyzed using repeated measures analysis of variance (RANOVA) methods with JMP statistical analysis software (Version 5.1; SAS Institute; Cary, SC). Significance was accepted when probabilities were below 0.05.

5. Results (Phase II)

5.1. Lateral inclination angles

As shown in Table 3, when compared to the 8° lateral inclination, which is the current industry standard, the prototype keyboard with the 14° lateral inclination reduced pronation by 5° ($p < 0.01$) with no significant effect on extension ($p = 0.91$) or ulnar deviation ($p = 0.54$). Participants typed five words per minute slower with the 14° lateral inclination keyboard ($p = 0.10$) and accuracy decreased by 8% ($p = 0.18$); yet, both of these differences did not reach significance. There were no self-reported fatigue perception differences in the hands, wrists, forearms and shoulders between lateral inclination angles.

5.2. Wrist rest heights

Wrist rest height affected posture (Table 3) as both wrist extension ($p < 0.01$) and forearm pronation ($p < 0.01$) decreased as the wrist rest height increased; however, ulnar deviation increased ($p < 0.01$) with increasing wrist rest height. The performance data indicated that wrist rest height did not affect typing speed ($p = 0.20$) but appeared to have an influence on typing accuracy ($p = 0.07$); typing accuracy increased as wrist rest height increased (Table 3). Finally, there were no significant differences in the self-reported hand, wrist, forearm, or shoulder fatigue perceptions between the three wrist rest heights.

5.3. Keyboard slopes

As shown in Table 3, when comparing the three different keyboard slopes, the negative slope setting reduced wrist extension ($p < 0.01$) and forearm pronation ($p < 0.01$); however, these postural improvements were at the expense of increasing ulnar deviation ($p < 0.01$). There was also a difference in typing speed between the three different keyboard slopes ($p = 0.05$), but no significant differences in typing accuracy ($p = 0.34$). Typing speed and accuracy was highest with the negative slope.

5.4. Subjective keyboard preferences

Table 4 shows the desirability ratings collected immediately after participants tested each keyboard type and configuration. In general, the benchmark ergonomic keyboard had the highest scores, followed by the prototype keyboard with the 14° lateral inclination, 7 mm high wrist rest and neutral slope setting. The 10 mm wrist rests did not receive favorable ratings when coupled with the positive and negative slope settings and in general the positive slope setting was preferred over the negative slope setting. At the end of the testing, after subjects had used all keyboards, participants were asked to rank all keyboards side-by-side from most to least preferable. When asked to rank all the keyboards, 10 out of 13 participants ranked the prototype as their first choice.

5.5. Keyboard comparisons

As shown in the bottom of Table 3, when comparing conventional, straight keyboard; benchmark ergonomic keyboard; and the preferred embodiment for the prototype keyboard (14° lateral inclination, 7 mm wrist rest, neutral slope), there were significant differences in pronation ($p < 0.01$), extension ($p < 0.01$), and ulnar deviation ($p < 0.01$). Relative to the benchmark ergonomic keyboard, the preferred embodiment of the concept keyboard reduced pronation by 7.5° and wrist extension by 4.5°; however, no significant difference was observed with ulnar deviation. Finally, there were no significant differences in typing speed ($p = 0.34$) or accuracy ($p = 0.30$) across the keyboards.

6. Discussion

The user-centered product design approach applied in this study presented a case-study of iterative-evaluative testing with representative users and a systematic presentation of design variables. The two iterative usability-design studies used a series of 22 models to test the variables of interest. The first study demonstrated that participants stated that the new "gull-wing" key design was favorable and that they preferred a greater lateral inclination of the two alphanumeric keyboard halves. The second study indicated that participants favored a 14 lateral inclination, the "gull-wing" key design, and a 7 or 10 mm taller wrist rest. Then, a third experiment with functional prototypes objectively measured arm-wrist postures, typing performance, and subjective preferences. The results of the third study confirmed many of the subjective observations identified in the earlier iterative usability-design experiments, primarily that the 7mm high wrist rest and 14 ° lateral inclination was preferred and improved postures while not significantly altering typing performance. The result of this research was the final design, development, and production of a next generation fixed-split keyboard (Fig. 5). This keyboard was manufactured with a 14° lateral inclination; gull-wing key layout; integrated, 7 mm padded wrist rest; and user-configurable negative, flat, and positive slopes.

6.1. Postures

Objectively, the new geometries of the next generation fixed-split keyboard were designed to improved wrist and forearm postures relative to its predecessor (Fig. 1). With the steeper 14° lateral inclination and built-in, taller wrist rest, these new keyboards should roughly reduce pronation by 7.5° and wrist extension by 4.5° relative to the prior design. No effect was observed on ulnar deviation except when the negative slope setting is used. The negative slope reduced extension and pronation at the expense of slightly increasing ulnar deviation.

6.2. Performance

Given the changes in geometries, the design goal for the new fixed-split keyboard was to maintain current typing speeds and error rates. Some learning with the prototype keyboards would be expected as the touch-typists adjusted to the slightly different positioning of the keys. Previous research demonstrates that learning to type on a new ergonomic keyboard from a straight keyboard can take anywhere from 30 minutes up to 2 to 3 weeks [17]. Even though they were experienced fixed-split keyboard users, the participants in the third experiment had to "learn on the fly" and only typed on the each of the prototype design embodiments for a period of 5 minutes each. So, it is not unexpected to see slight decrements in typing performance with the prototype keyboard.

6.3. Preferences

Based on preferences, the wrist rest height could have been increased up to 10 mm; however, the objective data showed that this 10 mm wrist rest height was not as functional in the positive and negative slope settings.

Table 4

The mean $\pm$ SE Likert responses from the participants for the production and prototype keyboards tested, $1 =$ strongly disagree and $7 =$ strongly agree. ($n = 13$) The keyboard with a 0° lateral inclination, 0 mm wrist rest and flat slope configuration was a conventional keyboard and the keyboard with a 8° lateral inclination, 0 mm wrist rest and neutral slope was a Micorosoft Natural Keyboard

	Production keyboards		Prototypes							
Lateral inclination angle	0°	8°	14°	14°	14°	14°	14°	14°	14°	
Wrist rest height	0 mm	0mm	0 mm	7 mm	10 mm	0 mm	10 mm	0 mm	10 mm	
Slope	Flat	Flat	Flat	Flat	Flat	Negative	Negative	Positive	Positive	P-value
This keyboard was easy to use.	4.5 ± 0.5	5.1 ± 0.5	4.2 ± 0.4	4.6 ± 0.4	4.0 ± 0.6	4.1 ± 0.4	3.4 ± 0.5	4.8 ± 0.3	4.1 ± 0.4	0.13
This keyboard feels comfortable for my hands and wrists while typing.	3.0 ± 0.4^{a}	5.3 ± 0.4^{b}	$4.5 \pm 0.5^{a,b}$	$4.6 \pm 0.4^{a,b}$	$4.2 \pm 0.5^{a,b}$	$3.7 \pm 0.4^{a,b}$	$3.0 \pm 0.5^{a,b}$	$4.2 \pm 0.5^{a,b}$	$3.9 \pm 0.4^{a,b}$	0.03
This keyboard feels comfortable for my arms and shoulders while typing.	3.0 ± 0.5^{a}	5.2 ± 0.4^{b}	$4.7 \pm 0.4^{a,b}$	$4.5 \pm 0.3^{a,b}$	$4.2 \pm 0.4^{a,b}$	$4.0 \pm 0.5^{a,b}$	$3.2 \pm 0.5^{a,b}$	$4.4 \pm 0.4^{a,b}$	$4.0 \pm 0.5^{a,b}$	0.05
I like using this keyboard.	3.1 ± 0.6^{a}	5.2 ± 0.5^{b}	$3.9 \pm 0.5^{a,b}$	$4.3 \pm 0.5^{a,b}$	$3.6 \pm 0.6^{a,b}$	$3.5 \pm 0.5^{a,b}$	2.7 ± 0.5^{a}	$4.3 \pm 0.5^{a,b}$	$3.6 \pm 0.5^{a,b}$	0.02
I like the overall feel of this keyboard when typing.	3.0 ± 0.6^{a}	5.1 ± 0.4^{b}	$3.9 \pm 0.4^{a,b}$	$4.7 \pm 0.5^{a,b}$	$3.5 \pm 0.6^{a,b}$	$3.6 \pm 0.5^{a,b}$	$3.2 \pm 0.5^{a,b}$	$4.2 \pm 0.5^{a,b}$	$3.7 \pm 0.4^{a,b}$	0.04
This keyboard would be beneficial to me.	3.2 ± 0.6^{a}	5.1 ± 0.4^{b}	$3.9 \pm 0.5^{a,b}$	$4.7 \pm 0.5^{a,b}$	$3.5 \pm 0.6^{a,b}$	$3.5 \pm 0.4^{a,b}$	$2.8 \pm 0.5^{a,b}$	$4.3 \pm 0.5^{a,b}$	$3.6 \pm 0.5^{a,b}$	0.03
Average Score	3.3	5.2	4.2	4.6	3.8	3.7	3.0	4.4	3.8	

*Values in the same row with the different superscripts are significantly different ($p < 0.05$).

Fig. 5. Top and side view of the final design for next generation ergonomic keyboard. Final keyboard was manufactured with a lateral inclination of 14°, a padded wrist rest which was 7mm higher than previous designs, a gull-wing key layout, and user configurable into three slopes: negative, neutral, and positive. The side view shows the keyboard with the front support installed to create the negative slope configuration. This keyboard is produced, marketed and sold as the Microsoft Natural Ergonomic Keyboard 4000.

As a result, the final design choice incorporated a 7 mm higher wrist rest.

When ascertaining keyboard preference based on ease of use, comfort, feel, and satisfaction just after use, the benchmark, fixed-split keyboard was preferred. However, when asked to rank order the keyboards at the end of the study after using all keyboards, 10 out of 13 participants preferred the geometries of the prototype keyboard over the existing geometry of the benchmark, fixed-split keyboard. Participants had a stronger preference and appreciation for the 12° and 14° lateral inclinations compared to the other lateral inclinations tested between 8° to 18°. Even small- and medium-hand size persons appreciated the steeper 14° lateral inclination compared to the 12° lateral inclination.

Given that people tend to prefer what is familiar to them, it is not surprising that the representative participants of current fixed-split ergonomic keyboards rated the benchmark, fixed-split keyboard more highly on subjective scales for ease of use, comfort, and satisfaction relative to the new prototype. While very effort was made to craft the functional prototype to sound and feel just like a production keyboard, it did not have the quality of typing experience that was present on the marketplace benchmarks. What is encouraging about the experimental results was – when forced to choose between keyboards – participants preferred the new prototype in spite of these issues with lack of familiarity and lower quality relative to production-level benchmarks. Combining the results of the three experiments, compared to the baseline fixed-split design, 32 of 36 (88%) of participants preferred the new "gull-wing" design with unique presentation of key caps and a steeper lateral inclination angle.

6.4. Limitations

This study did find significant differences in postural measures and keyboard preferences after short-term use in lab a setting. In addition, typing performance with the prototypes was slightly below the performance measures with the commercially manufactured benchmark. It is uncertain whether these differences would be present after longer-term use or change over time as participants get used to new, unfamiliar keyboards. In the future, longer-term studies would be beneficial to measure beyond these potentially short-term effects and better document the longer term postural and performance changes, if any. In addition, this study used a posture driven approach and there are other objective measures of biomechanics including measuring the forces applied to the keyboard while typing and measuring muscle activity with electromyography. There is a tradeoff between instrumenting the subject to collect objective exposure data and the limitations put on the subject due to all the wires and instrumentation. Posture was measured because it was a direct, well-documented, quick to analyze, and easy to interpret objective measure. Additionally, it is not certain whether these relatively short-term postural improvements measured with our prototypes would, over the long-term, reduce a computer operator's chances of developing a computer-related upper extremity disorder. However, fixed-split keyboards have been shown to reduce muscle strain [16], improve the health of those persons with hand pain [17], and reduce the incidence of new musculoskeletal disorders among an asymptomatic population after extended use [12]. One final concern may be the relatively small number of participants included in our study. Prior human factors and usability studies have shown that, if there are differences in where the product differences are large, these differences can be readily identified with small sample sizes [19,20]. This was the case in the present study: the differences between many of conditions evaluated were large and readily detected with our sample size and statistical methods. However, studies on larger samples of participants may be merited to ensure the representativeness of this study's results.

7. Conclusions

The user-centered, iterative-evaluative product design research created innovation for an existing product where there had been a decade of little-to-no change in design. Basic research inspired the creation of new models representing new ways of thinking about how to improve the fixed-split keyboard design. The steeper lateral inclination angle of 14° further reduced wrist pronation. The gull-wing key layout was designed to better match finger strike angles and to reduce reach distances to the peripheral keys. The taller wrist rest and a negative keyboard slope further reduced wrist extension. Performance, comfort, and desirability were the metrics for success in this study. This study demonstrates how the systematic evaluation of non-functional and fully-functional prototypes, for a relatively brief periods, with a relatively small number of participants, can be used to identify preferred design embodiments.

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