

## The Split Keyboard: An Ergonomics Success Story

David Rempel, University of California, Berkeley, Berkeley, California

**Objective:** The author reviews the paper by Kroemer (1972) on the design of the split geometry keyboard and the subsequent 35 years of research on the topic. **Background:** It was first suggested in the 1920s that arm strain in the typist could be reduced by splitting the keyboard into two halves and inclining the two halves laterally. The first systematic research on the split keyboard was conducted by Kroemer in the 1960s and published in his 1972 article. **Methods:** The literature on split geometry keyboards was identified, and the progression of the research was reviewed. **Results:** The Kroemer article marked the beginning of a prolonged, worldwide research effort to determine whether and how the split keyboard design might improve comfort and prevent pain in keyboard users. **Conclusions:** In the early 1990s, split keyboard designs began to be broadly commercially available. Clear evidence of a health benefit of the split keyboards emerged in the late 1990s. By 2006, a split keyboard was the number one-selling keyboard, of all keyboards sold, in the U.S. retail market. **Application:** The history of research on this topic, the challenges to changing the conventional design, and the broader acceptance of the split design are a success story with lessons for all of us.

### BACKGROUND

For the past 50 years, there has been increasing recognition and evidence that long hours of keyboard use are associated with hand, arm, shoulder, and neck pain and upper body musculoskeletal disorders (Gerr, Monteilh, & Marcus, 2006). These problems are related to work organizational issues (e.g., hours of computer use per day, job demands) as well as sustained awkward postures, such as shoulder elevation, wrist ulnar deviation, and head rotation. Some of these postural demands, such as ulnar deviation, wrist extension, forearm pronation, and shoulder abduction, are related to the design of the conventional, straight keyboard. There has been a long-standing interest in determining whether the split keyboard designs reduce these postural demands and reduce upper body pain in keyboard users.

The conventional, straight QWERTY keyboard design is based on the 1878 patent of Christopher Latham Sholes (U.S. patent 207,559). The keys are arranged in four staggered but straight rows,

as shown in Figure 1. In 1915, F. Heidner released a patent with split keyboard designs (U.S. patent 1,138,474), which were to enable the operator to write in a less cramped position, but the first research on split keyboards did not occur until the 1920s.

In 1926, Klockenberg conducted a series of experiments to assess subjective strain in the forearms of typists. He suggested that the keyboard be divided into two halves (one half for each hand) and that the halves be laterally inclined to reduce the muscle tension in the shoulders and arms. These changes were expected to lead to less muscular strain in the typists and to better typing performance. He wrote that although these strains may be small, they add up to considerable magnitude over many hours of keyboarding (Kroemer, 2001). There was relatively little work on the split keyboard concept until the work of Kroemer in the 1960s.

Definitions for positioning the two halves of a split keyboard are presented in Figure 2. The angles are based on a plane through the top of the

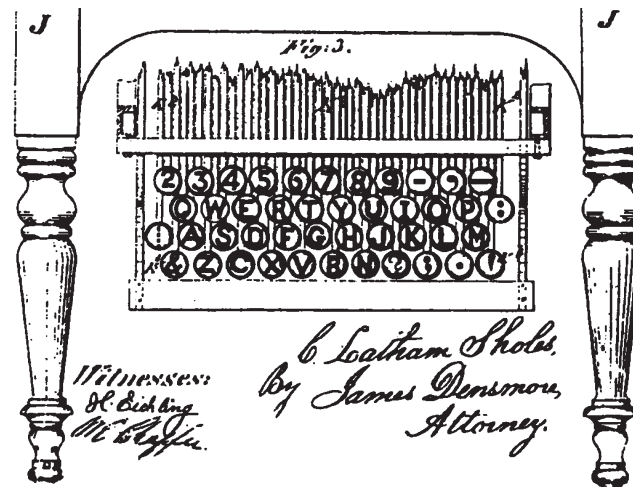


Figure 1. QWERTY keyboard layout from Christopher Sholes, 1878 U.S. patent (207,559).

alphabet keys for each half relative to the plane of the work surface. Lateral inclination ( $\beta$ ) is also referred to as gable or tenting. The front-to-back slope ( $\alpha$ ) is the angle of the plane about a line through the top of the home row keys (i.e., A, S, D, F, G or H, J, K, L). The opening angle ( $\gamma$ ), also referred to as split, rotation, or slant (slant is 1/2 the opening angle), is the rotation of the plane about the D or K key.

### KROEMER'S (1972) "HUMAN ENGINEERING THE KEYBOARD"

In a 1972 publication in *Human Factors*, Dr. Karl Kroemer summarized a series of experiments that he carried out and published in the 1960s in Germany. These studies evaluated the effects of a split adjustable keyboard on user preference and pain.

In the first experiment, 38 participants simulated the finger motion of typing while rotating the forearms about their long axes. The most comfortable forearm posture was approximately  $40^\circ$  to  $55^\circ$  of pronation (in  $0^\circ$  pronation, the palms face each other; at  $90^\circ$ , the palms face the desk surface); these findings were similar to those in Klockenberg's study.

In the next experiment, participants typed on a keyboard with different angles of lateral inclination. A split keyboard was built with an opening angle of  $30^\circ$  with hinged halves adjustable from  $0^\circ$  and  $90^\circ$  of lateral inclination (Figure 3). Kroemer called this the "K-keyboard" after Klockenberg. Participants ( $N = 65$ ) typed for 10 min at different angles of lateral inclination and reported some preference for  $30^\circ$  or  $60^\circ$  angles (Figure 4).

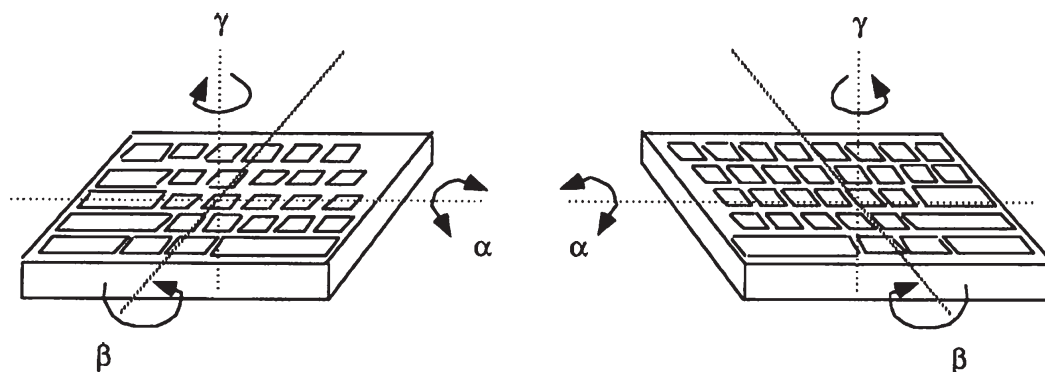


Figure 2. Conventions for rotation of keyboard halves.  $\alpha$  = slope,  $\beta$  = lateral inclination,  $\gamma$  = opening angle. The opening angle is a rotation about the D and K keys (Tittiranonda, Rempel, Armstrong, & Burastero, 1999).

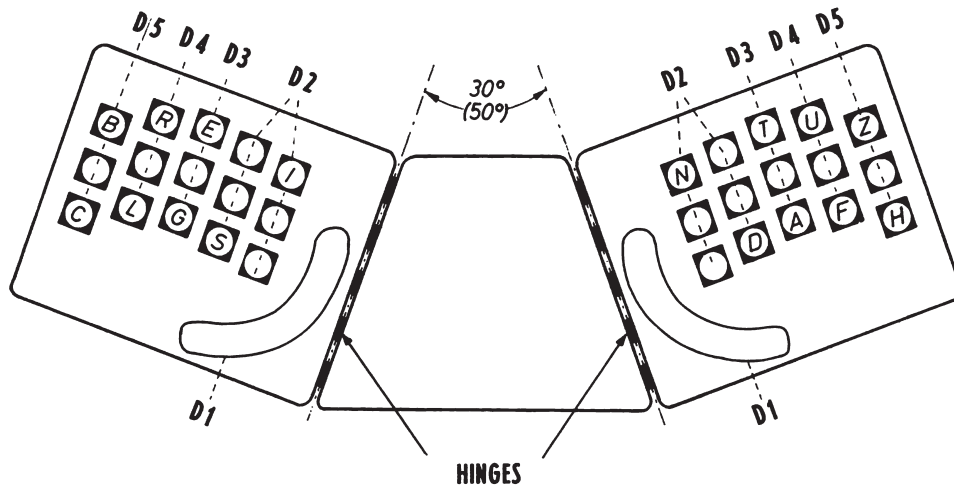


Figure 3. The K-keyboard used in the Kroemer studies. The sides were hinged and inclined laterally from  $0^\circ$  to  $90^\circ$  (Kroemer, 1972).

In the final experiment, 12 participants typed for longer durations on a standard keyboard and on the K-keyboard, which was set to an opening angle of  $50^\circ$  and a lateral inclination of  $45^\circ$ . After participants became familiar with the keyboards, the typing error rate was less on the K-keyboard. Pain was less on the K-keyboard in the back, arms, and wrists but was greater in the shoulders. The authors attributed the shoulder pain to too great an opening angle leading to too much shoulder ab-

duction. The article concluded that the keyboard halves should be laterally inclined to reduce postural muscular strain of the operator.

Although there were other advocates for the split keyboard in the 1970s (Ferguson & Duncan, 1974), there was little published research on this issue until the 1980s. This period from 1970 to the early 1980s was also notable for the beginning of reports from around the world on musculoskeletal problems among data entry operators. These came from Japan (Komoike & Horiguchi, 1971), Switzerland (Laubli, Nakaseko, & Hunting, 1980), the United States (Smith, Cohen, & Stammerjohn, 1981), Australia (McPhee, 1982), and other countries.

### 1980s: STANDARDS COALESCE AROUND THE STRAIGHT KEYBOARD DESIGN

Many journal articles and books were published in the 1980s presenting research and opinions on computer use, health, and productivity. The IBM PC was introduced in 1981, and this marked the rapid growth of computers in the office and home. In the 1980s, the first comprehensive VDT workstation design and use guidelines were promulgated, some with considerable attention to the features of the conventional, straight keyboard (Alden, Daniels, & Kanarick, 1972; ANSI/HFS-100, 1988; Cakir, Hart, & Stewart, 1980; International Standards Organization [ISO], 1971). In human factors circles, there was debate about the

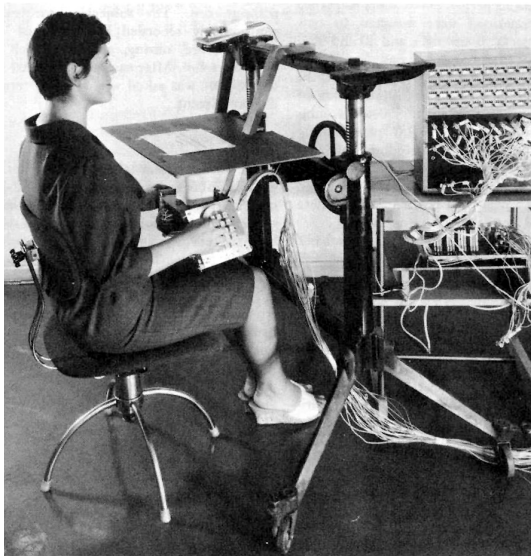


Figure 4. Experimental setup for the Kroemer studies. Note that the participant cannot see the keyboard during the typing task (Kroemer, 1972).

design of the keyboard and concern that the conventional QWERTY layout was becoming the de facto standard (Alden et al., 1972), even though the design was not optimal from a physiologic standpoint (Arndt, 1984; Ferguson & Duncan, 1974; Ilg, 1987; Zipp, Haider, Halpern, & Rohmert, 1983).

In Switzerland, Grandjean, Nakaseko, Hunting, and Laubli (1981) published a series of experiments on the split keyboard design that were later summarized by Nakaseko, Grandjean, Hunting, and Gierer (1985). They evaluated split keyboard designs with more modest lateral inclination and opening angles than those tested by Kroemer. The upward slope was fixed at 10°. In one experiment, the four keyboard designs tested were 0°, 0°; 15°, 0°; 25°, 10°; and 35°, 10° of opening angle and lateral inclination, respectively. The split keyboards included a built-in large (30 cm deep) forearm support that was sloped to 8°. After 45 min of use, the 20 typists most preferred the keyboard with a 25° opening angle and 10° of lateral inclination. Interestingly, the large sloped forearm support and split keyboard, which was set higher (82 cm) than the traditional keyboard (79 cm), induced the participants to lean backward more in the chair, which was one of the intentions of the researchers.

In a follow-up experiment, 31 participants typed for 30 min on a conventional keyboard and a split keyboard with the large forearm support (opening 25°, lateral inclination 10°). Participants again preferred the split keyboard. There was no difference in pain levels between keyboards, but participants reported less arm, hand, and back tension with the split keyboard. Ulnar deviation was reduced from 20° to 10°. The authors concluded that the split keyboard design with a large forearm support will decrease ulnar deviation, decrease complications in the forearm and hand, decrease the static effect of hand pronation, and allow for a more natural posture of the hands.

### **1990S: HEALTH EFFECTS OF THE SPLIT KEYBOARD**

The 1990s saw many more cross-sectional epidemiologic studies investigating musculoskeletal problems among computer users (Bergqvist, Wolgast, Nilsson, & Voss, 1995; Bernard, Sauter, Fine, Petersen, & Hales, 1994; Faucett & Rempel, 1994; Sauter, Schleifer, & Knutson, 1991). A common finding was a relationship between increasing hours of computer use and prevalence of muscu-

loskeletal problems. Work organizational problems and awkward postures (e.g., head rotation, shoulder flexion, and wrist extension) were also related to upper body pain.

Mechanisms of injury were also being explored. In a commentary, Rose (1991) recommended the split keyboard design to accommodate the limit of forearm pronation of 60° to 70°. There was some interest in the findings that the fluid pressure in the carpal tunnel was elevated with the forearm in full pronation or the wrist in extension or in ulnar deviation. The pressure was lowest with the forearm pronated to 45° compared with 0° or 90° (Rempel, Bach, Gordon, & Tal, 1998; Weiss, Gordon, Bloom, So, & Rempel, 1995). The implications were that a neutral wrist posture and a non-pronated forearm during typing would reduce the risk of median nerve or tendon injury at the wrist.

Many split keyboards were developed and brought to market by entrepreneurs in the 1990s (Table 1), but only a few of them are still being manufactured. Apple Computer launched the Apple Adjustable keyboard in 1992, and Microsoft launched the Microsoft Natural keyboard in 1994. The Apple keyboard had an adjustable opening angle but no lateral inclination. The Microsoft keyboard was a fixed split design with an opening angle of 24° and a lateral inclination of 8°.

The 1990s also saw an explosion of laboratory studies evaluating the effects of split keyboard designs on productivity, preference, posture, and pain. These were studies of adjustable keyboards, fixed split keyboards, commercial keyboards, and keyboards built just for research.

Across all studies, the productivity on split keyboards was the same as or less than on a conventional keyboard. Generally, productivity approached that of a conventional keyboard after an hour to a day of use (Cakir, 1995; Chen et al., 1994; Marklin & Simoneau, 2001; Swanson, Galinsky, Cole, Pan, & Sauter, 1997). Productivity was less for split keyboards with more lateral inclination or opening angle (Cakir, 1995; Chen et al., 1994; Gerard, 1994; Muss & Hedge, 1999).

In most short-term studies, experienced typists rejected the new split keyboard designs in favor of conventional designs (Cakir, 1995; Honan, Jacobson, Tal, & Rempel, 1996; Tittiranonda, Burastero, Armstrong, & Rempel, 1999). However, when participants used split keyboards for longer durations, 1 to 4 days, their preferences switched toward neutral (Morelli, Johnson,

**TABLE 1:** Partial List of Split Geometry Keyboards

Fixed Split	Adjustable
ErgoMax/SafeType <sup>a</sup>	Apple Adjustable
Logitech Ergo Split	Cherry Ergo-Plus
Logitech Wave <sup>a</sup>	Comfort
Kinesis Contoured <sup>a</sup>	Datahand
Marquardt	KeyOvation Goldtouch <sup>a</sup>
Maltron	Keytronic FlexPro/ErgoLogic
Microsoft Natural	Kinesis Maxim <sup>a</sup>
Microsoft Natural Elite <sup>a</sup>	Lexmark M15/SelectEase
Microsoft Natural Ergonomic 4000 <sup>a</sup>	TONY!
Microsoft Comfort Curve <sup>a</sup>	
STR	

<sup>a</sup>Still being manufactured.

Reddell, & Lau, 1995; Zecevic, Miller, & Harburn, 2000). Several short-term studies used adjustable keyboards to try to identify the most comfortable geometry for typing (Thompson, Thomas, Cone, Daponte, & Markison, 1990; Chen et al., 1994; Tittiranonda, Burastero, et al., 1999). Needless to say, there were large differences in design preferences.

At least eight studies evaluated the effects of the split keyboard design on wrist and forearm postures (Chen et al., 1994; Honan, Serina, Tal, & Rempel, 1995; Honan et al., 1996; Marklin, Simoneau, & Monroe, 1999; Muss & Hedge, 1999; Smith et al., 1998; Tittiranonda, Burastero, et al., 1999; Zecevic et al., 2000). Generally, the findings of these studies were similar. When participants typed on the split keyboards, the wrist and forearms were in more neutral postures (i.e., less extension, less ulnar deviation, and less pronation than when typing on a conventional keyboard).

Several studies also evaluated forearm muscle activity while participants typed on split keyboards. These studies reported a reduced activity of some forearm or shoulder muscles when typing on the split keyboard in comparison with a conventional keyboard (Gerard, 1994; Marek, Noworol, Wos, Karwowski, & Hamiga, 1992; Thompson et al., 1990).

Although there was good evidence that the split keyboards could reduce some of the posture-related risk factors for musculoskeletal problems and could reduce forearm muscle loads, the question remained: Would the split keyboard designs reduce pain? Several studies evaluated fatigue and pain over 2 to 5 days of typing on split and conventional keyboards (Morelli et al., 1995; Smith et al., 1998; Swanson et al., 1997). None of the stud-

ies found a difference in upper body pain severity between the keyboards studied.

However, a 6-month study found something different. The end of the decade saw the first randomized controlled trial evaluating the effects of four keyboard designs on pain in patients with hand or arm disorders (Tittiranonda, Rempel, Armstrong, & Burastero, 1999). The study demonstrated a reduction in pain in those who were assigned a fixed split keyboard compared with those who received the conventional design. Interestingly, the pain declined gradually among those assigned the fixed split keyboard and was only significantly different from that of the conventional keyboard group after 4½ months (Figure 5). At the end of the study, participants assigned to the two adjustable keyboards reported less pain than those using the conventional keyboard, but the differences were not significant. Participants were instructed on how to adjust these keyboards, but they may have made relatively small geometry changes to the keyboards compared with the conventional design.

### 2000s: THE ACCEPTANCE OF THE SPLIT KEYBOARD

Two large, prospective studies provided solid documentation of risk factors (e.g., hours of computer use and awkward postures) associated with upper extremity disorders and pain among computer users (Gerr et al., 2002; Lassen et al., 2004). In addition, more randomized controlled trials were conducted that evaluated the health effects of ergonomic and training interventions among computer users. These studies are summarized by large systematic reviews (Brewer et al., 2006; Verhagen, Karelis, & Bierma-Zeinstra, 2006).

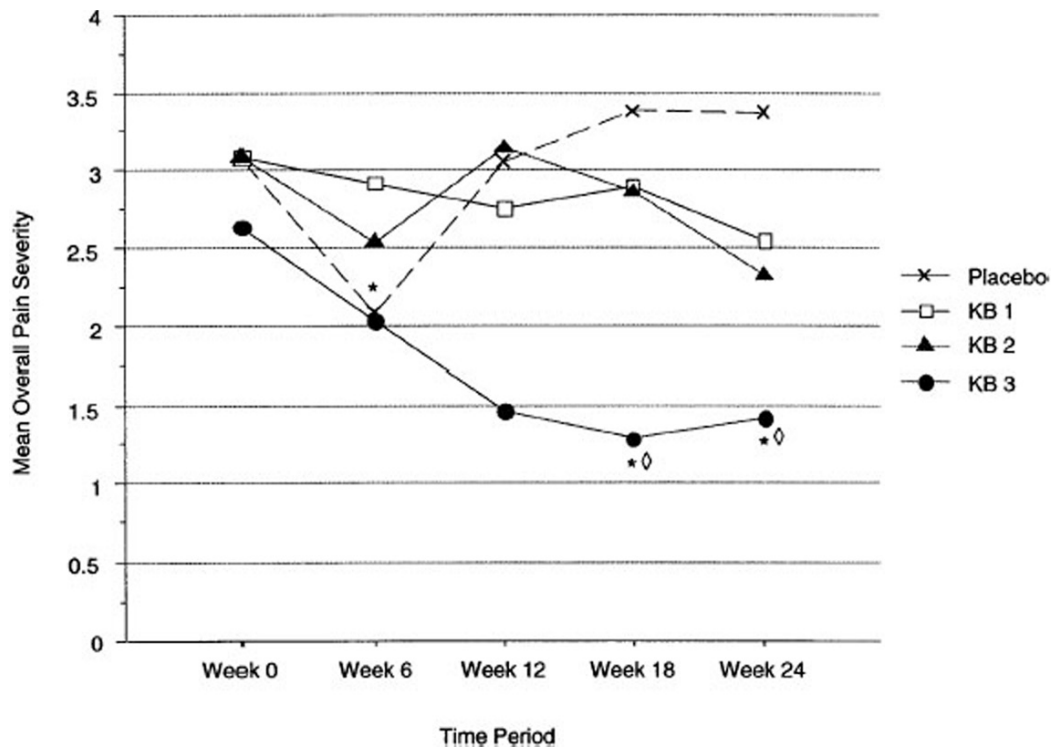


Figure 5. Changes in mean overall pain severity by the keyboard group from the Tittiranonda, Rempel, Armstrong, and Burastero (1999) study. The placebo is a conventional design, KB1 is the Apple Adjustable keyboard, KB2 is the Comfort keyboard, and KB3 is the Microsoft Natural keyboard. The decline in pain in KB3 is significantly different from the placebo (open diamonds) and from the beginning pain scores (\*) at Weeks 18 and 24 ( $N = 80$ ).

Through the 2000s, there were more laboratory studies investigating the effects of split geometry keyboard designs on postures and tissue loads (Simoneau, Marklin, & Berman, 2003; Marklin & Simoneau, 2004; Rempel, Barr, Brafman, & Young, 2007; Rempel, Keir, & Bach, in press; Rempel, Nathan-Roberts, Chen, & Odell, in press). These studies tended to evaluate more subtle differences in keyboard design changes on posture than during the previous decade. It should be noted that these studies used participants who were touch typists; the split keyboard may provide little benefit to nontouch typists.

The National Institute for Occupational Safety and Health (NIOSH) conducted a 2-year randomized controlled trial to evaluate the effects of different keyboard designs on pain and upper extremity disorders among 289 computer users (Moore & Swanson, 2003). Participants were randomized to receive a conventional keyboard, a fixed split keyboard, or an adjustable split keyboard. The study found that the fixed split keyboard prevented the occurrence of new symptoms in the

neck region. Both split keyboards also reduced pain in the hands, wrists, and forearms among those computer users with pain at the beginning of the study. The study provides the strongest evidence to date for both a primary and secondary prevention benefit of the split keyboard on upper body musculoskeletal health.

The design of commercial split keyboards evolved during the 2000s. The latest Microsoft split keyboard has a steeper lateral inclination ( $14^\circ$  instead of  $8^\circ$ ) to further minimize forearm pronation and curved key rows to reduce finger reach during typing. In 2006, a fixed split keyboard (Microsoft Natural Ergonomic Keyboard 4000) became the best-selling aftermarket, wired keyboard, of all wired keyboards, not just ergonomic keyboards, sold in the United States (NPD Group, 2006).

## DISCUSSION

It was first proposed in 1926 that a split geometry keyboard would reduce muscle strain during

typing compared with a conventional keyboard design by reducing forearm pronation. With his 1972 paper, Kroemer rekindled an interest in the split keyboard with the first studies that demonstrated an effect of keyboard design on productivity, preference, and pain. This coincided with the beginning of reports from around the world of musculoskeletal problems among data entry operators. In the 1980s, Swiss and German research groups provided more physiologic evidence in support of the split keyboard design. Although the conventional keyboard design was perceived by some in the human factors community as being inefficient and associated with increased arm strain, there was little interest from industry in modifying the design. In fact, ISO, DIN, and ANSI standards coalesced around the conventional keyboard design.

The rapid growth of personal computers in 1980 was accompanied by more reports of musculoskeletal problems among computer users and more laboratory studies of the effects of the split keyboard on muscle load, posture, productivity, and preference. There were scattered efforts by entrepreneurs to market split keyboards, but these efforts were usually short-lived. Apple computer was the first large computer manufacturer to develop a split keyboard in the early 1990s, and it was soon followed by Microsoft. The first randomized controlled trial of split keyboards in 1999 demonstrated a positive health effect, and these findings were later confirmed by a much larger study.

Overall, the research literature demonstrates a number of important lessons. First, subjective preference may not be sensitive to ergonomic benefits for devices that are used repetitively but require low activation forces. Second, health benefits of ergonomic keyboards were not apparent in short-term (2- to 5-day) studies of discomfort and pain but were observed only after 4 months of use. Third, in short-term studies, ergonomic principles (i.e., the reduction of postural risk factors and muscle loads) predicted positive health outcomes. Finally, the ideal keyboard design has yet to be identified; there is still much to be done on the geometry of the keyboard and keys. It may even be possible to incorporate features of the split keyboard design into laptop computers.

The history of the adoption of the split keyboard design is an unusual one in human factors research. Split keyboards are not associated with increased productivity – the main value is im-

proved health. Kroemer's (1972) research opened the door to considering ergonomics in the design of keyboard geometry. This was followed by research in other laboratories that confirmed and refined his initial findings. However, the widespread adoption of the split keyboard did not occur until two factors converged. One, a couple of large but relatively young computer software manufacturers committed to developing keyboards with the goal of improving worker and customer health. Two, laboratory and field research demonstrated a health value related to the split keyboard designs. We should be alert for other such opportunities to promote health and injury prevention in the workplace.

### ACKNOWLEDGMENTS

No funds were received for the preparation of the manuscript, but research in Professor Rempel's laboratory has been supported by gifts from Microsoft, Apple, Logitech, and the Keytronic Corporation.

### REFERENCES

- Alden, D. G., Daniels, R. W., & Kanarick, A. F. (1972). Keyboard design and operation: A review of the major issues. *Human Factors, 14*, 275–293.
- ANSI/HFS-100. (1988). *American national standard for human factors engineering of visual display terminal workstations*. Santa Monica, CA: Human Factors Society.
- Arndt, R. (1984). *Workbook for ergonomic considerations in office design*. Alexandria, VA: National Office Products Association.
- Bergqvist, U., Wolgast, E., Nilsson, B., & Voss, M. (1995). Musculoskeletal disorders among visual display terminal workers: Individual, ergonomic, and work organizational factors. *Ergonomics, 38*, 763–776.
- Bernard, B., Sauter, S., Fine, L., Petersen, M., & Hales, T. (1994). Job task and psychosocial risk factors for work-related musculoskeletal disorders among newspaper employees. *Scandinavian Journal of Work and Environmental Health, 20*, 417–426.
- Brewer, S., Van Erg, D., Amick, B. C., Irvin, E., Daum, K., Gerr, F., et al. (2006). Workplace interventions to prevent musculoskeletal and visual symptoms and disorders among computer users: A systematic review. *Journal of Occupational Rehabilitation, 16*, 317–350.
- Cakir, A. (1995). Acceptance of the adjustable keyboard. *Ergonomics, 38*, 1728–1744.
- Cakir, A., Hart, D. J., & Stewart, T. F. M. (1980). *Visual display terminals*. Chichester, UK: Wiley.
- Chen, C., Burastero, S., Tittiranonda, P., Hollerbach, K., Shih, M., & Denhoy, R. (1994). Quantitative evaluation of four computer keyboards. In *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting* (pp. 1094–1098). Santa Monica, CA: Human Factors and Ergonomics Society.
- Faucett, J., & Rempel, D. (1994). VDT-related musculoskeletal symptoms: Interactions between work posture and psychosocial work factors. *American Journal of Industrial Medicine, 26*, 597–612.
- Ferguson, B., & Duncan, J. (1974). Keyboard design and operating posture. *Ergonomics, 17*, 731–744.
- Gerard, M. J. (1994). An ergonomic evaluation of the Kinesis ergonomic computer keyboard. *Ergonomics, 37*, 1661–1668.
- Gerr, F., Marcus, M., Ensor, C., Kleinbaum, D., Cohen, S., Edwards, A., et al. (2002). A prospective study of computer users: I. Study design

- and incidence of musculoskeletal symptoms and disorders. *American Journal of Industrial Medicine*, 41, 222–235.
- Gerr, F., Monteilh, C. P., & Marcus, M. (2006). Keyboard use and musculoskeletal outcomes among computer users. *Journal of Occupational Rehabilitation*, 16, 265–277.
- Grandjean, E., Nakaseko, M., Hunting, W., & Laubli, T. (1981). Ergonomische Untersuchungen zur Entwicklung einer neuen Tastatur für Bueromaschinen [Ergonomic experiments for the development of a new keyboard for office machines]. *Zeitschrift Arbeitswissenschaft*, 35, 221–226.
- Honan, M., Jacobson, J., Tal, R., & Rempel, D. (1996). Changes in wrist posture during a prolonged typing task. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting* (pp. 629–631). Santa Monica, CA: Human Factors and Ergonomics Society.
- Honan, M., Serina, E., Tal, R., & Rempel, D. (1995). Wrist postures while typing on a standard and split keyboard. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 366–368). Santa Monica, CA: Human Factors and Ergonomics Society.
- Ilg, R. (1987). Ergonomic keyboard design. *Behavior and Information Technology*, 6, 303–309.
- International Standards Organization (ISO). (1971). *ISO 2126 – Alphanumeric keyboard operated with both hands*. Geneva, Switzerland: Author.
- Klockenberg, E. A. (1926). *Rationalisierung der Schreibmaschine und ihrer Bedienung* [Rationalization of the typewriter and its operation]. Berlin: Springer.
- Komoike, Y., & Horiguchi, S. (1971). Fatigue assessment on key punch operators, typists and others. *Ergonomics*, 14, 101–109.
- Kroemer, K. H. E. (1972). Human engineering the keyboard. *Human Factors*, 14, 51–63.
- Kroemer, K. H. E. (2001). Keyboards and keying: An annotated bibliography of the literature from 1879 to 1999. *Universal Access in the Information Society*, 1, 99–160.
- Lassen, C. F., Mikkelsen, S., Kryger, A. I., Brandt, L. P., Overgaard, E., Thomsen, J. F., et al. (2004). Elbow and wrist/hand symptoms among 6943 computer operators: A 1-year follow-up study (the NUDATA study). *American Journal of Industrial Medicine*, 46, 521–533.
- Laubli, T., Nakaseko, M., & Hunting, W. (1980). Arbeitsbedingte cervicobrachiale Beschwerden bei Büroarbeiten [Cervicobrachial occupational diseases in office workers]. *Sozial- und Preventivmedizin*, 25, 407–412.
- Marek, T., Noworol, C., Wos, H., Karwowski, W., & Hamiga, K. (1992). Muscular loading and subjective ratings of muscular tension by novices when typing with standard and split-design keyboards. *International Journal of Human-Computer Interaction*, 4, 387–394.
- Marklin, R. W., & Simoneau, G. C. (2001). Effect of setup configurations of split computer keyboards on wrist angles. *Physical Therapy*, 81, 1038–1048.
- Marklin, R., & Simoneau, G. (2004). Design features of alternative computer keyboards: A review of experimental data. *Journal of Orthopaedic & Sports Physical Therapy*, 34, 638–649.
- Marklin, R. W., Simoneau, G. G., & Monroe, J. F. (1999). Wrist and forearm posture from typing on split and vertically inclined keyboards. *Human Factors*, 41, 559–569.
- McPhee, B. (1982). Deficiencies in the ergonomic design of keyboard work and upper limb and neck disorders in operators. *Journal of Human Ergology*, 11, 31–36.
- Moore, J. S., & Swanson, N. (2003). The effect of alternative keyboards on musculoskeletal symptoms and disorders. In J. Jacko & C. Stephanidis (Eds.), *Proceedings of the 10th International Conference on Human-Computer Interaction, Part I* (pp. 103–107). Mahwah, NJ: Erlbaum.
- Morelli, D. L., Johnson, P. W., Reddell, C. R., & Lau, P. (1995). User preferences between keyboards while performing “real” work. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 361–365). Santa Monica, CA: Human Factors and Ergonomics Society.
- Muss, T., & Hedge, A. (1999). Effects of a vertical-split keyboard on posture, comfort and performance. In *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting* (pp. 496–500). Santa Monica, CA: Human Factors and Ergonomics Society.
- Nakaseko, M., Grandjean, E., Hunting, W., & Gierer, R. (1985). Studies on ergonomically designed alphanumeric keyboards. *Human Factors*, 27, 175–187.
- NPD Group. (2006). *Retail tracking and market research for input devices*. Port Washington, NY: Author.
- Rempel, D., Bach, J., Gordon, L., Tal, R. (1998). Effects of forearm pronation/supination on carpal tunnel pressure. *Journal of Hand Surgery*, 23, 38–42.
- Rempel, D., Barr, A., Brafman, D., & Young, E. (2007). The effects of six keyboard designs on wrist and forearm postures. *Applied Ergonomics*, 38, 298–308.
- Rempel, D., Keir, P. J., & Bach, J. M. (in press). Effect of wrist posture on carpal tunnel pressure while typing. *Journal of Orthopaedic Research*.
- Rempel, D., Nathan-Roberts, D., Chen, B. Y., & Odell, D. (in press). The effects of split keyboard geometry on upper body postures. *Ergonomics*.
- Rose, M. J. (1991). Keyboard operating posture and actuation force: Implications for muscle over-use. *Applied Ergonomics*, 22, 198–203.
- Sauter, S. L., Schleifer, L. M., & Knutson, S. J. (1991). Work posture, workstation design, and musculoskeletal discomfort in a VDT data entry task. *Human Factors*, 33, 151–167.
- Simoneau, G. G., Marklin, R. W., & Berman, J. E. (2003). Effects of computer keyboard slope on wrist posture and forearm electromyography of typists without musculoskeletal disorders. *Physical Therapy*, 83, 816–830.
- Smith, M. J., Cohen, B. G. F., & Stammerjohn, J. W. (1981). An investigation of health complaints and job stress in video display operations. *Human Factors*, 23, 387–400.
- Smith, M. J., Karsh, B.-T., Conway, F. T., Cohen, W. J., James, C. A., Morgan, J. J., et al. (1998). Effects of a split keyboard design and wrist rest on performance, posture, and comfort. *Human Factors*, 40, 324–336.
- Swanson, N. G., Galinsky, T. L., Cole, L. L., Pan, C. S., & Sauter, S. L. (1997). The impact of keyboard design on comfort and productivity in a text-entry task. *Applied Ergonomics*, 28, 9–16.
- Thompson, D., Thomas, J., Cone, J., Daponte, A., & Markison, R. (1990). Analysis of the TONY! variable geometry VDT keyboard. In *Proceedings of the Human Factors and Ergonomics Society 34th Annual Meeting* (pp. 365–369). Santa Monica, CA: Human Factors and Ergonomics Society.
- Tittiranonda, P., Burastero, S., Armstrong, T., & Rempel, D. (1999). Workplace use of an adjustable keyboard: Adjustment preferences and effect on wrist posture. *American Industrial Hygiene Association Journal*, 60, 340–348.
- Tittiranonda, P., Rempel, D., Armstrong, T., & Burastero, S. (1999). Effect of four computer keyboards in computer users with upper extremity musculoskeletal disorders. *American Journal of Industrial Medicine*, 35, 647–661.
- Verhagen, A. P., Karels, C., & Bierma-Zeinstra, S. M. (2006). Ergonomic and physiotherapeutic interventions for treating work-related complaints of the arm, neck or shoulder in adults. *Cochrane Database Systematic Reviews*, 19(3), CD003471.
- Weiss, N. D., Gordon, L., Bloom, T., So, Y., & Rempel, D. M. (1995). Wrist position of lowest carpal tunnel pressure and implications for splint design. *Journal of Bone and Joint Surgery*, 77A, 1695–1699.
- Zecevic, A., Miller, D. I., & Harburn, K. (2000). An evaluation of the ergonomics of three computer keyboards. *Ergonomics*, 43, 55–72.
- Zipp, P., Haider, E., Halpern, N., & Rohmert, W. (1983). Keyboard design through physiological strain measurements. *Applied Ergonomics*, 14, 117–122.

David Rempel is the director of the Ergonomics Program at the University of California at Berkeley and professor in the Department of Bioengineering at UC Berkeley and the Department of Medicine at UC San Francisco. He received his M.D. degree in 1982 from UC San Francisco.

Date received: December 8, 2007

Date accepted: April 25, 2008