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Jeong Ho Kim [a] & Peter W. Johnson [a b]

[a] Department of Industrial and Systems Engineering, University of Washington, Seattle, USA

[b] Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, USA

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Viability of using digital signals from the keyboard to capture typing force exposures

Jeong Ho Kim[a] and Peter W. Johnson[a,b]*

[a]*Department of Industrial and Systems Engineering, University of Washington, Seattle, USA;* [b]*Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, USA*

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Although previous studies have shown that systematic temporal changes in keystroke durations may be used as surrogate measures of muscle fatigue, software-based keystroke duration may be adversely affected by different keyswitch force-displacement characteristics. Therefore, this study used a force platform to measure the keystroke durations and compared them to software-based measures in order to determine whether the software-based keystroke duration is a robust surrogate measure for the force-derived durations (independent of keyswitch designs). A total of 13 subjects typed for 15 minutes each on three keyboards with different force-displacement characteristics. The results showed that the software-based keystroke durations closely mirrored and approximated the true force-derived keystroke durations, regardless of the force-displacement characteristics. Furthermore, the subject-dependent correlations indicated that the software-based keystroke durations approximated the true force-derived keystroke durations. Therefore, the software-based keystroke durations could be used as a surrogate non-invasive, cost-effective measure to identify muscle fatigue during computer use for large-scale epidemiological studies.

Practitioner Summary: Developing non-invasive, cost-effective computer exposure assessment tools can help researchers develop a better understanding on the underlying mechanisms of computer-related musculoskeletal disorders. This study demonstrates how software measured keystroke duration can be used as a non-invasive, cost-effective exposure assessment measure during computer use.

Keywords: computer use; musculoskeletal disorders; exposure assessment; keystroke duration; office ergonomics

1. Introduction

Although intensive computer use has been associated with musculoskeletal disorders (MSDs) in the upper extremities (Chang *et al*. 2009, Gerr *et al*. 2006), the association between computer use and MSDs has long been debated. Recently, Ijmker *et al*. (2011) and Gerr and Fethke (2011) revived the debate on this issue. A part of the reason for this longstanding debate may be due to the lack of a clear clinical diagnosis for MSDs despite a high prevalence of self-reported symptoms (Waersted *et al*. 2010). Also, a main reason for this longstanding debate is that the exposure–response relationship between computer use and MSD-related injuries are not fully understood. Developing an adequate, non-invasive, cost-effective, exposure assessment method for large-scale epidemiological studies on computer use could contribute to the body of knowledge on potential underlying injury mechanisms.

Despite the debate, previous studies have shown that rapid and repetitive finger movements during keyboard use and prolonged static muscle loading during mouse use are associated with upper extremity MSDs (Rempel *et al*. 1992, Ijmker *et al*. 2007, Tayyari and Smith 1997). Most work-related MSDs develop from the accumulation of micro trauma to the soft tissues (muscles, tendons, ligaments and nerves) over time (Punnett and Wegman 2004) and muscle fatigue is believed to be a precursor to MSDs (Rempel *et al*. 1992). Accordingly, an early detection of the physiological detriment (i.e. muscle fatigue) may reduce a computer operator's chances for developing MSDs. There are several laboratory-based assessment tools to objectively measure muscle fatigue (electrical stimulation, electromyography, and mechanomyography); however, due to their invasiveness, lack of portability and cost, these measurement tools may not be appropriate for measuring computer-related muscle fatigue in field-based or occupational settings.

An exposure–response relationship has been shown between muscle fatigue and its effect on keystroke duration. Chang *et al*. (2009) showed that keystroke durations measured from individual keystrokes systematically changed in the presence of muscle fatigue, and therefore temporal changes in keystroke durations may be an objective surrogate measure of muscle fatigue. Because the temporal changes are usually small (5–20 ms), an assessment tool to measure keystroke durations should have decent accuracy and sensitivity to be used as a reliable measurement system.

*Corresponding author. Email: petej@uw.edu

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Keystroke durations can either be measured non-invasively using keyboard monitoring software or more invasively using a force platform mounted under the keyboard. Force platforms have been used to objectively assess typing force exposures including force, frequency, and duration of keystrokes (Rempel *et al*. 1994, Radwin and Jeng 1997, Radwin and Ruffalo 1999, Jindrich *et al*. 2004a,b). Keyboard monitoring programs can provide information on keystroke frequency and duration; however, it is not known whether keyboard force-displacement characteristics affect the measurement of keystroke duration. The software-based keystroke durations may be affected by the electromechanical make- and release-point when the key is pressed and released, whereas keystroke durations measured by force platforms will not be affected by the electromechanical differences in keyswitch designs. The tradeoff between the two methods is cost and methodological complexity. For large-scale epidemiological studies, force platforms may not be appropriate due to their invasiveness and cost.

Therefore, using keyboards with different force-displacement characteristics, this study used a force platform to measure the keystroke durations directly from individual keystroke force profiles and compared them to software measured keystroke durations. The purpose of the study was to determine whether the software measured keystroke durations derived from the digital signal could be used as a non-invasive, surrogate measure in lieu of the more invasive measurements collected with a force platform.

2. Method

2.1. Subjects

Through e-mail solicitations, a total of thirteen subjects including 6 males and 7 females were recruited to participate in this study. All participants were right-handed touch typists with no history of upper extremity MSDs. The average age of the participants were 26.9 years old (SD: 7.9), ranging from 20 to 49 years old. Their average years of computer use were 13.4 years (SD: 4.9). The experimental protocol was approved by the Human Subject Committee at the University of Washington, and all subjects provided their written informed consent before participating in the experiments.

2.2. Experimental design

The experimental task consisted of having subjects type for 15 minutes each on the three keyboards which were mounted on top of a force platform. The workstation was adjusted based on the subject's anthropometry in accordance with ANSI/HFES 100–2007. The chair was adjusted so the subject's feet rested firmly on the floor. With subjects relaxing their shoulders, resting their arms comfortably at their side and forming roughly a 90 degree angle at the elbow, the height of the workstation was adjusted so the table height was set at approximately 2 cm below elbow height. However, subjects were instructed not to rest their hands or wrists on either the device being tested or the force platform so as to artificially increase the measured typing forces in the z-direction. The monitor was placed at arm's reach with the top of the viewing portion of the screen just below eye level and the keyboard had the spacebar centred on the subject's body.

The three keyboards tested, which had different keyswitch force-displacement characteristics, included: (1) a keyboard with 4.0 mm of key travel (Model SK-8115; Dell Inc; Round Rock, TX), (2) a keyboard with 2.0 mm of key travel (Model HP G62; Hewlett Packard Inc.; Palo Alto, CA) and (3) a keyboard with 1.8 mm of key travel (Model HP Envy; Hewlett Packard Inc.; Palo Alto, CA). Force-displacement characteristics of all three keyboards are shown in Figure 1. Force-displacement curves were obtained by the Reliability Engineering Groups from major equipment manufactures. The keyboard with 4.0 mm travel distance had rubber dome switches whereas the keyboards with 2.0 and 1.8 mm of key travel distance had scissor switches. The activation forces on all the keyboards were approximately 0.6 N. The order of keyboard use was counterbalanced to minimise any potential confounding due to keyboard testing order.

For the typing task, a typing program (Mavis Beacon Teaches Typing – Platinum Edition A; Broderbund Software, Inc.; Novato, CA, USA) was used to evaluate typing performance including speed and accuracy. During the typing tasks, keystroke durations were simultaneously collected from the force platform and the keyboard at 500 Hz in order to accurately characterise the peak forces during keyboard typing. The force platform consisted of a 36 cm × 18 cm aluminium plate mounted on top of a force/torque transducer (Mini-40 E; ATI Inc.; Apex, NC). Testing over the full area of the force platform demonstrated that the absolute mean force measurement errors over a 0 to 4 N range were less than 10%. The keyboards were placed on the force platform with the 'H' key of each keyboard centred over the force transducer. A thin piece of plexiglass surrounded the force platform to offset the height of the platform and create a flat worksurface. The detailed experimental setup is shown in Figure 2.

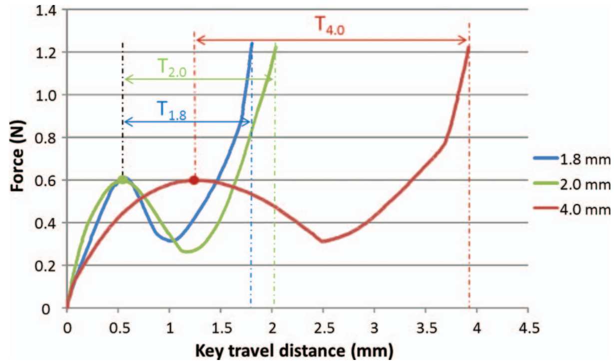

Figure 1. Force-displacement curves of the three keyboards: 1.8 mm, 2.0 mm and 4.0 mm. The solid dots indicate the activation forces (make point) and the arrows are the distances between the make point and the end of key travel for 1.8, 2.0, and 4.0 mm keyboards, respectively.

2.3. Data analysis

The statistical analysis was conducted in JMP (Version 8.0.2; SAS Institute Inc.; Cary, NC, USA). A mixed model with restricted maximum likelihood estimation (REML) was used to determine whether there were differences in keystroke durations measured by digital keystroke signals and applied individual keystroke forces. In the model, keystroke duration measurement method, keyboard, hand, and finger were included as fixed effects while subject was included as a random effect. To test whether there were differences in keystroke durations among the keyboards, the *Tukey-Kramer method* for multiple comparisons was used. In addition, linear regression methods were used to determine how well the software-based keystroke durations approximated the force-based measures. All data are presented as mean and standard error; and significance was noted when Type I error was less than 0.05.

3. Results

3.1. Software-based measures

The software-based keystroke durations from the 1.8, 2.0, and 4.0 mm travel keyboards were 131.7 ($\pm$5.48), 122.5 ($\pm$5.46), and 94.4 ($\pm$5.48) milliseconds, respectively (Figure 4a). This result indicated that the software-based keystroke durations were dependent on key force-displacement characteristics ($p < 0.0001$). The keystroke durations from the non-dominant left hand were 15.1 ms or approximately 15% longer than those from the dominant right hand on average ($p < 0.0001$) (Figure 3a). In addition, the keyboard by hand interactions were not significant ($p = 0.29$); that is, the dominant right hand had shorter keystroke durations than the non-dominant hand regardless of the keyboards. Despite the significant hand by finger interactions ($p < 0.0001$), the keystroke durations from the little and ring fingers were longer than those from index and middle fingers ($p < 0.0001$) as shown in Figure 3b. Lastly, although the keyboard by finger interactions were significant ($p < 0.0001$), all the keyboards showed a similar pattern where the little and ring fingers had longer keystroke durations than the index and middle fingers (Figure 3e).

3.2. Force-based measures

The force-based keystroke durations from the 1.8, 2.0, and 4.0 mm travel keyboards were 119.3 ($\pm$5.9), 111.3 ($\pm$5.9), and 116.2 ($\pm$ 5.9) milliseconds (Figure 4a), respectively ($p = 0.07$). When compared to the differences in the software-based keystroke durations between keyboards, the differences in force-based keystroke durations between keyboards were smaller. Similar to the software-based keystroke durations, the force-based keystroke durations from the non-dominant left hand were 10.6 ms or approximately 10% longer than those from the dominant right hand ($p = 0.007$) on average (Figure 3c). In addition, there were significant differences in keystroke durations across fingers ($p < 0.0001$); the keystroke durations from the ring and little fingers were longer than those from the index and middle fingers (Figure 3d). Although the keyboard by hand interactions were significant ($p = 0.014$), the keystroke durations from the right hand were consistently shorter than those from the left hand. The differences between the right and left hand on 1.8 mm keyboard were slightly smaller than those on 2.0 and 4.0 mm keyboard. Despite the significant keyboard by finger interactions ($p = 0.0005$), the little and ring fingers had consistently

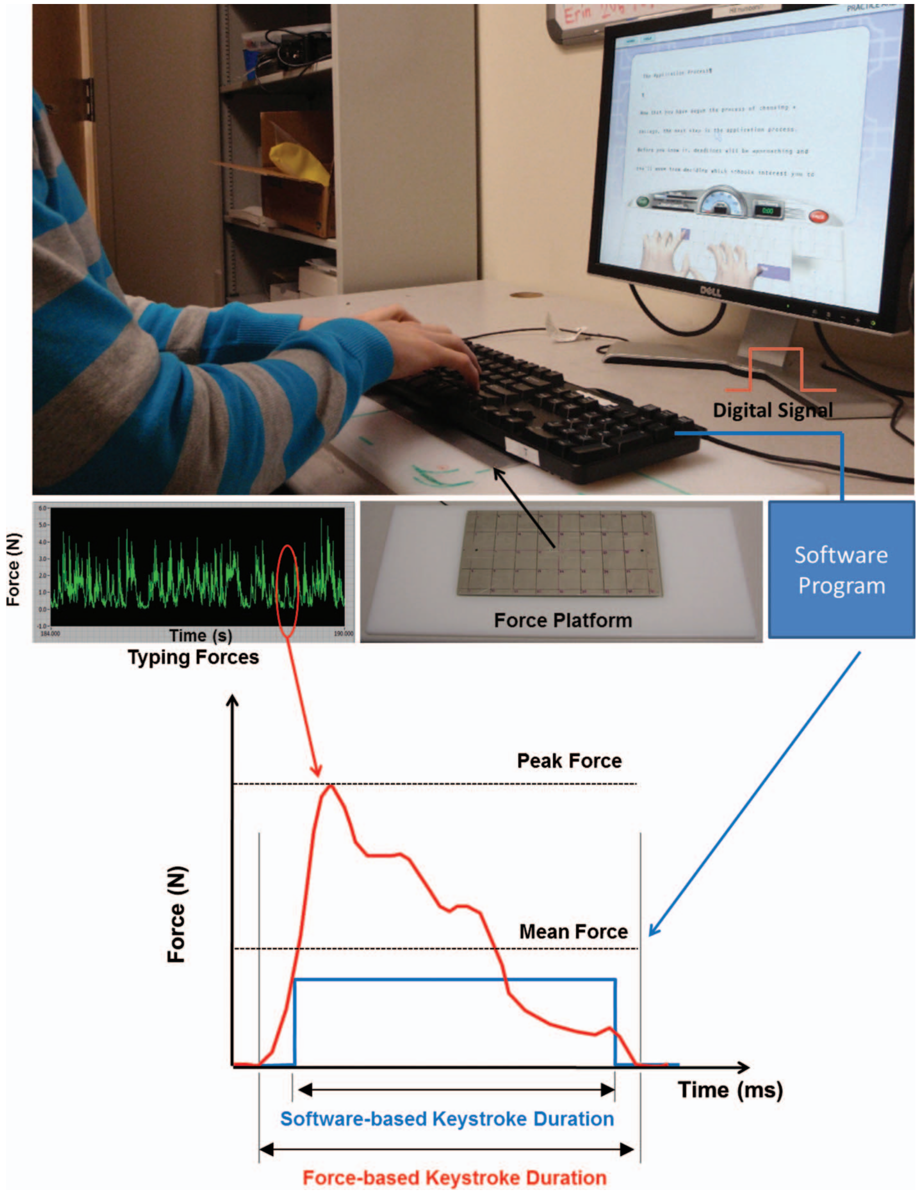

Figure 2. Experimental setup and schematic comparisons of the methods: the red and blue solid line represents the force profile and digital signal of an individual keystroke, respectively.

longer keystroke durations across all the keyboards (Figure 3f). Lastly, the hand by finger interactions were significant ($p < 0.0001$), indicating that finger-related differences in keystroke durations varied depending on hand (Figure 3d).

3.3. *Difference between software and force-based measures*

The results showed that there were significant differences between the keyboards in the software-measured keystroke durations ($p < 0.0001$) whereas the differences in the force-based measures between keyboards were not as large ($p = 0.07$). The differences between the software- and force-based measures on 1.8, 2.0, and 4.0 mm travel keyboards were 12.2 ± 1.9 ($p = 0.001$), 10.6 ± 1.9 ($p = 0.001$), and -21.8 ± 1.9 ($p < 0.0001$) ms, respectively. Despite the significant differences, the software-based keystroke durations were highly correlated with the force-based measures (Figure 4b–d).

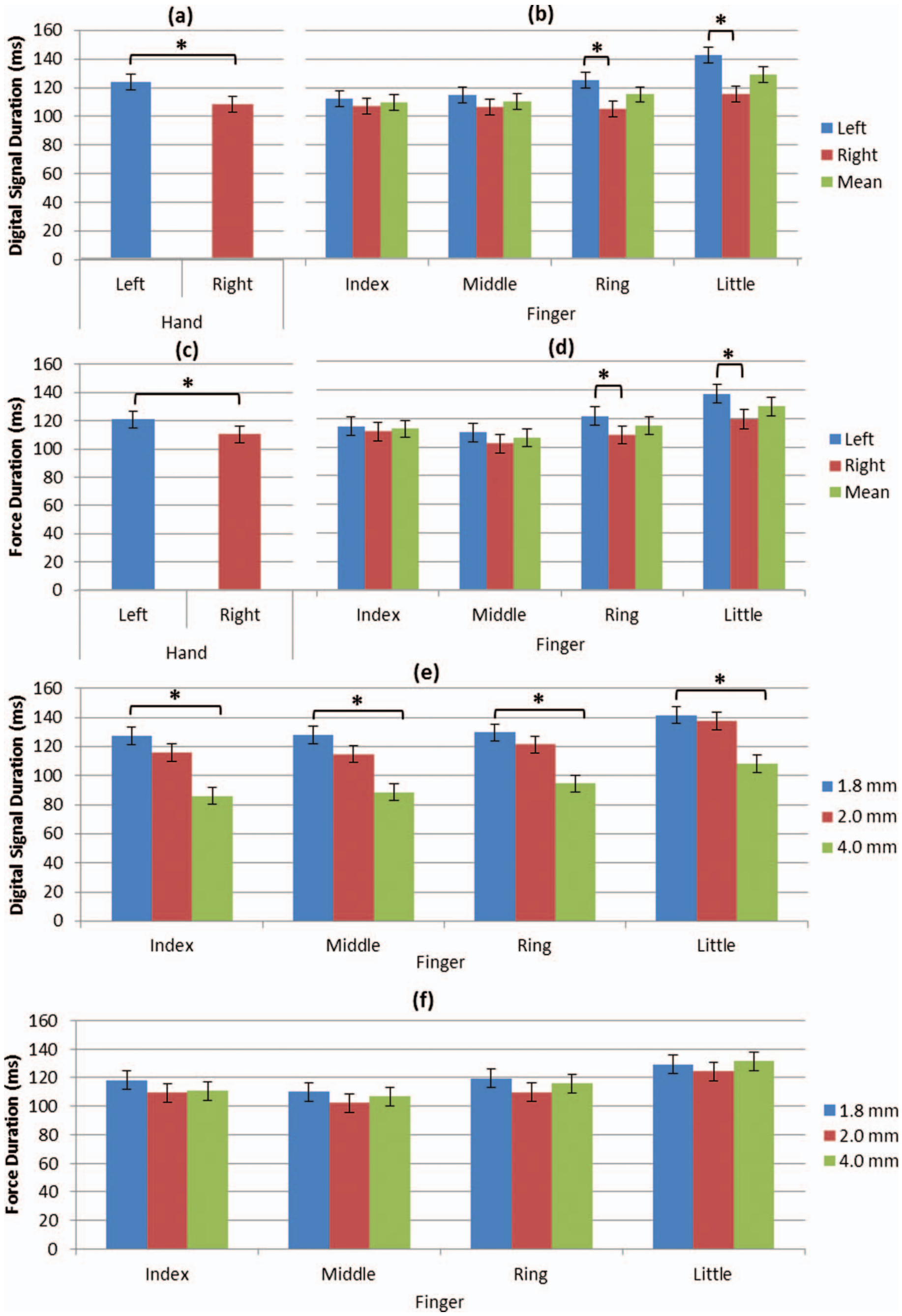

Figure 3. Comparisons of software-based keystroke durations: (a) by hand; (b) by finger and hand, (e) by finger and keyboard. Comparisons of force-based keystroke durations: (c) by hand; (d) by finger and hand; (f) by finger and keyboard [$N = 13$]. The * denotes statistical significance.

3.4. Typing forces

Applied finger typing forces are summarised in Figure 5. The results showed that there were keyboard- and finger-related differences in applied typing forces ($p = 0.0003$ and 0.0001, respectively) whereas the forces did not vary by hand ($p = 0.47$) (Figure 5a). In addition, the two-way interactions between keyboard and hand (Figure 5b) and between hand and finger (Figure 5c) were statistically significant ($p < 0.0001$) while the keyboard by finger interaction (Figure 5d) was not significant ($p = 0.66$).

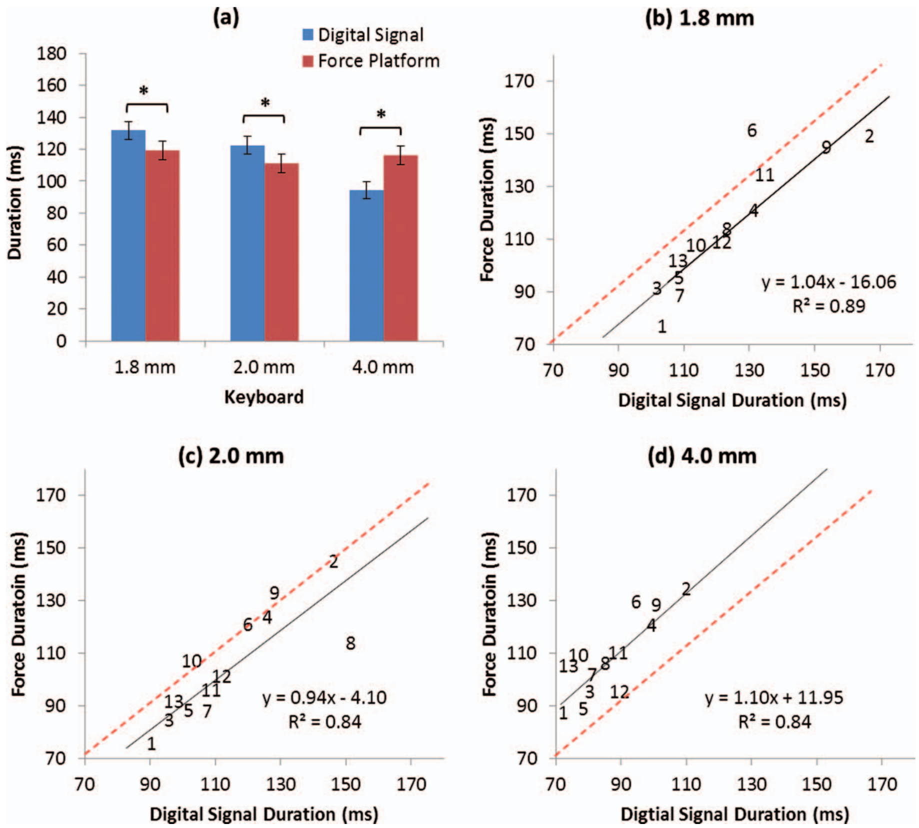

Figure 4. Comparisons of software- and force-based keystroke durations: (a) the differences in the two measures grouped by keyboard; (b–c) Linear fits and correlations between the keystroke durations measured from digital signals (software) and applied finger forces (force platform) on 1.8, 2.0 and 4.0 mm travel keyboard, respectively. The numbers on regression plots (b-c) represent subjects. The *denotes statistical significance. The dotted lines are the ideal identity lines.

4. Discussion

Using keyboards with different keyswitch force-displacement characteristics, the present study tested the hypothesis that keystroke durations measured from the keyboard's digital signals approximates those measured from the keystroke force profiles. The group- and individual-level results showed that the force-based keystroke durations were strongly associated with software-based durations, supporting our hypothesis that the software-measured keystroke durations derived from the digital signals could be used as a non-invasive, cost-effective, surrogate exposure measure in lieu of the more invasive force measurements.

The results showed that the differences in keystroke durations between keyboards were greater with the software-based measures compared to the force-based measures. This was not surprising since the applied force profiles were not affected by the electromechanical differences in keyswitch designs whereas digital signal durations were dependent on the electromechanical and force-displacement differences among keyboards. Although the software-based keystroke durations appeared to be more dependent on the force-displacement characteristics of the keyboard and therefore different from force-based keystroke durations, the software-based measures demonstrated similar hand- and finger-related differences to force-based keystroke durations. Furthermore, the high correlation between the two different measures (Figure 4b–d) indicated that the software-based keystroke durations were accurate surrogate measures for the true force-based keystroke durations.

The present study revealed that the force-based keystroke durations from the non-dominant left hand were approximately 10 % longer than those from the dominant right hand on average (Figure 3c). This hand-related difference in keystroke durations may be due to strength-related differences between hands. Numerous studies have suggested that the dominant hand is significantly stronger than the non-dominant hand (Petersen *et al.* 1989, Crosby and Wehbe 1994, Armstrong and Oldham 1999). Given that there were no differences in applied forces between hands ($p = 0.47$), the strength-related differences between hands may have resulted in higher relative load

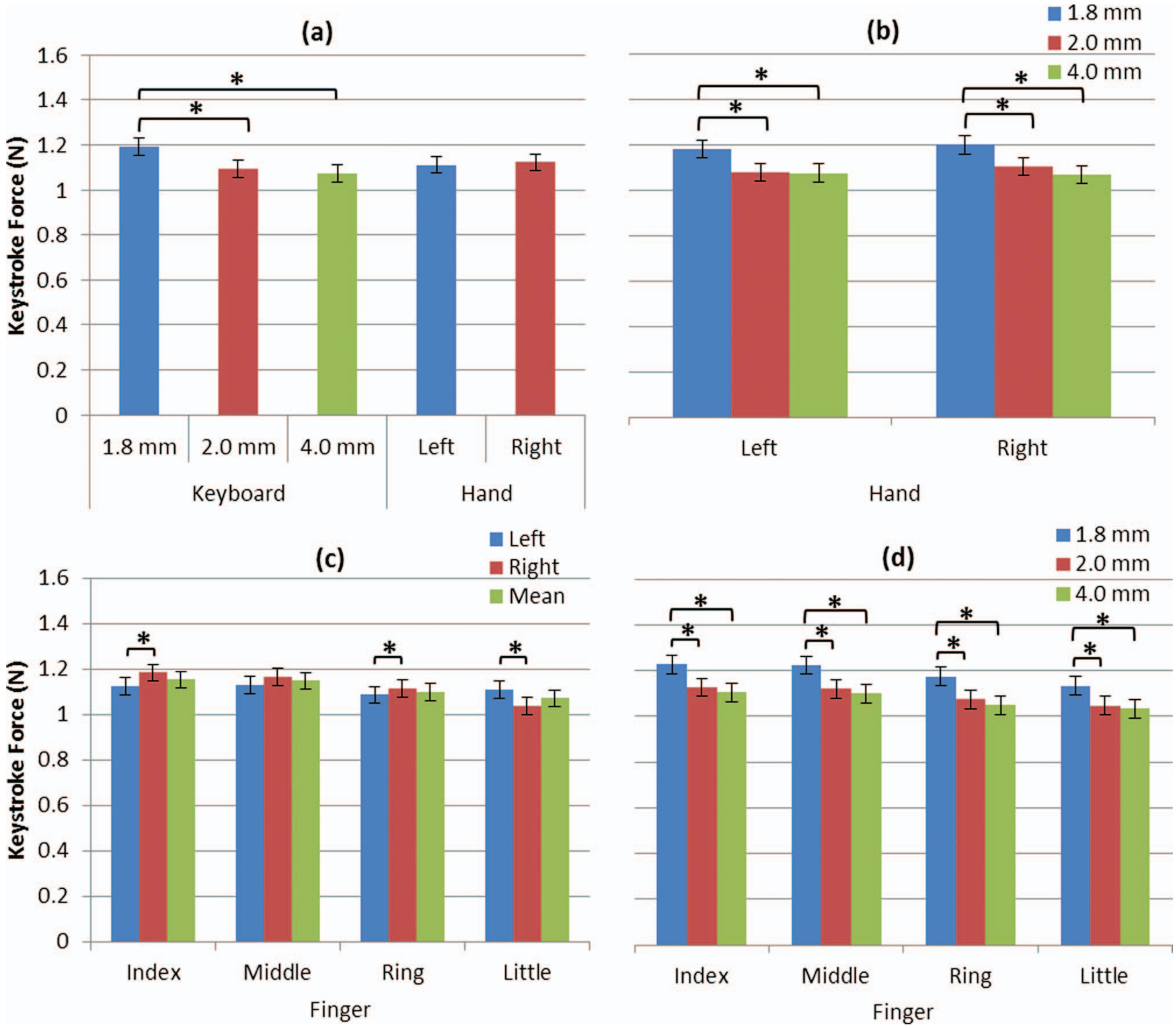

Figure 5. Comparisons of mean keystroke forces: (a) by keyboard and by hand; (b) by hand and keyboard; (c) by finger and hand; (d) by finger and keyboard [$N = 13$]. The * denotes statistical significance.

and therefore longer keystroke durations on the non-dominant left hand. Interestingly, this hand-related difference in force-based keystroke durations was also captured by the software-based keystroke durations. This finding also demonstrated that software-based keystroke durations would be a viable surrogate measure for force-based keystroke durations.

The results also demonstrated that there were significant differences among fingers in the force-based keystroke durations ($p < 0.0001$); the keystroke durations from the ring and little fingers were longer than those from index and middle fingers (Figure 3d). The ring and little fingers are known to be 50–60% of the strengths of the index and middle fingers (Dickson *et al*. 1972, Martin *et al*. 1996, Radwin and Jeng 1997). The differences in mean keystroke forces between fingers were small (at most, 0.12 N) but statistically significant (Figure 5c) and paralleled the differences in finger strengths. Given the similar mean keystroke forces and different strengths of fingers, the relative workload on the weaker ring and little fingers would be approximately two-fold greater than that on the index and middle fingers. This higher relative workload may explain the longer software- and force-based keystroke durations on the weaker ring and little fingers. The software-based keystroke durations not only mirrored the hand-based differences but they also mirrored the finger-related differences in the force-based keystroke durations. This finding may imply that the relative load on fingers during keyboard typing could be optimised by designing key activation forces to be proportional with the respective strengths of the fingers.

The keyboard-related differences in applied finger forces may also be related to force-displacement differences between keyboards. Previous studies showed that the travel distance and key activation forces also affect typing forces (Radwin and Ruffalo 1999, Rempel *et al.* 1999). According to Figure 1, the 1.8 and 2.0 mm keyboard had a similar activation force (0.6 N) and travel distance to the make point (0.6 mm) whereas 4.0 mm keyboard had longer travel distance to the make point, less key stiffness (more gradual slope) and a greater overall key travel. Also, the differences in applied finger forces between 1.8 and 2.0 mm keyboard may be due to differences in travel distances, with the difference being the travel distance from the make point and the end of key travel ($T_{1.8}$ and $T_{2.0}$ in Figure 1). These differences in the shape of the force-displacement curves may have resulted in the different applied finger forces between the keyboards.

The significant hand by finger interaction in applied finger forces indicated that the finger-related differences in applied forces were more pronounced on the non-dominant, left hand (Figure 5c). This may be explained by potential differences in typing biomechanics between the two little fingers. That is, the right little finger has only one designated alphabet key, p, whereas the left little finger has three keys, a, q, z. Since p key is located in the upper row among the alphabetical keys, biomechanical movements of the right little finger may be different than those from the left little finger where the keystrokes are spread across all three alphabetic rows. Previous studies have shown that finger postures affect finger joint characteristics and therefore determine applied finger forces during keyboard typing (Jindrich *et al.* 2004a,b, Wu *et al.* 2008). The postural differences between the right and left little finger may have contributed to the significant hand by finger interaction. Given the known strength differences among the fingers, the relative applied forces would be highest in the left little finger. This would imply that the left little finger had to exert the greatest relative force and had the greatest difficulty in activating the keys; consequently, it would be reasonable to expect the left little finger to have the longest keystroke durations. In fact, the force-based keystroke durations revealed the hand by finger interactions (Figure 3d), indicating that the left little finger had disproportionately longer keystroke durations. This phenomenon was also captured by the software-based keystroke durations (Figure 3b). According to the direct relationships between applied finger force and key activation force discussed in the previous paragraph, the higher relative applied forces of the left little finger could be reduced by adjusting the key activation forces to be proportional to finger strength.

In conclusion, the study findings indicated that software-based keystroke durations derived from the digital signals approximated the true force-derived keystroke durations, independently of the keyswitch force-displacement characteristics. Therefore, the software-based keystroke durations, which can be readily and non-invasively measured by software programs installed on the user's computer, could potentially be used as a surrogate, force duration measure in lieu of the more complicated, expensive and invasive force platform derived measurements. The loss of being able to measure the actual peak and mean force exposures is the limitation of basing keystroke force duration measurements on the keyboard's digital signals as force measures provide important potential interests as a source of feedback to the users (Samani *et al.* 2010). However, the gain is the simplicity, low cost and ability to collect large samples of keystroke frequency and duration exposures for epidemiological purposes. In addition, the study results also indicate that hand- and finger-based differences in keystroke durations and applied finger forces could be minimised by scaling keyboard activation forces to be proportional to some measure of finger strength. This may imply that the current paradigm of designing keyboards with the same fixed activation force for all fingers may not be optimal. Hence, it might also be worthwhile to investigate if adjusting activation forces of individual keys by finger and/or hand strength may be beneficial.

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References

Armstrong, C.A. and Oldham, J.A., 1999. A comparison of dominant and non-dominant hand strengths. *Journal of Hand Surgery-British and European Volume*, 24B (4), 421–425.

Chang, C.H., Johnson, P.W., Katz, J.N., Eisen, E.A., and Dennerlein, J.T., 2009. Typing keystroke duration changed after submaximal isometric finger exercises. *European Journal of Applied Physiology*, 105 (1), 93–101.

Crosby, C.A. and Wehbe, M.A., 1994. Hand strength – normative values. *Journal of Hand Surgery – American Volume*, 19A (4), 665–670.

Dickson, R.A., Nicolle, F.V., Calnan, J.S., and Petrie, A., 1972. Device for measuring force of digits of hand. *Biomedical Engineering*, 7 (6), 270–273.

Gerr, F. and Fethke, N., 2011. Ascertaining computer use in studies of musculoskeletal outcomes among computer workers: differences between self-report and computer registration software. *Occupational and Environmental Medicine*, 68 (7), 465–466.

Gerr, F., Monteilh, C.P., and Marcus, M., 2006. Keyboard use and musculoskeletal outcomes among computer users. *Journal of Occupational Rehabilitation*, 16 (3), 265–277.

Ijmker, S., *et al*., 2007. Should office workers spend fewer hours at their computer? A systematic review of the literature. *Occupational and Environmental Medicine*, 64 (4), 211–222.

Ijmker, S., *et al*., 2011. Software-recorded and self-reported duration of computer use in relation to the onset of severe arm-wrist-hand pain and neck-shoulder pain. *Occupational and Environmental Medicine*, 68 (7), 502–509.

Jindrich, D.L., Balakrishnan, A.D., and Dennerlein, J.T. 2004a. Effects of keyswitch design and finger posture on finger joint kinematics and dynamics during tapping on computer keyswitches. *Clinical Biomechanics*, 19 (6), 600–608.

Jindrich, D.L., Balakrishnan, A.D., and Dennerlein, J.T., 2004b. Finger joint impedance during tapping on a computer keyswitch. *Journal of Biomechanics*, 37 (10), 1589–1596.

Martin, B.J., *et al*., 1996. Keyboard reaction force and finger flexor electromyograms during computer keyboard work. *Human Factors*, 38 (4), 654–664.

Petersen, P., *et al*., 1989. Grip strength and hand dominance – challenging the 10-percent rule. *American Journal of Occupational Therapy*, 43 (7), 444–447.

Punnett, L. and Wegman, D.H., 2004. Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology*, 14 (1), 13–23.

Radwin, R.G. and Jeng, O.J., 1997. Activation force and travel effects on overexertion in repetitive key tapping. *Human Factors*, 39 (1), 130–140.

Radwin, R.G. and Ruffalo, B.A., 1999. Computer key switch force-displacement characteristics and short-term effects on localized fatigue. *Ergonomics*, 42 (1), 160–170.

Rempel, D., *et al*., 1994. A method of measuring fingertip loading during keyboard use. *Journal of Biomechanics*, 27 (8), 1101–1104.

Rempel, D., *et al*., 1999. Effect of keyboard keyswitch design on hand pain. *Journal of Occupational and Environmental Medicine*, 41 (2), 111–119.

Rempel, D.M., Harrison, R.J., and Barnhart, S. 1992. Work-related cumulative trauma disorders of the upper extremity. *JAMA – Journal of the American Medical Association*, 267 (6), 838–842.

Samani, A., *et al*., 2010. Active biofeedback changes the spatial distribution of upper trapezius muscle activity during computer work. *European Journal of Applied Physiology*, 110 (2), 415–423.

Tayyari, F. and Smith, J.L., 1997. *Occupational ergonomics: principles and applications*. London: Chapman & Hall.

Waersted, M., Hanvold, T.N., and Veiersted, K.B. 2010. Computer work and musculoskeletal disorders of the neck and upper extremity: a systematic review. *BMC Musculoskeletal Disorders*, 11, 1–15.

Wu, J.Z., *et al*., 2008. Analysis of musculoskeletal loading in an index finger during tapping. *Journal of Biomechanics*, 41 (3), 668–676.