Pergamon

J. Biomechanics, Vol. 27, No. 8, pp. 1101–1104, 1994

0021–9290/94 $7.00+0.00

0021-9290(93)E0017-J

TECHNICAL NOTE

A METHOD OF MEASURING FINGERTIP LOADING DURING KEYBOARD USE

DAVID REMPEL,* JACK DENNERLEIN*†, C. D. MOTE, JR† and THOMAS ARMSTRONG‡

*Ergonomics Laboratory, Division of Occupational Medicine, University of California, San Francisco, U.S.A.; †Department of Mechanical Engineering, University of California, Berkeley, U.S.A.; and ‡Department of Industrial Engineering, University of Michigan, Ann Arbor, U.S.A.

Abstract—A single keycap on a standard alphanumeric computer keyboard was instrumented with a piezoelectric load cell and the fingertip motion was recorded with a high-speed video motion analysis system. Contact force histories between the fingertip and the keycap were recorded while four subjects typed a standard text for five minutes. Each keystroke force history is characterized by three distinct phases: (I) keyswitch compression, (II) finger impact and (III) fingertip pulp compression and release. Each keystroke force history contained two relative maxima, one in phase II and one in phase III. The subject mean peak forces ranged from 1.6 to 5.3 N and the subject mean peak fingertip velocities ranged from 0.3 to 0.7 m/s. Motion analyses and force measurements suggest a ballistic model of finger motion during typing.

INTRODUCTION

Developing a biomechanical model of the finger, tendon, bone, muscle system during typing may lead to an improved understanding of tissue strains, muscle fatigue and productivity associated with this type of work. To develop the input function for such a model, fingertip motion and fingertip contact force histories must be identified. Although biomechanical models for dynamic finger motion have been proposed (Buckner, 1988; Xio, 1992), a detailed characterization of the input function (e.g. finger loading) for typing does not exist. This paper describes a system for studying fingertip forces during typing and presents a scheme for classifying the phases of the force history of a keystroke. In this pilot study a standard keyboard was instrumented to measure the vertical contact force between the finger and the 'h' key during a typical typing task.

METHODS

The 'h' key of a standard Apple Extended II keyboard was instrumented with a piezoelectric load cell to measure the vertical force between a thin keycap and the keyswitch. The top 2 mm thick surface was cut from a standard keycap and a 15 mm diameter, open disk piezoceramic transducer was secured to the underside. The keycap post (which inserts into the switch) was reattached to the underside of the load cell. The completed assembly, which retained the original dimensions of the standard keycap, replaced the 'h' keycap and inserted into the switch. The mass of the original keycap was 1.0 g and the mass of the instrumented keycap was 1.2 g. Output from the load cell was amplified by a Kissler 5004 dual mode amplifier, sampled at 0.1 ms intervals and stored on magnetic media. Data were recorded over 400 ms with a 20 ms pretrigger lead. The load cell was calibrated using standard weights (accuracy ±0.5% of reading). Linearity was ±3% over 712 g. The natural frequency of the keycap–load cell unit is 4.4 kHz.

Four male touch typists with varying skill levels typed alphanumeric sentences for approximately 5 min. The chair and keyboard height were adjusted as recommended by the American National Standards Institute (ANSI, 1988). No support was provided for the subjects' palms, wrists or forearms. After 2 min of typing, data were recorded for six successive 'h' keystrokes.

Fingertip motion was recorded for one subject using a Kodak SP2000 high-speed motion analysis system recording at 1000 frames per second. The field of view was 6 × 6 mm at the key. The distal edge of the volar surface of the right index fingernail was marked and the mark was manually digitized during a frame-by-frame viewing of the finger motion during a keystroke. A vertical resolution of ±0.04 mm was confirmed by comparing the distance between marks on the nail as measured during digitizing to the distance as measured with a caliper.

The static force–displacement relationship of the keyswitch (Apple Extended II, Alps KCM QSIII) was measured by depressing the switch in 0.01 mm increments and simultaneously collecting force values using a Chatillon Universal Electronics Tester Model ET1100 (displacement accuracy of ±0.1 mm, force accuracy ±2%). The static switch force–displacement relationship of the Alps KCM QSIII keyswitch showing the characteristic curve of a mechanical switch is presented in Fig. 1.

RESULTS

A sample of a keystroke force–time curve and the corresponding vertical fingertip displacement–time curve (Fig. 2) demonstrates three phases of a single keystroke: keyswitch compression (I), finger impact (II) and fingertip pulp compression and release (III). Keyswitch compression begins when the fingertip first contacts the keycap (displacement $=0$) and ends when the keyswitch has been fully depressed (displacement $= -3.5$ mm). Finger impact, which occurs at the end of key travel when the fingertip decelerates, is associated with a maximum force of short duration. During

---

Accepted in final form 14 *October* 1993.

Address correspondence to: D. Rempel, University of California, Ergonomics Laboratory, 1301 South 46th Street, Building 112, Richmond, CA 94804, U.S.A.

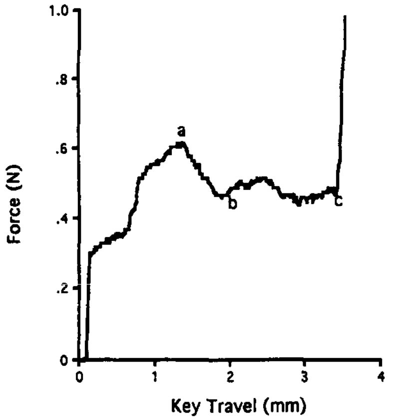

Fig. 1. Static Force–displacement curve for 'h' key on Apple Extended II keyboard with Alps KCM QSIII switches. The switch make force (a) is 0.62 N. The switch electrical make point (b) occurs at 2.0 mm of key travel, well before full key travel (c) which is 3.5 mm. The fingertip must overcome these forces in order to fully depress the keyswitch.

the final phase (III), a second relative force maxima occurs at the point of greatest nail displacement. The fingernail moves an additional 0.3 mm downward after the keyswitch is fully compressed and the keycap is stationary. A review of the high-speed video demonstrated that this additional motion was due to the compression of the fingertip pulp. In the last half of this phase the fingertip withdraws, the force decreases and the keycap moves up to its resting position.

While different timing and magnitude characteristics of the keystroke force history were noted between subjects (Fig. 3), all keystrokes contained the three phases described above. Keyswitch compression (I) and finger impact (II) accounted for a relatively short duration of the total keystroke, averaging 9.1 ms (range 5.3–12.6 ms) and 8.8 ms (range 6.8–10.4 ms), respectively. The average duration of a keystroke was 77.2 ms (S.D. 11.2 ms). The fingertip force recorded during keyswitch compression (I) (Fig. 3) approximated the static switch activation force of 0.6 N (Fig. 1). The highest forces were recorded during the finger impact phase (II) with the maximum force ranging from a low of 2.4 N in subject 1 to a high of 7.0 N in subject 4. The mean maximum within subject force during this phase ranged from 1.6 to 5.3 N (S.D. 0.4–1.3).

The longest component of a keystroke was the third phase, during which the fingertip pulp was compressed and the

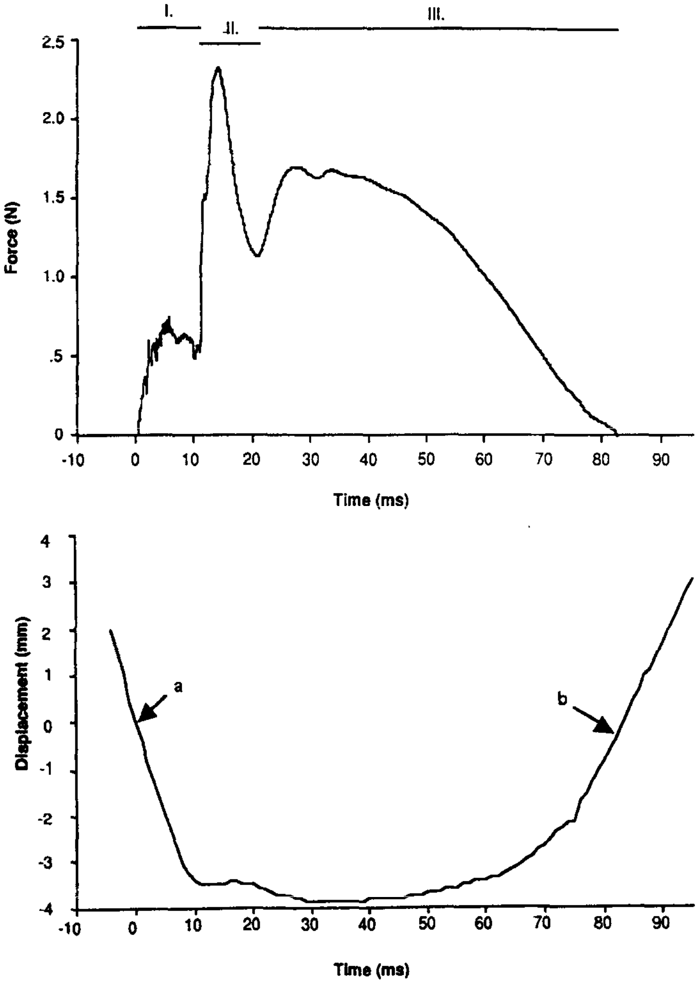

Fig. 2. Typical fingertip force history (top) and simultaneous vertical fingernail displacement (bottom) during a single keystroke. Three phases in the force history, not previously observed with load cells mounted under the keyboard, are identified here: keyswitch compression (I), impact (II), and fingertip pulp compression and release (III). Initial point of fingertip contact with the keycap (a) and release of fingertip from keycap (b) are marked.

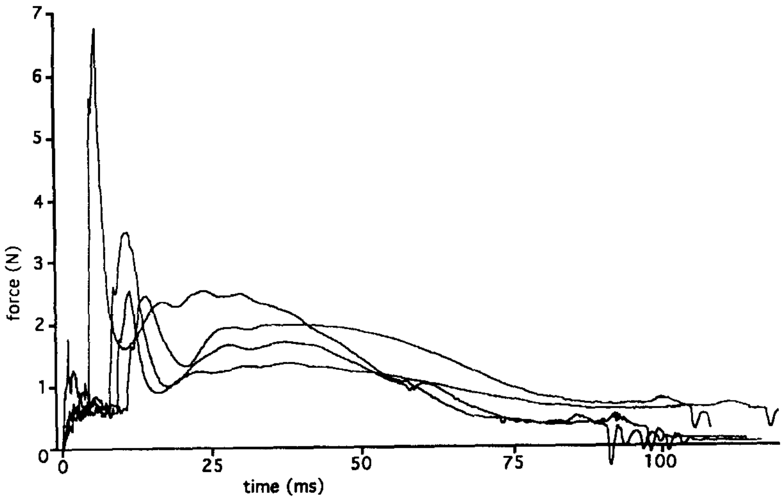

Fig. 3. Four typical fingertip force histories during an 'h' keystroke; each is from a different subject. The shapes of the curves are similar although different force magnitudes and event times are apparent between subjects. The force measured during phase I converges on the switch make force of 0.6 N. These curves are more descriptive than under the keyboard force measurements.

finger was withdrawn from the key. The average duration of this phase was 59.7 ms, which accounted for 77% of the keystroke duration. The maxima during this phase was less than the maxima during the impact phase; the mean maxima ranged from a low of 1.4 N (S.D. 0.3) for subject 2 to a high of 2.5 N (S.D. 0.4) for subject 4. The mean within subject duration of phase III ranged from 51.9 (S.D. 4.6) to 72.0 ms (S.D. 14.1 ms); and the duration was not correlated with the force maxima.

Although differences in keystroke force histories were observed between subjects, the same characteristics within a subject appeared to be more constant. For example, the between subject coefficient of variation (C.V.) for maximum force during finger impact (II) was 0.57, while the average within subject C.V. was 0.21. Similar differences in C.V. were observed for the durations of phases I and II and the maximum force during phase III.

Fingertip velocity during the initial phase (I) of the keystroke was calculated and ranged from approximately 0.3–0.7 $m s^{-1}$ between subjects; with a group mean velocity of 0.42 $m s^{-1}$. The calculation was based on the distance of key travel (3.5 mm) and the duration of the keyswitch compression (I). As seen in the lower curve of Fig. 2, the slope of fingernail displacement (velocity) is relatively constant through this phase, through the initial contact with the keycap ($y = 0.0$ mm) and through the electrical make point (2.0 mm).

DISCUSSION

A methodology is presented for measuring fingertip force and displacement during a keystroke on a computer keyboard. To characterize the details of fingertip force during a keystroke, the duration of which is less than 100 ms, a piezoelectric load cell with a rapid response time was used and sampled at 10 kHz. The instrumented keycap was of a similar mass and shape as a standard keycap. Fingertip displacement was recorded for one subject by tracking a mark on the fingernail with a high-speed video system. The system accuracy and linearity were determined using static calibration techniques. Since the system has a high-frequency response and low mass, it is assumed that the calibration results carry over into the dynamic realm.

Data were collected from a limited number of typists for only one key. Nonetheless, three distinct phases were identified in all keystroke force history curves: keyswitch compression (I), finger impact (II), and fingertip pulp compression and release (III). During the first phase the fingertip contacts the keycap, pushes the cap down, compresses the spring in the keyswitch and triggers the switch mechanism. The force measured during the initial phase is approximately the same as the static switch activation force. After the switch is fully compressed, fingertip impact occurs, and this event is associated with the first of two force maxima. The fingertip force history was observed to be double peaked. The second maxima occurs approximately 25 ms later, when the fingertip pulp is fully compressed. The mean duration of a keystroke was 77 ms.

Two previous investigations have attempted to characterize fingertip force and motion during typing. By mounting a keybroad on a force platform and sampling at 20 Hz, mean maximum forces were recorded for 10 typists using a similar keyboard and ranged from 1.2 to 2.7 N (Rempel, 1991). These forces are less than the maximum forces reported here (2.4–7.0 N). The difference can be accounted for by the slower sampling speed used in the earlier study, which may have missed the brief (6–10 ms) impact peak, or by the filtering of the signal performed by structures between the keycap and the force platform. Guggenbuhl (1990) measured finger motion in typists with ultrasonic emitters attached to a finger and sampled at 60 Hz. The finger trajectories recorded were more coarse than the trajectory reported here (Fig. 2), however, the curves are roughly similar. Extensor EMG activity was recorded but the authors were unable to determine whether finger downward motion was slowed by the extensor muscles or stopped purely by impact. The relative constant fingertip velocity observed in our study during switch compression combined with the high-impact force observed suggests modeling finger motion during typing as a ballistic process.

Fingertip force histories collected from the system described in this paper can be used as input functions to biomechanical models to translate the fingertip impact force to the physiologically significant measures of tendon tensile force. Static models predict flexor tendon tensile force up to 3.4 times the force applied at the fingertip (Goldstein, 1987; Schuind, 1992). However, in a dynamic activity the material properties of fingertip pulp, flexor tendon, muscle and intra-articular structures modulate the forces in the flexor tendons. These items have not been addressed in proposed dynamic models (Buchner, 1988; Xio, 1992).

Instrumenting individual keys on a keyboard to measure fingertip contact force has several advantages over measuring force by placing the keyboard on a force platform. First, the keystroke force history at each key is reproduced. The distinct phases observed here have not been observed during force platform measurements (Rempel, 1991; Sind, 1990). Sampling under the keyboard with a force platform does not permit isolation of the finger contact forces; the switch, circuit board and keyboard frame add higher-order dynamics to the force measurement. Second, when sampling with a force platform, measurements are corrupted by resting or tapping fingers on the keyboard or contact between the palm and the keyboard.

The disadvantage of instrumenting individual keys is that the system is complicated, expensive and difficult to carry into the field. Transducers, amplifiers and recording systems are required for each key and each key requires individual calibration. The transducer design is a function of keyboard design, making comparisons between keyboards difficult and making it difficult to sample from subjects while they use their own keyboard. Note also that the force is measured between the load cell and the top piece of the keycap and not between the keycap and the fingertip. Even though this top piece has a small mass (0.48 g) the force curves shown include the inertia effects of this mass.

In conclusion, the empirical force data required to develop a biomechanical model for keying should be collected near the fingertip, not under the keyboard. A system to accomplish this is presented and preliminary results have identified three distinct phases in a keystroke contact force history. Furthermore, these preliminary results suggest modeling initial finger motion during a keystroke as a ballistic process, although further research is necessary to clarify this issue definitively.

REFERENCES

American National Standards Institute (1988) American National Standard for Human Factors Engineering of Visual Display Terminal Workstations. Standard No. 100-1988. Human Factors Society, Santa Monica, CA.

Buchner, H. J., Hines, M. J. and Hemami, H. (1988) A dynamic model for finger interphalangeal coordination. *J. Biomechanics* **21,** 459–468.

Goldstein, G. A., Armstrong, T.J., Chaffin, D. B. and Matthews, L.S. (1987) Analysis of cumulative strain in tendons and tendon sheaths. *J. Biomechanics* **20,** 1–6.

Guggenbuhl, U. and Krueger, H. (1990) Musculoskeletal strain resulting from keyboard use. In *Work with Display Units* (Edited by Berlinguet, L. and Berthelette, D.) Elsevier, North-Holland, pp. 121–128.

Rempel, D., Gerson, J., Armstrong, T.J., Foulke, J. and Martin, B. (1991) Fingertip forces while using three different keyboards. *Proc. Human Factors Society 35th Annual Meeting.* Human Factors Society, Santa Monica, pp. 253–255.

Schuind, F., Cooney, W.P., An, K.N. and Chao, E. (1992) Direct measurement of tendon forces in the hand. *J. Hand Surg.* **17A,** 291–298.

Sind, P. (1990) The effects of structural and overlay design parameters for membrane switches on the force exerted by users. *Proc. Human Factors Society 34th Annual Meeting,* Human Factors Society, Santa Monica, pp. 380–384.

Xio, L. and Wells, R.P. (1992) The interaction of muscular forces during unloaded finger movement: a forward dynamic model. *Proc. North American Congress on Biomechanics.* American Soc. of Biomechanics, Chicago, pp. 453–454.