Measurement of Stiffness and Damping Characteristics of Computer Keyboard Keys

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To determine the stiffness and damping of computer keyboard keys, a computer-controlled test rig that can measure computer key displacement, velocity, and contact force has been designed. The test rig, consisting of a single-axis stage carrying a probe for contacting keys, has been used to collect contact force and motion data as computer keys are depressed and released at constant velocities up to 80 mm/s. *Keys that employ a rubber-dome under their caps to achieve the necessary compliance and toggling action were tested. The results demonstrate a nonlinear stiffness force versus displacement characteristic at a given speed and the presence of damping-type forces that increase with key depression speed at a given displacement. In particular, the results indicate that the peak force at the* 80 mm/s *rate of depression increases relative to the quasistatic* (0.5 mm/s) *force level by over 12% for the "Enter," "K," and "Spacebar" keys. This paper describes the hardware and software configuration, and presents sample results of the stiffness and damping characteristics of keys during depression-return stroke tests.* [DOI: 10.1115/1.1902823]

1 Introduction

Typing is a low-force but highly repetitive activity. Many touch typists easily type 90 words per minute, which translates roughly into 200,000 keystrokes or more for an 8-h day. Despite the forces being low, the repetitive nature of typing may result in or contribute to muscle, nerve, and tendon dysfunction. Studies have shown an association between keyboard use and symptoms of musculoskeletal disorders (MSDs) as well as pain and discomfort [1–3], although questions remain whether there is a specific cause and effect relationship.

The keys of computer keyboards serve as the haptic interface for a typist. Through compliance and toggling (buckling-like) action, the keys provide the tactile "feel" for successful typing. The "feel" is often represented by the mechanical impedance, that is, the effective stiffness, damping, and mass of the key. The mass of the key is due to the key cap, whereas the stiffness and damping properties are predicated on the design underlying the key cap. The most common design, called a *rubber-dome* key, has a monolithic rubber dome under the key cap, as shown in Fig. 1. It produces a resistance force against key depression, a restoring force after key release, and tactile feedback through a toggling or buckling-like action during which the rubber-dome gives way. The elastomeric material as well as the thickness and size of the rubber dome influence how the key "feels." These properties of the rubber dome could possibly affect physical discomfort and muscle fatigue after sustained typing.

Although prior research has investigated key layout [4] and keyboard shape [5–7], studies of key tactile feel have been limited to static properties only. A premise of this paper is that the dynamic characteristics may also contribute to the total contact force of a fingertip depressing a key. In a one-dimensional model of key motion, the total contact force can be written as the summation of a static stiffness term and two dynamic terms, i.e., $F_{\text{total}} = F_{\text{stiffness}} + F_{\text{damping}} + F_{\text{mass}}$ where $F_{\text{stiffness}}$ is the force contribution due to key stiffness, F_{damping} is the force contribution due to key damping, and F_{mass} is the force due to key mass acceleration. In general, $F_{\text{stiffness}}$ and F_{damping} are nonlinear functions of displacement and velocity, respectively, exhibiting linear behavior, if at all, only over a limited region, and $F_{\text{mass}}=0$ for static and constant velocity tests.

1.1 Force-Displacement Characteristics of Keys. The force versus displacement characteristics of keyboard keys have been studied extensively [8–13]. In general, the static force applied to the key is determined by measuring the reaction force between the keyboard and the underlying work surface or, less commonly, by measuring the force with a transducer on the underside of a key cap. The typical measurement approach is a "stepped" method in which a key is depressed to a preset position and held until a force transducer records a stable signal, and the results are presented in terms of static force-displacement curves.

These static force-displacement graphs have been the primary tool to compare computer key characteristics. A nonlinear relationship exists between key force and displacement for a rubber-dome key, as depicted in Fig. 2. The relationship is specified formally in the ISO/DIS 9241.4 standard [14], which refers to a rubber-dome key as a snap-action key. This key has a force-displacement characteristic that exhibits a regime of negative stiffness (indicated by decreasing force with increasing travel). The snap point corresponds to the displacement at which the force has a local maximum. According to ISO/DIS 9241.4, electrical actuation of the key leading to character generation occurs at a force less than or equal to the snap point force.

1.2 Force-Velocity Characteristics of Keys. Although the force versus velocity characteristics of keys have not been reported previously, these properties may be important because typing is a dynamic activity. An individual typing at 90 words per minute (reasonable for a trained touch typist) is depressing and releasing each key in approximately 133 ms (assuming no time for finger travel between keys). Although an individual does not type at constant velocity, it is still possible to calculate an average key velocity. Typing at 90 words per minute corresponds to 60 mm/s on a keyboard with an assumed key travel of 4 mm. (In typing W words per minute, with a word defined as having five characters, an individual types $5 \times \mathrm{W}/60$ characters per second. The time needed for typing one character is then $12/\mathrm{W}$ second, which is the total time for the key being depressed and returned. Assuming the time a key is de-

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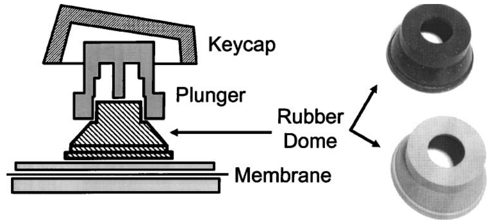

Fig. 1 Schematic of rubber-dome key mechanism and photograph of rubber domes

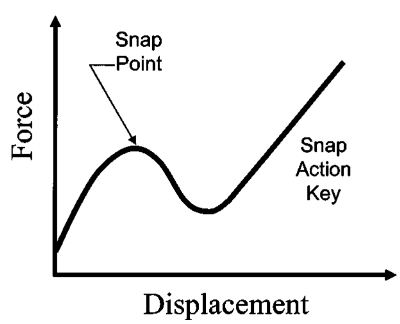

Fig. 2 Relationship between key force and key displacement, adapted from ISO/DIS 9241/4.2 standard (ISO, 1998 [14])

pressed is half of the total time, the key down time is 6/W s. The distance a key travels from its rest position to the end of travel is S mm. As a result, the average velocity a key goes down is S $\times$W/6 mm/s. For a value for W of 90 words per minute (reasonable for a fast typist) and a value for S of 4 mm, the average velocity that a key travels is 60 mm/s.) This calculation does not account for depression and release of shift and spacebar keys, and provides a lower bound for the key velocity in actual typing.

Velocity-dependent forces, i.e., damping forces, of keys may augment the static, i.e., stiffness, forces and be more evident during higher speed typing. These forces may have an effect on the muscle force necessary for key activation and possibly on muscle fatigue. Such forces may play a more dominant role at higher typing speeds if the key mechanism follows a viscous-type damping model in which the force increases with velocity. If this is the case, damping of the key mechanism would serve to dissipate energy imparted to the key from the fingertip and would require that a typist exert greater contact force as the speed of depression increases.

To prevent key ringing and dampen unwanted oscillations, some damping may be desirable in the key mechanism. This damping would dissipate the energy imparted to the key suspension and the energy associated with accelerating the key mass during key strike and return. Significant damping would not be desirable, since it would increase the force exerted by the fingers during fast keystrokes. There may be a range of damping that offers a compromise in minimizing key vibration and muscle force for activation.

1.3 Scope. The objective of this work is to quantify the mechanical stiffness and damping properties that contribute to the tactile characteristics of computer keyboard keys. To accomplish this goal, a special-purpose test rig was developed. The design of this test rig and the associated experimental methodology are addressed in this paper. In addition, the paper presents sample results for rubber-dome keys and suggests a potential model for key damping.

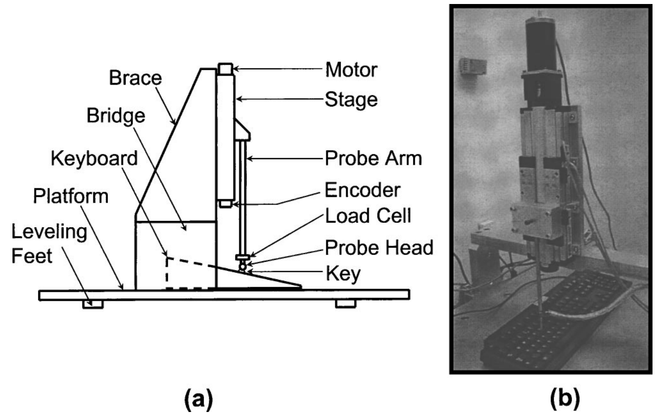

Fig. 3 Test rig: (*a*) side view; and (*b*) photograph

2 Design of Test Rig

The test rig, shown in the drawing of Fig. 3(*a*) and in the photograph of Fig. 3(*b*), consists of a motorized positioning stage mounted to a brace that is attached to a bridge on a platform. The stage drives a probe that depresses the key to be tested; a load cell measures the applied key force. An optical encoder measures the displacement of the stage-probe assembly and hence the key during key depression. The velocity of the probe and hence the key stroke motion is controlled by the speed of a stepper motor.

In conducting a test, a keyboard is placed on a platform, and the carriage of the positioning stage, carrying an arm with a load cell and probe head, is driven up and down. The keyboard is adjusted under the probe such that the probe head is centered over the key strike surface to be tested. Keys of different keyboards can be tested quickly by simply interchanging keyboards on the platform without reconstruction of the test rig.

To accelerate the key to constant velocity, the probe starts from rest and reaches the target speed before impacting the key. The test rig has a large stroke specification of 100 mm, to enable the probe to reach the constant speed prior to key contact. (The largest allowable value for key displacement is 6 mm of travel in one direction, as specified by the ISO 9241.4 standard [14].) The velocity specification for the test rig was set at a maximum speed of 125 mm/s.

By design, the force measurement and displacement measurement systems are integrated with the stage, as described in the following subsections.

2.1 Force Measurement. A miniature-sized strain-gauge load cell (Sensotec, Inc., Model 31) mounted in-line with the probe measures the contact force between the probe head and the key cap. This load cell has two male-threaded rods on both surfaces for attachment to the probe head and arm. The load capacity of the cell is 1 kg_f (9.81 N), which surpasses the maximum force subjects exert on computer keyboard keys during typing [12]. The bandwidth of the load cell is 1870 Hz, well above the high frequency force information captured during dynamic tests. The accuracy of the load cell is within 0.6%, and its precision is $\pm$0.01 N.

A data acquisition (DAQ) system consisting of a PC-bus board (National Instruments, model AT-MIO-16E-10) is used to digitize the force signal from the load cell amplifier (Sensotec, Inc., Models SA-4 and SA-B). The smallest detectable force change (resolution) after digitization with the board, which has a 12-bit resolution, is 0.0024 N. The maximum throughput of the DAQ card is 100 kHz, and different sampling rates can be set by software.

2.2 Position Actuation and Measurement. Positioning is accomplished using a 5-mm-lead ground ball screw and square rail positioning stage (Daedal, Parker Hannifin Corp., model

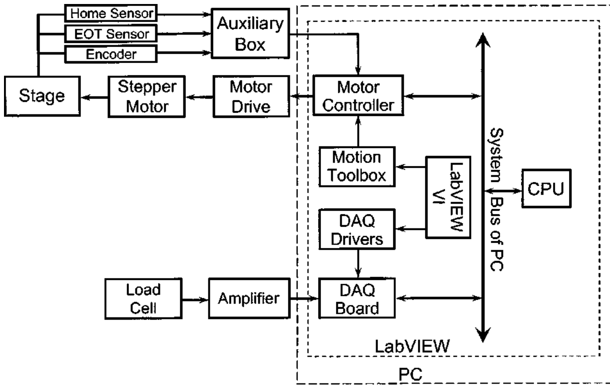

Fig. 4 Test device actuation and measurement block diagram showing subsystems

404100XR). The stage converts rotational motion of an input shaft into translational motion of the carriage, enabling 100 mm of travel. A rotary optical incremental encoder is attached to the lead screw of the stage. It measures the movement of the shaft, and thus indirectly the displacement of the carriage with a resolution of 1 μm. The stage includes three Hall effect sensors: a positive direction end-of-travel (EOT) sensor, a negative direction EOT sensor, and a home sensor. The accuracy of the displacement measure recorded by the data collection system is within 0.15% and its precision is ±0.006 mm [15,16].

The motor (Compumotor, Parker Hannifin Corp., model ZETA57-102) is a standard 200 full step hybrid motor, driven by a microstepping motor drive (Compumotor, Parker Hannifin Corp., model ZETA4) that allows for digital step and direction servo control of the motor. With a resolution of 25,000 steps per revolution and at a shaft speed of 0.1 rev/s (corresponding to the minimum test velocity of 0.5 mm/s), the step pulse frequency is 2500 Hz. At a shaft speed of 25 rev/s (corresponding to the maximum test velocity of 125 mm/s in dynamic measurement), the step pulse frequency is 625 kHz.

The step pulses are supplied by a PC-bus motion controller card (Compumotor, Parker Hannifin Corp., model AT6200) through which displacement information is sent to the PC from the encoder. External signals from the encoder, home sensor, and EOT sensors are not fed directly to the controller card but wired to an auxiliary box. The box isolates external circuitry from the controller card, thus protecting the card from the hazards of voltage spikes and current surges. Encoder and sensor information is then transmitted from the box to the controller card through a high-density data-transfer cable.

2.3 Data Flow and Processing. The integration of data acquisition (for force and position) and motion control is represented in the overall system block diagram of Fig. 4. The motor controller card and DAQ board are installed in a Pentium PC running LabVIEW (National Instruments). In the test system, DAQ drivers (National Instruments) operate the DAQ board (AT-MIO-16E-10), and a "Motion Toolbox" (Compumotor) is used to communicate with and command the motor controller card (AT6200). The Motion Toolbox is actually a library of LabVIEW virtual instruments (VIs). The DAQ system allows for buffer-event counting from which velocity is computed through differentiation using the centered difference approximation (one time-step before and after).

2.4 Control of Test Rig. The test rig can be used to conduct static and dynamic measurements of keyboard keys to determine force-displacement and force-velocity characteristics, respectively. Static measurements are actually quasistatic, in that the probe does not stop but depresses the key at a very slow constant velocity of 0.5 mm/s. The sample rate is adjusted depending on speed to capture 40 samples of data per mm. This corresponds to 160 force and displacement values for an average key stroke of 4 mm displacement.

In dynamic measurements, the probe is accelerated from rest above the key and presses against the key at constant velocities up to a maximum of 125 mm/s. These measurements provide force, displacement, and velocity data for analysis and cross plotting, and thus the ability to obtain the force-velocity characteristic of a key at any given travel position during its stroke. Since the velocity of the key is not constant when the probe bottoms out at the end of the key's travel, data from the last 0.5 mm of travel are not analyzed. The bottom position is detected using the force signal as feedback. When the force exceeds a threshold value (set here at 1.2 N), the key is assumed to be fully depressed and the probe is commanded to move in the opposite direction. In addition, a threshold position (3.5 mm) is also set to detect the end of a constant velocity depression stroke test.

3 Experimental Study

3.1 Protocol. Rubber-dome keys on keyboards from different manufacturers were tested [15,16]. All keyboards were of a conventional, flat design (no split or tilted keyboards) with a QWERTY layout of keys. The study involved a total of 22 keyboards, consisting of 13 different models from four major manufacturers. (Two replicates of keyboards were available for nine of the 13 models; one keyboard was available for four of the 13 models.) For each keyboard, the contact forces were measured at seven constant velocities of depression and release applied to three keys: "K," "Enter," and "Spacebar." These three keys were selected because they represent the smallest to largest keys, in terms of size, mass, and number of rubber-domes in the underlying mechanism on a typical desktop computer keyboard. A single rubber dome is employed for the "K" and "Enter" keys, whereas two are used under the "Spacebar."

The keyboards were placed on the platform with the legs retracted. Since most keyboards have a built-in slope of 6 deg, the probe's direction of travel did not coincide exactly with each key's travel axis. Based on calculations, the error in the off-axis key depression and release force was less than 1% and considered negligible.

Each of the three keys of the 24 keyboards was tested three times at the following speeds: 0.5, 20, 30, 40, 50, 60, and 80 mm/s (speed in mm/s corresponds to wpm rate of 50% greater, e.g., 80 mm/s corresponds to 120 wpm). Within each keyboard, the order of speeds and keys tested was randomized. For each speed the force values at each discrete displacement (1/40 mm) were averaged over three trials, and the force versus displacement curve was then smoothed using a polynomial fit (ranging from sixth to twentieth order). Polynomial fitting resulted in minimal discrepancy between raw force values and smoothed data. The force, displacement, and velocity data were cross plotted to highlight the stiffness and damping characteristics.

3.2 Results. To avoid showing many similar force-displacement graphs, data from only one rubber-dome desktop keyboard are presented. Graphs from the selected rubber-dome keyboard were typical of the overall trend of force displacement as a function of depression speed for all 22 rubber-dome keyboards tested.

Figures 5(*a*)–5(*c*) are the force-displacements graphs of the "Enter," "K," and "Spacebar" keys, respectively. The snap action behavior of the force is evident at the quasistatic speed of 0.5 mm/s and at the highest speed tested of 80 mm/s. In depression for the quasistatic case, the contact force peaks at the snap point at approximately 1.3 mm displacement. The force then decreases to a local minimum (trough) level at approximately 2.5 mm displacement and then increases again (as the key starts its bottoming out phase). When the key is reversed through a controlled release (referred to in the plots as "release") it returns

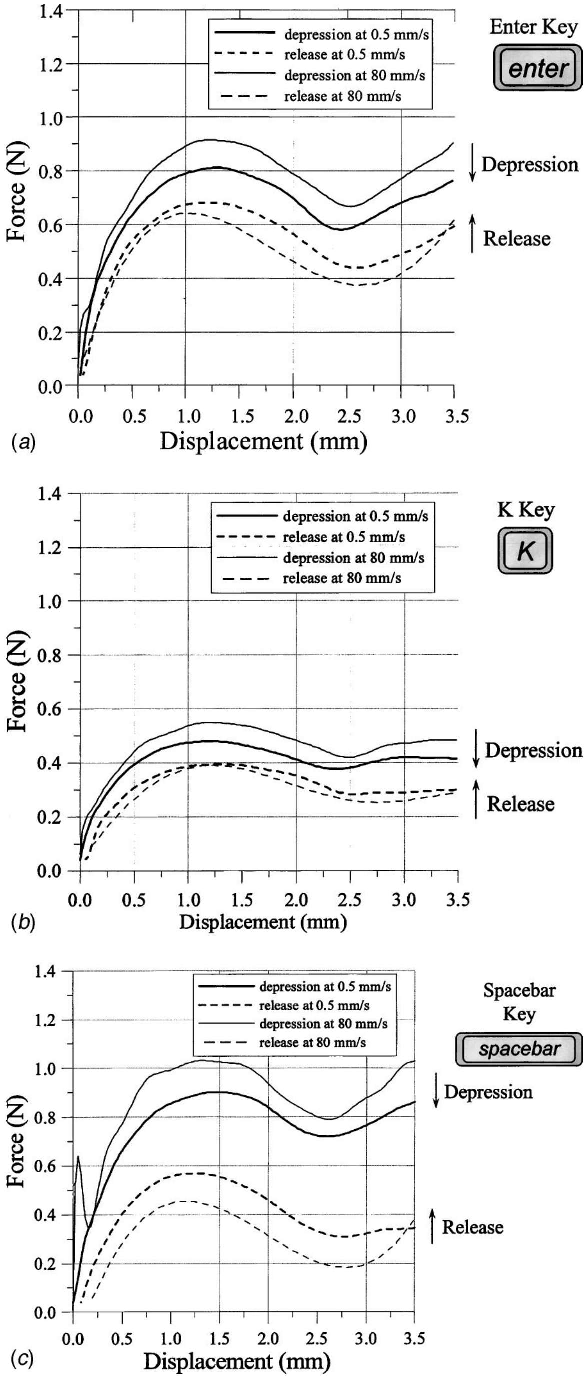

Fig. 5 Force-displacement of depression and release of rubber-dome keys at 0.5 and 80 mm/s speeds for (*a*) "Enter," (*b*) "K," and (*c*) "Spacebar"

to its resting position. During the release, the contact force is less than the depression force throughout the key's displacement range. This direction-dependent effect indicates the presence of Coulomb friction.

At any displacement up to 3.5 mm, the contact forces for all three keys are greater at 80 mm/s depression rate than at 0.5 mm/s. The contact forces for the depression speeds tested (0.5, 20, 30, 40, 50, 60, and 80 mm/s) increase, in general, as velocity increases. At 80 mm/s the impact between the rigid probe and the greatest mass key (the Spacebar) induces an initial shock, which generates a ringing force signal that decreases with

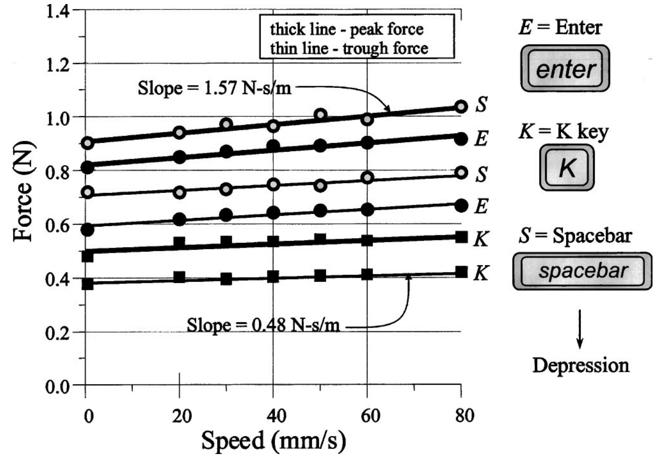

Fig. 6 Peak and trough forces of three rubber-dome keys as a function of depression speed

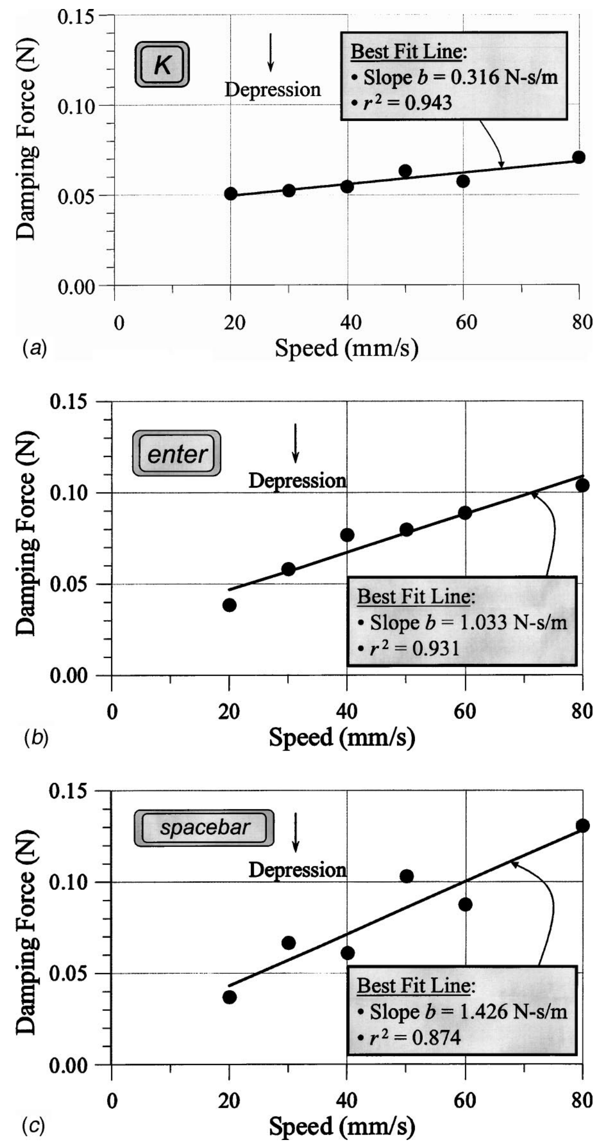

Fig. 7 Damping force as a function of depression speed of rubber-dome keys at the peak force displacement for (*a*) "Enter," (*b*) "K," and (*c*) "Spacebar"

ensuing displacement. During the release stroke the higher speeds of release result in forces lower than or equal to the quasistatic rate (0.5 mm/s) across the displacement domain.

At the peak level (snap point) of depression and at its trough (local minimum), the contact force for the three keys rises approximately 0.5–1.5 N s/m over a range of 80 mm/s, as indicated in Fig. 6. The peak force increases linearly with respect to depression speed, and relative to the quasistatic (0.5 mm/s) force level, the force increases over 12% for the three keys at the 80 mm/s rate of depression. The damping force at a given position and speed can be isolated from the total contact force (that is, the measured force) by subtracting the static (or quasistatic) force from the total force. (The inertial contribution is absent since it is assumed the key is moving at a constant velocity.) The results are shown in Figs. 7(*a*)–7(*c*), which present the damping force as a function of speed at a displacement corresponding to the peak force. The damping force characteristics of Figs. 7(*a*)–7(*c*) indicate a viscous-type damper model for rubber-dome keys with damping coefficient values of 0.316 N s/m for the "K" key, 1.033 N s/m for the "Enter" key, and 1.426 N s/m for the "Spacebar" key.

4 Discussion

In contrast to previous studies that measured static force versus displacement characteristics of computer keyboard keys, this study investigates the influence of speed on the force-displacement characteristic, a subject previously unreported in the literature. Although some manufacturers test their keyboards to meet the current ISO standard that focuses solely on static parameters, no manufacturers to our knowledge have reported testing keys for velocity-dependent characteristics.

For the rubber-dome keys tested, the peak force in general increases with speed of depression. Although the increase in peak force for rubber-dome keys, as shown in Fig. 6, may seem small (0.05–0.1 N for speeds up to 80 mm/s), the percentage increase in peak force approaches 14% above the quasistatic peak force.

The increase in force is attributed to damping, namely a speed-dependent force effect, as displayed in Figs. 7(*a*)–7(*c*) and the results suggest that a linear (viscous) damper model for the peak force may be appropriate for the speeds tested. A plausible model for 20–80 mm/s is $F_{\text{damper}}=b\nu$, where the slope b is the damping coefficient, as supported by the high values of the coefficients of determination ($r^2=0.87-0.94$). This paper does not develop a damping force model that applies below 20 mm/s or above 80 mm/s, since these speeds were not tested. For all three keys, the linear damping model has a damping force of approximately the same magnitude (0.05 N) at 20 mm/s, and then rises at different rates (i.e., different b values).

An intriguing observation is that the slope of the damping model increases with key size (i.e., b for "K" key $<b$ for "Enter" $<b$ for "Spacebar"). This phenomenon may be attributed to several possible factors: the specific design of guide posts, the underlying switch design, and the parallel arrangement of two domes for the "Spacebar" key.

For speeds ranging from 0.5 to 80 mm/s, the data suggest that the peak forces required to depress the nonalphabetic keys tested ("Enter" and "Spacebar") can be almost twice the magnitude of peak forces for alphabetic keys, such as the "K" key (refer to Fig. 6). The results indicate that the forces increase with speed, and hence damping is present, for the nonalphabetic as well as the alphabetic keys. Compared to quasi-static forces, dynamic forces were greater than 12% at 80 mm/s.

Small increases in the forces needed to activate keys may have a cumulative effect that contributes to user discomfort, muscular fatigue in the forearm, and possibly to the development of MSDs affecting the wrist, such as tenosynovitis and carpal tunnel syndrome.

4.1 Study Limitations. The basis for selecting keystroke speeds in this study was an algebraic conversion from "words per minute" (wpm) to "average key depression-release velocity" (80 mm/s corresponds to 120 wpm). This theoretical conversion assumes (1) the key is moving at the same constant velocity during the full stroke of depression and release, (2) the fingertip is in contact with the key during both the depression and release phases, and (3) no time was allocated to move fingers between sequential keystrokes. Although these assumptions do not reflect the kinematics of an actual finger interacting with a key during typing, they do provide a lower bound and a starting point for investigating dynamic interactions.

A finger is not a rigid probe, as used in the test rig, but offers a pulpy, compliant surface that depresses a key. In addition, a finger may not be in contact with the key during the full depression and controlled release phases of a stroke. Furthermore, a typist's finger does not move at constant velocity during a keystroke—it accelerates, reaches peak velocity, and decelerates [17]. This would suggest higher velocities than those presumed here. Damping effects were present and distinctly measurable at the speeds of this study, and may be even greater at higher keystroke speeds. Finally, although the authors observed the probe staying in contact with the key throughout the trials, the probe could have lost contact with the keys at the higher velocity tests.

The data collected are meaningful only for a key moving at a constant velocity. Inferences from our data are not drawn for the acceleration and deceleration phases of key movement (the initial and bottoming-out phases, respectively). These nonconstant velocity phases will have inertial effects that contribute to the mechanical properties. Their relative significance to tactile "feel" of keys remains unknown.

4.2 Future Studies. Future studies will be directed to quantifying the damping effects at additional speeds. More data points in Figs. 7(*a*)–7(*c*), especially at lower speeds, would clarify whether there is a Coulomb-like effect superimposed on viscous behavior. At higher speeds, with inertial effects contributing, a more complete impedance model can enhance our understanding of the dynamics of key depression and release. A more extensive parametric identification process than the one adopted in the current approach would enable better estimation of the velocity dependent characteristics.

Future studies will include testing of additional nonalphabetic keys, such as "shift" and "control," considering their frequency of usage. In addition, future studies will include testing of keyboards relying on spring-loaded keys (sometimes called *buckling spring* or *coil spring* keys) that employ a mechanical spring to achieve toggling and compliance. Although this design is older and less common than rubber domes, it provides a mechanically robust alternative that some typists prefer.

Future studies will also be directed to the bottoming out phase, during which the velocity is not constant, and to designing a more biofidelic probe that mimics the compliance of a fingertip.

5 Summary

The mechanical stiffness and damping properties of rubber-domed computer keyboard keys were ascertained by measurement of key force versus key displacement and key force versus key velocity characteristics, respectively, using a specially designed test rig. The test rig is computer automated and uses PC-bus-based data acquisition and motion controller cards running under LabVIEW. The paper has focused on the development of the test rig, including its mechanical design and its associated computer control. The paper has also presented results that indicate that rate-dependent damping forces are present above the static stiffness forces.

A hypothesis of this work is that mechanical damping plays a perceptible and potentially significant role in the design of computer keyboard keys and in the selection of an "optimal" keyboard by a typist. It is hoped that the quantification of both the static and dynamic mechanical properties of computer keyboard keys will lead to an enhanced understanding of ergonomic factors, such as muscle fatigue and tendon loading. Furthermore, this work could form the basis for a subsequent ISO standard for force-velocity characteristics of computer keyboard keys.

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