# The Effects of Structural and Overlay Design Parameters of Membrane Switches on the Force Exerted by Users

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(ABSTRACT)

Two experiments were conducted to evaluate the effects on applied force of structural design parameters and feedback conditions inherent in the aesthetic overlay of membrane switch touchpads. In the first experiment, which evaluated structure, 12 males and 12 females keyed 100 4-digit sequences into a computer using 6 of a total of 12 touchpads which differed in membrane ply thickness, spacer thickness, and spacer aperture diameter. The same task was completed by nine males and nine females in the second experiment, which evaluated feedback conditions inherent in flat, embossed, domed, embossed with dome, flat with escutcheon, and domed keycap aesthetic overlays.

The apparatus employed for force measures was a force platform system integrating seven strain gauge force transducers Subjects received auditory feedback for correct actuations.

Results of the studies indicate that applied forces are correlated quite highly with the required actuation force (RAF) of the switch ($r = 0.89$, $p < 0.01$). However, membrane switch structure had a significant effect on the applied forces, even after the effects of RAF were controlled. Feedback conditions inherent in the aesthetic overlay also had an effect on the forces applied. A significant preference for RAF was found in the structure experiment. There were no significant differences among touchpads with respect to preference for feedback conditions inherent in different aesthetic overlays.

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# INTRODUCTION

Membrane switches are a class of low-profile or flat switches characterized by minimal displacement (generally less than 1.0 mm) and a total thickness of less than 4.0 mm. Membrane switches are discrete, momentary-contact (push-on, release-off) control devices, and are used in a number of military, industrial, and consumer products. Because of its sealed construction and extended lifetime, membrane switch technology has proven valuable in the development of data entry keypads for hostile environments. Unlike most other key technologies, the basic membrane switch is relatively immune to contamination from dust accumulation and liquids, and is easily cleaned and maintained. The thin profile design of membrane switches make them suitable for many products, particularly those where space conservation is critical. Additionally, membrane switch technology provides a great amount of flexibility in touchpad layout and key size, shape, and labeling.

There are, however, certain disadvantages of membrane switches which have limited their use. In particular, membrane switches are lacking in the salient tactile and kinesthetic feedback characteristic of elastomer, Hall-effect, and other key technologies. As a result, users may exert excessive force during actuation. Excessive force may contribute to more rapid fatigue of the user as well as to a decrease in the switch life.

For certain applications, its sealed construction, easy maintainability, and other characteristics make membrane switch technology the only viable design solution. Thus, there is a need to evaluate membrane switches and identify

those factors which could lead to an improved design. This research addressed the forces exerted on membrane switches, on the principle that touchpads which elicited the greatest forces would be most likely to lead to rapid fatigue of the user. Also, since the force applied is related to structural fatigue of the membrane, minimizing exerted forces could contribute to increased switch life. Finally, knowing typical force levels exerted on a membrane touchpanel during actual use would provide a more valid basis for switch life testing than the minimum RAF or some arbitrarily-selected force level, as is currently used.

Two design parameters, the internal structure of the membrane switch and the aesthetic overlay, were hypothesized to have an effect upon exerted forces. The following section is an introduction to membrane switch technology and the design parameters under investigation. Thereafter, user characteristics which are likely to impact membrane switch use are discussed. Finally, two experiments investigating the forces applied to membrane switch touchpads are presented.

*Membrane Switch Construction*

In addition to a graphics overlay, the membrane switch itself generally consists of three layers: a thin polyester or polycarbonate membrane ply with conductive contacts on the underside, a printed circuit board or flexible film substrate layer with contacts on the top surface, and a non-conductive spacer which separates the two layers (Figures 1 and 2). The spacer contains holes through which the flexible upper membrane can be depressed, allowing closure of the conductive contacts, actuating the switch. When force on the upper

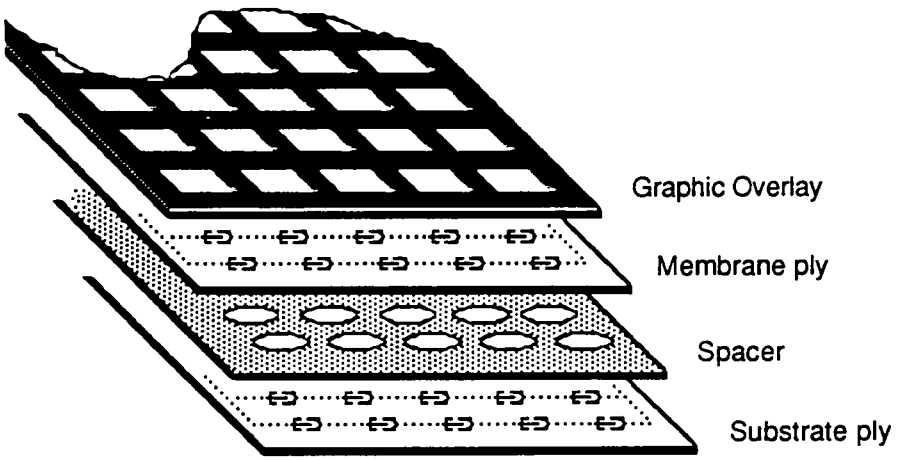



Figure 1. Basic membrane switch construction.

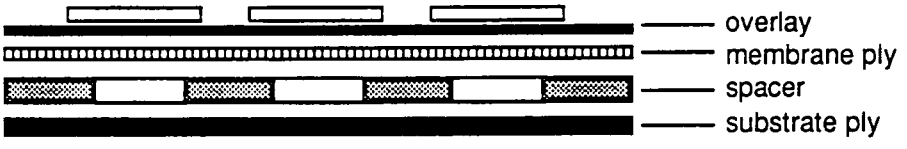



Figure 2. Unscaled cross-section of three membrane keys, shown with an embossed key overlay to illustrate alignment.

membrane is relieved, the upper membrane returns to its former position, breaking the contact.

Kunita (1981) identifies six basic types of membrane switches, varying in complexity of construction, tactual characteristics, and materials. The type of membrane switch most widely used today has the electrodes printed with conductive ink on the membrane ply and substrate layers. This type is amenable to mass production, contains few components, offers high reliability, and is very inexpensive to manufacture. The substrate ply may consist of a flexible material or a rigid circuit board with the contacts printed on it.

DeFosse, Williams, Gostomski, and Cobb (1985) made several recommendations for membrane switch construction, including structural bonding of all layers, strict tolerances for layer thicknesses, and venting of switch cavities. Vented membrane switches contain channels in the spacer which permit pressure relief of the spacer chamber. Venting minimizes actuation force differentials and membrane collapse resulting from relative chamber pressure fluctuations due to temperature or altitude changes.

*Actuation Resistance in Membrane Switches*

By varying specific parameters in the construction of the membrane switch, differing amounts of elastic resistance may be obtained, thus affecting the requisite actuation force (RAF). This is particularly useful if increased resistance is desirable to reduce accidental actuation, or simply to obtain an operating force which is appropriate for the application.

The increase in resistance can be explained in terms of a few simple properties of physics. Hooke's Law states that stress is proportional to elastic deformation, or strain. As the rigidity of the membrane is increased, more stress (force per unit area) is required to deform it (Figure 3a). An increase in the thickness of the spacer results in an increase in the amount of deformation necessary to enable contact. Increasing the amount of necessary deformation results in an increase in the RAF (Figure 3b). Similarly, if the requisite deformation remains constant but a smaller aperture diameter decreases the area of the membrane subject to deformation, a greater force must be applied to elicit equivalent strain (Figure 3c).

The actuation of a membrane switch is a *displacement* phenomenon. Displacement results from elastic deformation (or strain) of the membrane layer. *Force,* per se, is relevant in the actuation of a membrane switch only to the extent that it is a component of strain. Since displacement varies with force, velocity and acceleration are relevant in membrane switch actuation only to the extent that they are a component of force.

The actuation force for a membrane switch has been modeled as a function of four variables: membrane thickness/rigidity, spacer thickness, spacer aperture diameter, and base plate curvature (DeFosse et al., 1985). The base plate is a rigid plate located beneath the substrate ply which provides a solid foundation for mounting the membrane switch to the panel bezel. When a printed circuit board (PCB) is used as the substrate, the PCB serves as the base plate. A more rigid membrane, a thicker spacer, a smaller spacer aperture diameter, or some combination of these variations in the switch design results in a

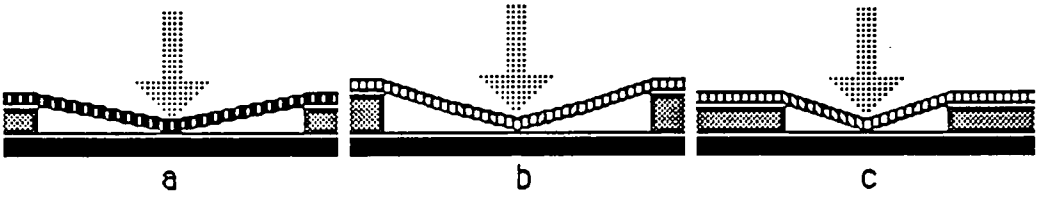



Figure 3. Resistance achieved through variations in structural design: (a) rigid membrane requires greater stress to deform over the same area, thus requiring greater applied force; (b) thicker spacer increases amount of strain required for actuation, necessitating greater applied force; (c) smaller aperture decreases the area which is subject to strain, thus requiring greater applied force to yield equivalent stress.

higher RAF. Although increasing the curvature of the base plate also results in an increase in RAF, the manipulation of base plate curvature is undesirable. The reason for manipulating base plate curvature is to enhance the user's ease of access and feel for the key tops (Harris, 1977), as shown in Figure 4. Hence, the degree of curvature is determined by the position and anthropometry of the user's fingers, rather than the switch requirements. Furthermore, it should be noted that base plate curvature is not commonly employed in flat membrane keypads, only in those with full-travel key mechanisms.

*Full-Travel versus Touchpanel Keypads*

Classic studies comparing full-travel and touchpanel keypads demonstrate certain shortcomings in touchpanel technology. Pollard and Cooper (1979) investigated performance differences between conventional, full-travel telephone key sets and an alternate key set utilizing membrane switches. Although keying times were significantly shorter, error rates were found to be significantly higher on the membrane touchpad. Various aural feedback conditions were evaluated, but even when feedback was optimized for the touchpad, accuracy was still superior when using the conventional key set. However, further analysis of the errors led the authors to attribute the higher error rate to contact bounce. They concluded that employing an electronic polling mechanism with a 25 ms lockout in the membrane switch design could reduce the error rate.

Figure 4. Base plate curvature.

Loeb (1983) compared performance using membrane keyboards with that of conventional full-travel keyboards for a text typing task. For novice typists, there was no significant difference in performance. For expert typists,performance was initially better on the conventional keyboard; however, the advantage of the conventional over the membrane keyboard was reduced substantially with practice, although not completely. In this study, subjects were not trained to asymptotic levels; thus, whether performance on the membrane keyboard would ever have matched or exceeded that on the conventional keyboard is unknown. Furthermore, the RAF was not held constant between the two configurations, the conventional keyboard requiring an actuation "force" of 68 g, while the membrane switch keyboard required 82 gm. (The "force" commonly specified by manufacturers of key-switch devices is actually the mass (gm) which must be applied to actuate the switch.) The differences in the RAF might have accounted for part of the performance differences observed by Loeb. Additionally, Loeb notes that no attempt was made to optimize the membrane switch configuration. Had this been done, performance might have been as good as, or superior to, that of the full-travel configuration.

Differences between novice and expert typists could be characterized in terms of differences in typing speeds, a factor which has been identified as impacting keyboard performance and preference. Where keying speeds are under 1.5 keystrokes per second (ks/s), studies have failed to demonstrate performance differences between conventional and touch-sensitive keyboards, for both numeric and alphanumeric applications. Between 1.5 and 2.0 ks/s, the differences become significant. As the skill level increases, both performance

and preference measures favor the conventional key technologies (W.H. Emmons, personal communication, November 30, 1987).

It has been suggested that conventional, full-travel keypads are superior to membrane touchpads. Because of the weaknesses identified in the design of the studies described above, further research is necessary before one can assert this statement with certainty.

*Human Tactile Sensitivity*

How sensitive the volar and tip surfaces of the finger are to applied forces is not clearly established. VanCott and Warrick (1972) identified the smallest detectable stimulus intensity for pressure as 0.04 to 1.10 erg, or approximately 3 $g/mm^2$. Although the source for these values is not identified, they coincide with the research findings of Wolf (1937), who identified thresholds of 0.037 to 1.090 ergs for the tip and volar surfaces of fingers other than the thumb.

Weber (1846) established that the proportion of change in a stimulus with respect to its original quantity required for differentiation of fingertip pressure ($\Delta I/I$) is 0.04, using weight pairs of 411 and 425, 822 and 850, and 25.7 and 26.6 g.

Biedermann and Löwit (unpublished research, cited by Hering, 1875), investigated cutaneous pressure sensitivity over several intervals within the broad range used by Weber, and found the "Weber Fraction" varied. Figure 5 gives the Weber function for cutaneous pressure based on Biedermann and Löwit's work.

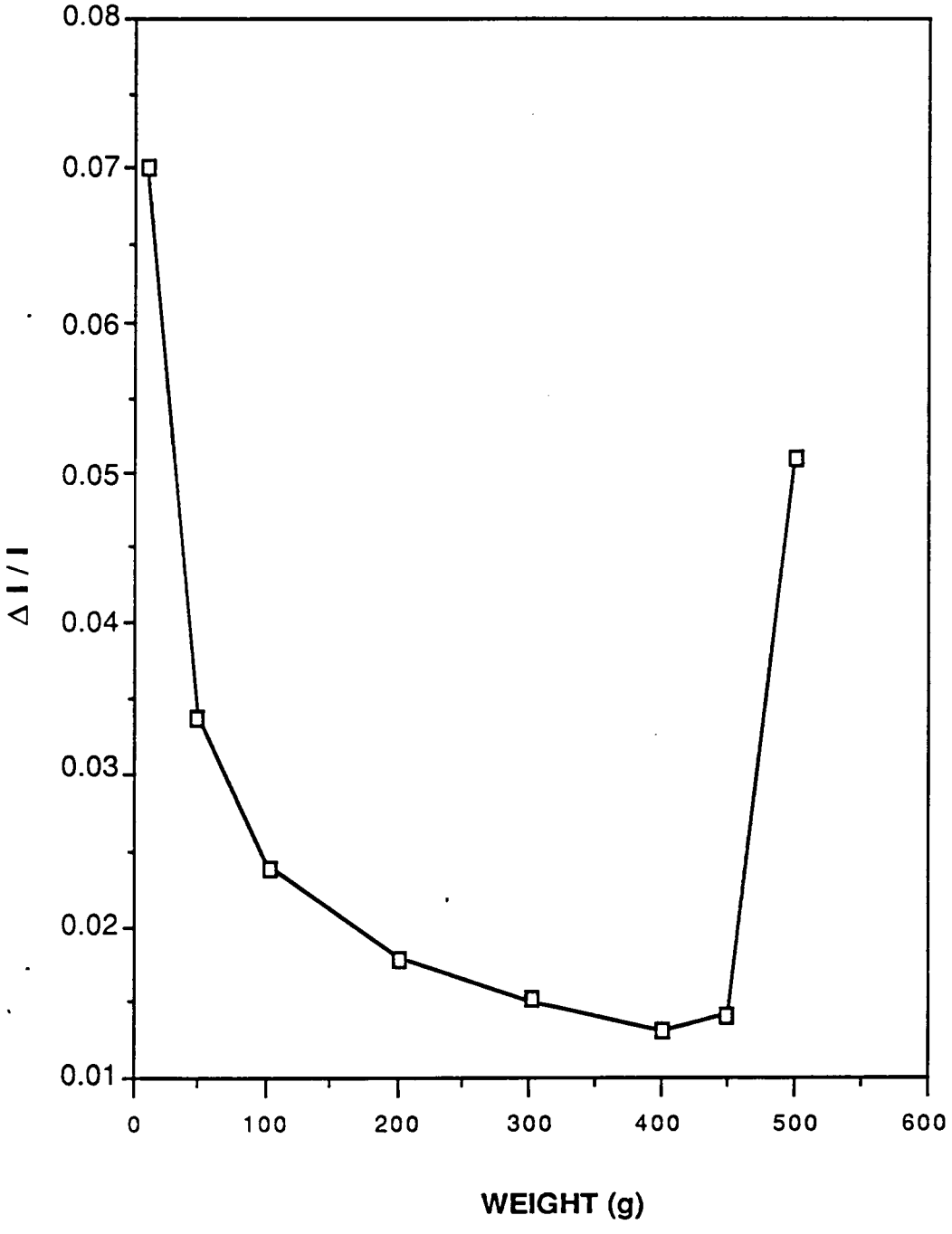



Figure 5. Weber function for cutaneous pressure sensitivity, based on Biedermann and Löwit (1875, cited by Boring, 1942).

Kiesow (1922) established the Weber function for cutaneous pressure sensitivity using vonFrey hairs on single pressure spots. (VonFrey hairs are fine hairs or filaments calibrated with respect to the force they can exert before bending.) Gatti and Dodge (1929) sought to verify and refine these findings, using a more sensitive measure of intracutaneous tension sensitivity (Boring, 1942). Figure 6 shows the Weber functions for cutaneous sensitivity established by Kiesow (1922) and Gatti and Dodge (1929).

Geldard (1972) noted that tension (force per linear extent of skin surface contacted), not force or pressure per se, is critical in cutaneous sensation, at least for small stimuli applied to the skin surface. As the size of the stimulus and the force with which it is applied are increased, the relationships for absolute and difference thresholds shown in the previous figures fail. The physiological mechanisms for the sensation of a force applied to the finger surface differ, depending on the magnitude of the force applied. Small forces such as those applied by Gatti and Dodge (1929) and Kiesow (1922) invoke a cutaneous sensation, while larger forces such as those used by Biedermann and Löwit (1875) invoke not only intracutaneous tension, but deep pressure sensation as well. As different receptors or mechanisms respond to these two types of stimulation, the resulting sensation is the combination of both. When stimulation is strictly cutaneous, the absolute and difference thresholds will be different than when the stimulation also invokes deep pressure sensitivity.

The physical phenomenon that gives rise to the sensation of pressure is the relative deformation of adjacent skin areas. For the sensation of pressure to

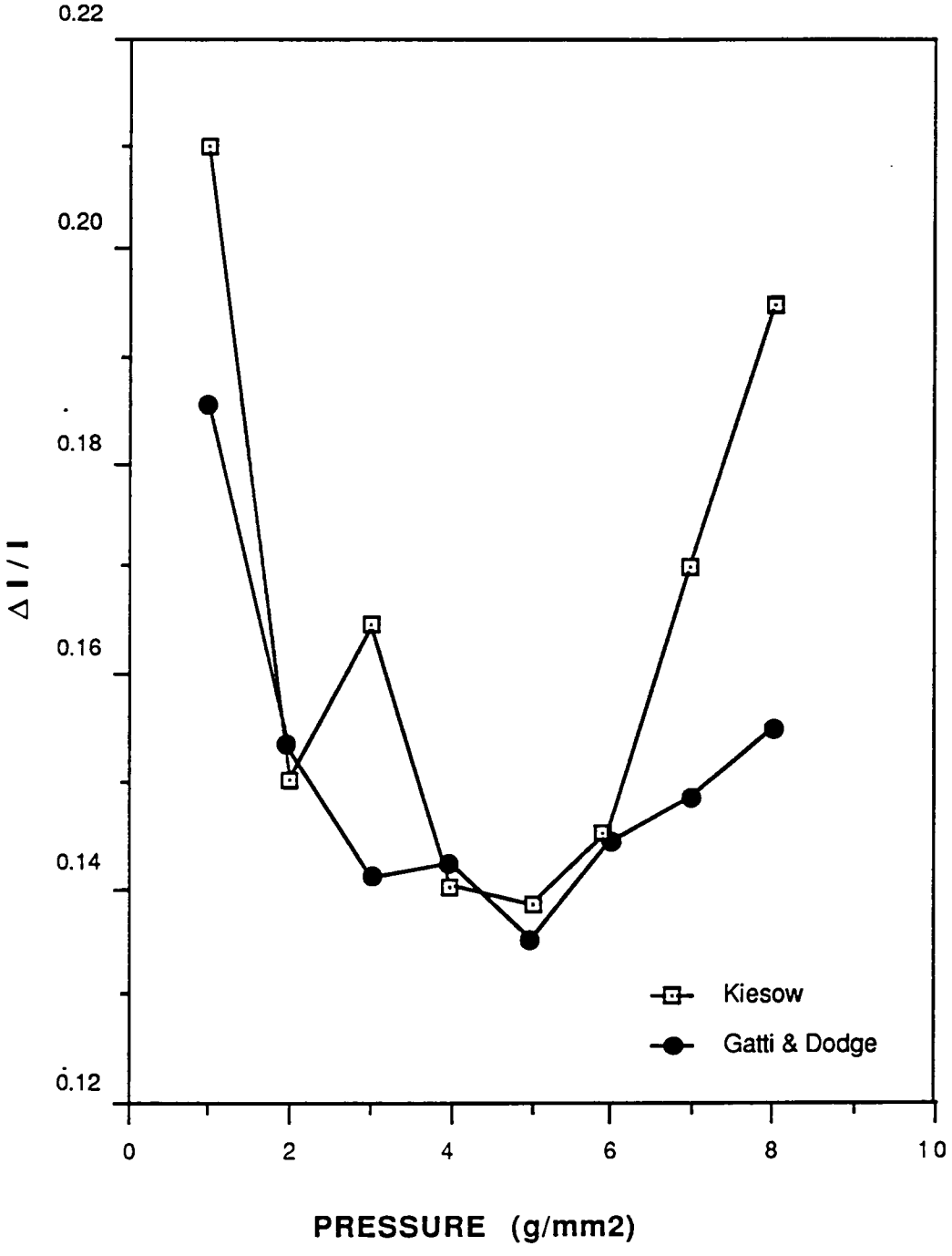



Figure 6. Weber functions for cutaneous sensitivity established by Gatti and Dodge (1929) and Kiesow (1922).

occur, a sufficiently steep deformation gradient is necessary. The steepness of the gradient is related to the intensity of the sensation, steeper gradients facilitating more intense sensations (Geldard, 1972). A mild gradient is created when a large area is contacted, while a steep gradient is created when the stimulus contacts only a small area, as is the case with vonFrey hairs. Thus, threshold values will be higher as the surface area contacted increases.

Unfortunately, research on intracutaneous tension sensitivity has been primarily limited to the study of point force, as opposed to plane force application. With regard to tactual feedback from variations in membrane construction or overlay, where plane contact is at issue it can only be concluded that the absolute and difference thresholds would be greater than those found by Biedermann and Löwit (1875), Gatti and Dodge (1929), Kiesow (1922), Weber (1846), and Wolf (1937); but the actual thresholds for sensitivity to tactual feedback from touchpads are as yet unknown.

*Force-Displacement Characteristics*

Much research has been conducted on the force-displacement requirements of keypad and keyboard input devices, but the results are not clearly interpretable. Table 1 summarizes the recommendations given for force and displacement values for push buttons and keys in general. It is clear that there are vast discrepancies in these recommendations. The problem arises from attempts to specify quantitative attributes for keyboards across technologies which differ in their fundamental characteristics, and the failure to qualify these guidelines with relevant parameters of the configurations tested.

Table 1. Summary of Force-Displacement Recommendations

| Source | Recommendations | |
|---|---|---|
| | Force † | Displacement |
| Dreyfuss (1959) | 1.15 - 3.06 N | 0.47 cm |
| Deininger (1960) | 0.98 - 3.92 N | 0.08 - 0.48 cm |
| Pollock and Gildner (1963) [1] | 0.56 - 2.23 N | 0.71 - 1.59 cm |
| Kinkead and Gonzalez (1969) | 0.25 - 1.47 N | 0.13 - 0.64 cm |
| Chapanis and Kinkade (1972) | 2.78 - 11.13 N | 0.32 - 3.81 cm |
| Stevens (1977) [2] | 0.278 - 0.695 N | — |
| Bullinger et al. (1987) [3] | 1 - 8 N | — |
| Greenstein and Arnaut (1987) | 0.25 - 1.47 N | 0.1 - 0.6 cm |
| Sanders and McCormick (1987) | 2.78 - 11.13 N | 0.32 - 3.81 cm |
| ANSI VDT Standard (1988) | 0.25 - 1.5 N<br>0.5 - 0.6 N* | 0.15 - 0.6 cm<br>0.2 - 0.4 cm* |

† all recommendations converted to equivalent force units
1 cited in Alden, Daniels, and Kanarick (1972)
2 pokeboard (membrane touchpanel mounted at 90 degrees)
3 push button; no recommendation is made for *sensor key*, although the distinction is made between push buttons and sensor keys for dimensions
* preferred range

Given differing dynamic responses of snap, elastomer, and linear spring keys, as illustrated in Figure 7, differences in preference and performance are inherent. Furthermore, problems relating to the methodologies employed in determining these guidelines (Deininger, 1960) make such discrepancies unsurprising, and greatly limit their utility.

Even within key technologies, there appears to be a wide range of acceptable values for force and displacement. The choice then is dependent upon the particular use for which the device is to be employed. As Flynn (1984) stated, "The sensitivity of membrane keypads must fit the application— from occasional one or two keystroke entries by a factory-worker wearing gloves to rapid keyboard entry of programs or data by a fast-fingered engineer" (p. 80). Although inadvertent actuation may be effectively reduced by increasing elastic resistance, Huchingson (1981) questions this strategy for control design in general, arguing that the optimal resistance for normal operation should not be exceeded in the attempt to reduce undesired inputs. Manipulation of resistance for this purpose results in a trade-off between what is best for speed and comfort, and what is best for safety or accuracy. A low RAF makes a switch easy to actuate, but may increase the frequency of accidental activations. Increasing the RAF reduces accidental activations, but may increase user fatigue and discomfort. In the design of a touchpanel intended for extended periods of use, an increase in resistance that, in turn, increases user fatigue is undesirable. Instead, other techniques for controlling inadvertent actuations would be more appropriate, such as strategic panel layout or use of an escutcheon overlay (i.e., one which has the effect of recessing the keys).

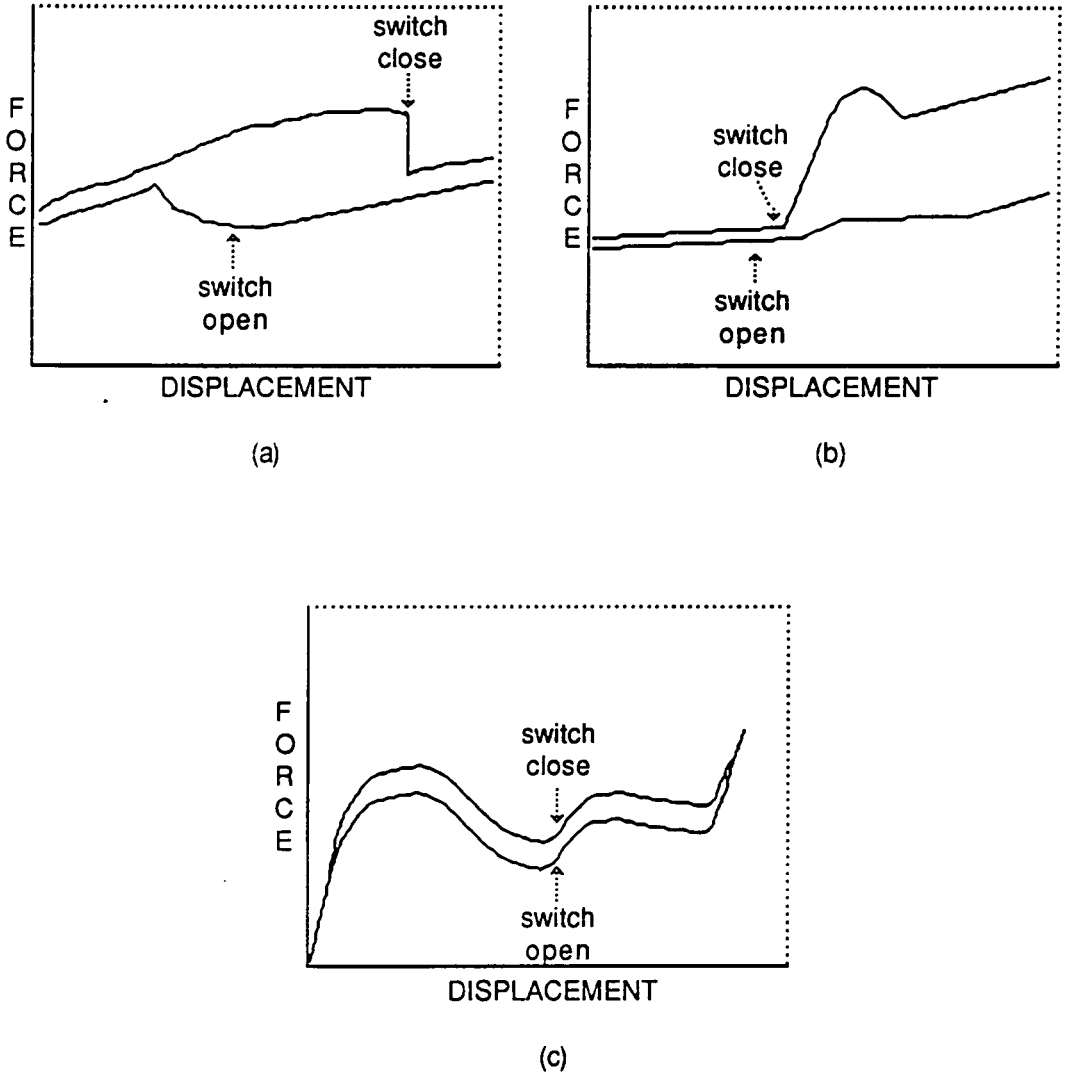



Figure 7. Force-displacement hysteresis functions for keyboards used in studies by Brunner and colleagues (a) snap-spring key with marked hysteresis; (b) foam-pad key with minimal hysteresis; (c) elastomer key with no hysteresis (Brunner, Marken and Briggs, 1984; Brunner and Richardson, 1984). Hysteresis describes the tendency of the switch to remain in its closed position during part of the return stroke of the keypress.

*Feedback*

Normally, one of the favorable characteristics of elastic resistance is the feedback it provides regarding displacement (Chapanis and Kinkade, 1972). In membrane switches, the amount of displacement is virtually imperceptible to the human user (Loeb, 1983; Pollard and Cooper, 1979; Roe, 1984). As the amount of elastic resistance is increased or decreased, the user may be completely unaware of such changes; hence, it is unable to provide salient feedback.

Research addressing key feedback has been conducted, primarily using full-travel keyboards, although a few studies using force-sensitive or capacitive technologies exist. Many studies cite the necessity of adequate feedback and some even recommend the addition of supplemental feedback. Pollard and Cooper (1979) reported that errors on no-travel membrane keys can be as high as 20 percent when no supplementary feedback is provided. In typing, feedback appears to be more important for the expert typist than the novice, and especially important upon initial exposure to a new keyboard (Brunner and Richardson, 1984). This reliance on feedback appears to hold for kinesthetic (West, 1967) and auditory (Brunner and Richardson, 1984) modes. Even with full travel keyboards which generally exhibit a high level of kinesthetic feedback, supplementary auditory feedback in the form of an electronically generated click was not only found to be preferred, but also to yield small (but significant) improvements in text entry time as compared to a similar keyboard without supplemental auditory feedback (Monty, Snyder, and Birdwell, 1983). Adams

(1968) concluded that while some type of feedback is required for learning, no one type is essential.

Klemmer (1971) disagreed, suggesting that visual feedback is crucial, particularly in the early stages of learning and for the maintenance of home-row location, while auditory feedback is of little importance. West (1957) found that deprivation of visual feedback did not affect speed, but impaired accuracy. He suggested the desirability of unlimited use of vision in learning, since visual feedback appears to act as a source of guidance for responses, as a source of positive and negative feedback, and as a means for reducing the tensions and anxieties associated with non-visual work.

Clare (1976), however, presents a case for kinesthetic or tactile feedback over other types of feedback. Kinesthetic feedback provides information regarding movement or displacement; tactile feedback provides information regarding contact of the finger with the membrane surface. Clare (1976) stated:

> When pushed, a button should provide a stimulus closely related to the action potential of pushing....
>
> Some sounds provide inadequate feedback because they are not sufficiently time-definitive in relation to the action that initiated them. Visual completion signals (lights, CRT displays, etc.) are also unsatisfactory, because they aren't natural consequences of the tactile action potential of pushing.
>
> ...the natural or expected consequence of a push is a tactile response (p. 99).

Kinesthetic feedback has been implicated as an important component in the self-detection of errors. It is estimated that 70% of all errors in keying tasks are self-detected (Klemmer, 1971). Rabbitt (1968) demonstrated that correction response times following self-detected errors were shorter than correct re-

sponse reaction times. Nakatani and O'Connor (1980) found that over 80% of all errors could be self-detected and corrected when speech, rather than simple auditory tone feedback, was provided. They also found that speech feedback resulted in slightly faster touch keying than auditory tone feedback.

Rosinski, Chiesi, and Debons (1980) emphasized the importance of the task requirements in determining the utility and effectiveness of feedback. Where errors must be monitored and corrected, they suggested that visual feedback can be extremely beneficial. Where the emphasis is on initial speed and accuracy, however, there is no advantage to the provision of visual feedback.

Further evidence suggesting that feedback is unnecessary, or even undesirable, exists. In a study by Leonard and Newman (1964), subjects were able to achieve and maintain high speed and high accuracy levels in a typing task without immediate augmented feedback. Keele (1968) found that motor skill patterns can survive the elimination of kinesthetic feedback. Studies of experienced typists support the hypothesis that augmented feedback may be withdrawn without undesirable consequences after the keyboard has been learned (Diehl and Seibel, 1962; Galitz, 1965; Leonard and Conrad, 1963).

Kinkead and Gonzalez (1969) and Deininger (1960) contended that kinesthetic feedback from key displacement is not necessary for efficient keying performance. In the study by Kinkead and Gonzalez, snap-action feedback increased the number of errors in data entry. The authors did not attempt to optimize the snap-action feedback used in their study; they caution against unqualified generalization of their findings. They concluded that the specific type

of snap-action feedback (or specific aspects of the type of feedback) used in the study may be undesirable. Deininger (1960) stated that additional feedback is unnecessary in a key that has desirable force-displacement characteristics. Membrane keys may present the exception, however, due to their negligible displacement.

Klemmer (1971) noted that the advantage gained from kinesthetic feedback is offset by the additional time and work involved in pressing a key with displacement. He suggested efforts to evaluate keyboards requiring virtually no force and no displacement. Roe, Muto, and Blake (1984) described studies in which this has been done. They investigated two levels each of kinesthetic (metal domes), tactile (embossed key boarders), and auditory (electronic tones) feedback in a full factorial design. A significant effect of feedback on keying performance and subject preference was found. Auditory feedback was most effective in reducing errors of omission and improving subject preference when combined with domes and/or embossing. No preference was found for embossed or non-embossed keypads except for configurations with tone and no dome, where embossing was preferred. Thus, it appears that users desire auditory feedback as well as some type of tactual cue as to key location, whether it is an embossed key border or a bubble in the center of the key created by a dome. This result suggests that feedback, at least to some extent, is preferred.

One weakness in these studies, however, was the confounding of the provision of both tactile and kinesthetic feedback with actuation force, and the failure to account for force differentials in the analyses. The addition of tactile

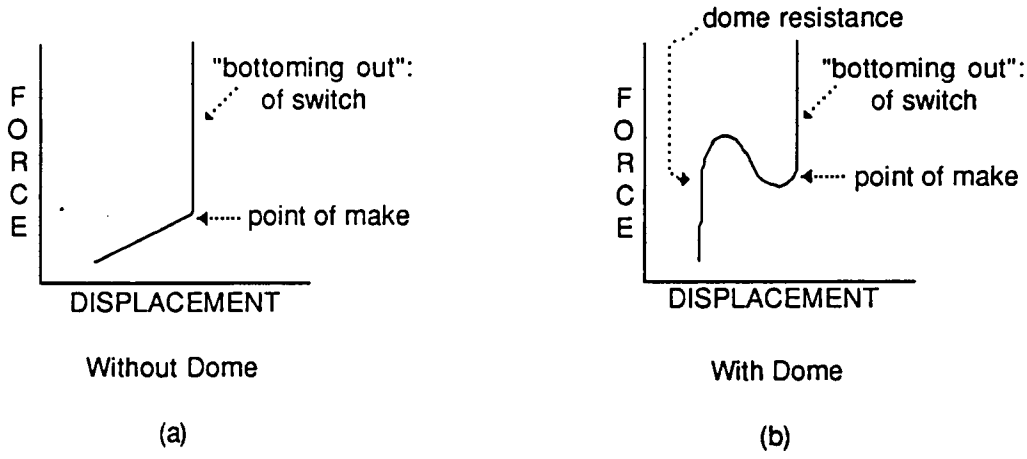



Figure 8. Force-displacement characteristics for (a) membrane switch, and (b) membrane switch with dome (adapted from Meleard, 1984).

domes to membrane switch construction results in an increase in RAF, as well as a change in the resistance characteristics, as illustrated in Figure 8. Furthermore, the specific type of domes used can affect switch operation and feel.

Three types of collapsible domes are available which provide tactile/kinesthetic feedback in membrane switches; each type has its own limitations. In one type, a *dome* is created in the membrane graphic overlay using heat forming processes during manufacturing. The limitation of this type stems from the difficulty in maintaining close tolerances in manufacturing. Inconsistencies in dome formation result in variances in elastic resistance of the overlay, thus affecting RAFs across the panel.

In a second type of dome construction, conductive domes replace the printed contacts on the upper membrane ply. Here, the dome is an integral part of the switch, making contact with the substrate ply electrodes when deformed. Because this shorting of the domes upon contact causes rapid structural fatigue, switch life is decreased, compromising the desirability of conductive domes as a feedback option from a reliability standpoint.

The third type of dome configuration makes use of metallic or polyester domes placed between the graphic overlay and the membrane, as shown in Figure 9. Placement of the dome outside the electrical field prolongs its life, yet still provides tactile and kinesthetic feedback. However, the dome tends to have a shorter life expectancy than the membrane switch, depending on the actual

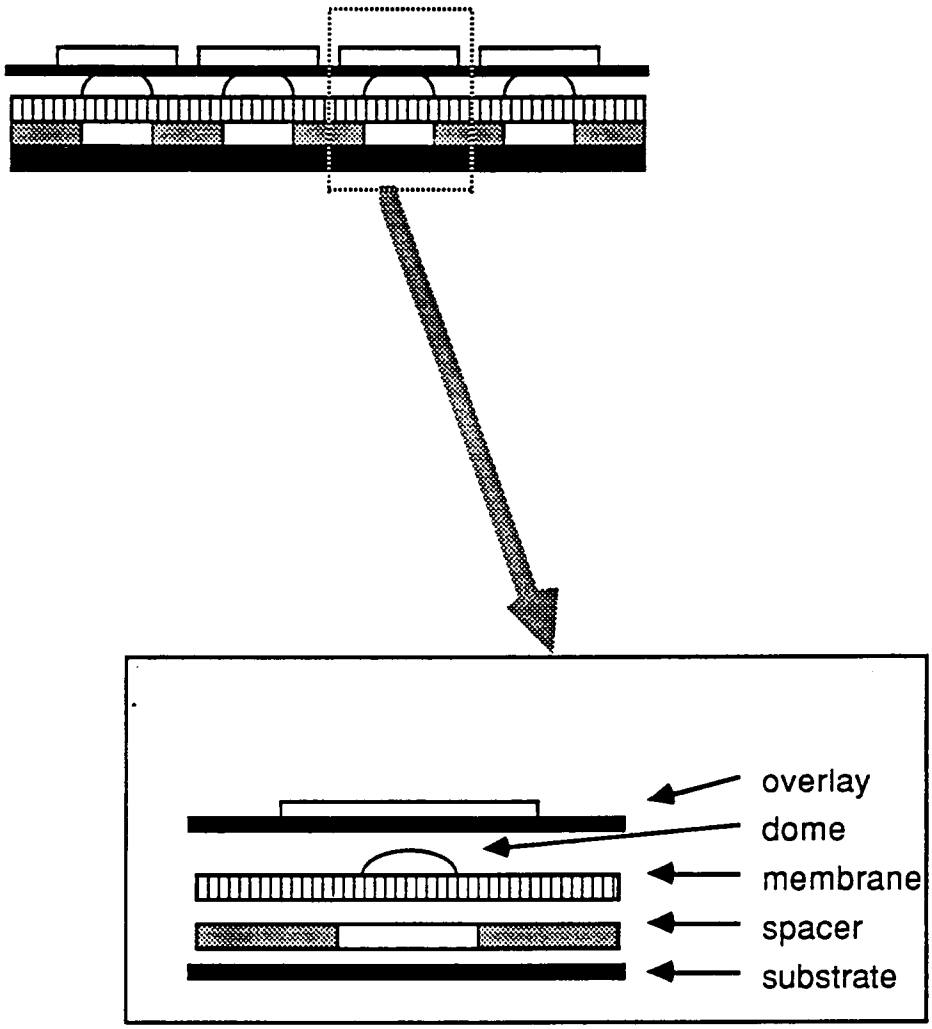



Figure 9. Membrane switch with non-conductive dome.

characteristics of the dome. While failure of the dome in this configuration results in a loss of feedback, it does not necessarily result in switch failure (failure to break contact), as does fatigue of the conductive dome. This result makes non-conductive domes the preferred of the three alternatives, by providing feedback that is consistent across a panel without seriously impairing switch life.

The specific design parameters of the dome itself affect the resulting feel. Byxbee (1987) discusses the relationship between dome design and the resulting response or feel, noting that domes may yield a *crisp* or *squishy* feel, depending on factors such as the chemical composition, physical properties, and thickness of the material from which they are formed, deburring or stress relieving processes used, plating, and the specific geometry of the dome. He notes that it is difficult to "spec" the subjective tactile feel, but that the resulting feel can be modeled in terms of its construction parameters, as can the expected life of a dome so constructed.

It appears that specifying the *optimal* force and displacement, or even an acceptable range of these parameters for a key, membrane or otherwise, is not very simple. It does not seem advisable to attempt to generalize from one key technology to another, because the individual factors are not independent. To date, there has been no systematic attempt to identify those factors which impact the preferred force and displacement characteristics, perhaps because the variables are numerous and the relationships are vague.

While membrane switches are characteristically non-travel devices, the addition of key cap overlays minimizes some of the technology's shortcomings with respect to feedback. With key cap overlays, the travel (and appearance) of conventional keys can be reproduced, while maintaining most of the environmental ruggedness associated with membranes. Furthermore, unlike tactile domes, no evidence has been provided to indicate that key cap overlays decrease switch life. In fact, by increasing feedback to the user, key cap overlays might prolong switch life by reducing excessive applied forces.

*Aesthetics in Touchpad Design*

The graphics overlay is an important component of the membrane switch, as it is the visual interface between the touchpad and the user. The overlay serves not only a cosmetic, but also a functional purpose—that of designating the key locations, dimensions, and functions through the use of text, color, texture, shape, and graphics.

A problem arises from the independence of actuation area and key size in membrane switches, as shown in Figure 10. The actual contact area is indistinguishable from the surround. Pressing a membrane *key* is not sufficient for activation; a downward force of sufficient magnitude must be exerted in the actuation area to close the contacts. If the force is mis-located, the contacts are prevented from closing by the spacer, resulting in the failure to make contact and omission of the input. Although both full-travel and membrane keys are actuated by a finger of the same anthropometric proportions, and despite the fact that key dimensions are independent of displacement, guidelines for key

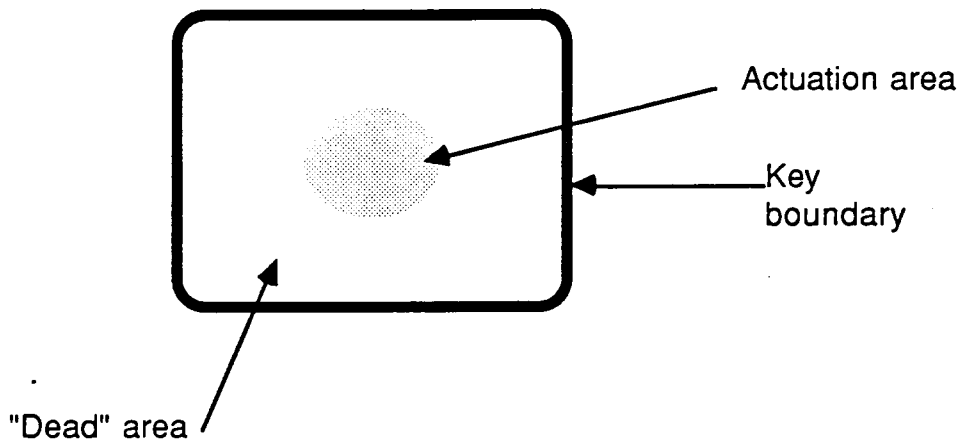



Figure 10. Key dimensions depicted on the graphics overlay versus actual contact area.

dimensions emanating from full-travel key research cannot be generalized to membranes. Increasing the size of a full-travel key top increases the target size; increasing the size of a membrane key designation does not. Moreover, increasing the dimensions of the key designation on the graphics layer increases the disparity between the apparent and actual key size. This may adversely affect performance through an increase in the number of errors of omission, as the visual feedback of finger placement is not indicative of placement relative to the actual target. Decreasing key size to more closely approximate the spacer aperture size is not a viable alternative, as it would require keys which are too small for finger actuation. Conversely, increasing the spacer aperture diameter shortens switch life, as the membrane tends to sag after repeated use, leading to its failure to break contact (Ford, 1983). This tendency to sag increases with greater exerted forces.

Although the influence of the graphics overlay on performance has not been addressed at length in the literature, Chapanis and Kinkade (1972) implied an effect of aesthetics on operator performance, in particular, on the user's subjective response to the mechanical characteristics or *feel* of a control. Additionally, the finding by Brunner, Marken, and Briggs (1984) that aural feedback affects users' perceptions of the feel of the key action suggests that aesthetics and other indirect factors may influence users' perceptions of control operation and have the potential to affect performance. Furthermore, membrane switch overlay aesthetics affect the user's perception of the product. As Flynn (1984) stated, "Proper switch appearance is important to create a psychological effect of operator confidence in the machine's efficiency" (p. 79).

*Keypad Configuration*

Several studies have investigated performance and user preference for keyboards and keypads of different heights and angles of orientation. Table 2 summarizes the results of these studies. The recommended heights and angles are specified with reference to the supporting surface. Except for Cooper (1976), these studies failed to demonstrate any effect of angle on performance. As for height, there is a preference for moderately high keyboards (in spite of Deutche Industrie Norm [DIN] standards which specify keyboard heights to be less than or equal to 30 mm), although performance differences are equivocal (Burke, Muto, and Gutmann, 1984; Cushman, 1984). Although keyboard height recommendations are made in reference to the height of the supporting surface, only the ANSI VDT Standard (1988) includes recommendations for table height. To the extent that table height influences performance, the results of supporting surface-referenced heights are difficult to interpret.

The keyboard angle and height studies included variables such as speed of entry, error frequency, and subjective preference. The variables of fatigue and physiological trauma were not addressed.

Although no universal standard exists, several alternate key logics for numerical keypads have been evaluated. Two key logics, the *telephone* arrangement (Figure 11a) and the *calculator* arrangement (Figure 11b) have received the most attention. The findings of numerical key logic research are summarized in Table 3. The *telephone* arrangement has been demonstrated to be equal to or slightly better than the calculator arrangement. Nonetheless,

Table 2. Summary of Keyboard Angle and Height Research and Recommendations.

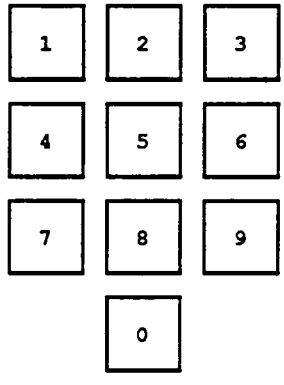
| | |
|---|---|
| Scales and Chapanis (1954) | Found no significant difference in the time taken to key 150 sequences on keypads mounted at eight angles between 0 and 40 degrees. Used eight telephone operators as subjects. |
| Galitz (1965) | Found no significant differences in performance using keyboards mounted at 9, 21, and 33 degrees although 21 degrees was preferred. |
| Dreyfuss (1967) | Recommends 11 degrees as the optimum and 20 degrees as the maximum keypad angle. Cites no research. |
| Armbruster and Frädrich (1970) | Found no significant difference between keying errors on keypads mounted at 25 and 90 degrees. † |
| Cooper (1976) | Found a significant effect of angle on keying rate, but error rate was independent of angle. Recommends keypad angle of 25 ± 10 degrees. |
| Suther and McTyre (1982) | Found no significant difference in performance using keyboards mounted at 5, 10, 15, and 25 degrees although 10 and 15 degree keyboards were preferred. † |
| Emmons and Hirsch (1982) | Found performance to be superior on 38 and 45 mm over 35 mm high keyboards, for slopes greater than 5 degrees. |

† confounded keyboard angle with keyboard height

Table 2 (continued).

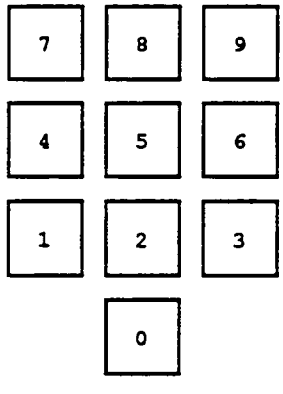
| | |
|---|---|
| Hansen (1983) | Found no performance differences for keypads oriented at 0, 15, and 25 degrees, although 15 degrees was preferred. |
| Abernethy (1984) | Found finger posture differences between 30 mm (8 degree) and 66 mm (12 degree) keyboards. Undesirable "curl" of fingers found with 30 mm/8 degree keyboard. |
| Burke, Muto, and Gutmann (1984) | 64 and 84 mm high keyboards were preferred over 35 and 104 mm high keyboards when oriented at 11 degrees, although there were no performance differences. |
| Cushman (1984) | Error rates were lower for 74 mm high keyboards than 70, 78, 82, and 86 mm high keyboards, when oriented at 14 degrees. Subjects' preferred height for the home row was 5 to 10 cm above elbow height. |
| ANSI VDT Standard (1988) | Defines the appropriate angle and height in terms of the user's posture. Specifically states that the angle between the upper arm and the forearm should be between 70 and 135 degrees and the angle between the forearm and the superior frontal plane should be between 70 + Y/2 and 90 + Y/2, where Y is the seat back angle from the vertical. Recommends keyboard slope between 0 and 25 degrees. |

**telephone layout**




(a)

**calculator layout**




(b)

Figure 11. The *telephone* (a) and *calculator* (b) three-by-three-plus-one matrix numerical key logics.

Table 3. Results of studies investigating the relative superiority of *Telephone* or *1-2-3* and *Calculator* or *7-8-9* Numeric Key Logics.

| Study | Preferred layout | | Variable |
|---|---|---|---|
| | 1-2-3 | 7-8-9 | |
| Lutz and Chapanis, 1955 | X | | expectancy |
| Deininger, 1960 | - | - | speed |
| Minor and Revesman, 1962 | X | | speed |
| | X | | accuracy |
| Paul et al., 1965 | - | - | |
| Conrad and Hull, 1968 | - | - | speed |
| | X | | accuracy |
| Seibel, 1972 | X | X | practice |

- : not significant

ANSI Standard X4.6-1979 specifies the 7-8-9 key logic as the standard for adding and calculating machines (ANSI, 1979) and the International Standard Organization specifies this logic as the standard for all office machine and data processing equipment keypads (ISO, 1976). The calculator arrangement has been used by convention in computer and accounting machine interfaces for decades. The ANSI standard notes the criterion for acceptance of this logic as the retraining problem which would result from changing to another key logic (ANSI, 1979).

The "telephone" arrangement is used on some electronic cash registers and is the recognized standard for telecommunications devices worldwide, aircraft keypads in the United States and United Kingdom, and keypads aboard the National Aeronautics and Space Administration's space shuttle (Koppa, 1985). The ANSI Standard for Human Factors Engineering of Visual Display Terminal Workstations (1988) noted that key logic is application-dependent. It recommended either of the two layouts shown in Figure 11. Until recently, the distinction between telecommunications and accounting-type devices was a clear one. However, the distinction between these types of equipment is diminishing, as computer keypads are used as interfaces for telecommunications systems and telephones are used to enter data via remote. Noting the slight superiority of the 1-2-3 key logic, Potosnak (1988) predicts increased usage of this key logic on computer keyboards as a result of "proposed additions of telephone-related functions to computer terminals."

*Fatigue*

Fatigue has been defined as

> ... all those determinable changes in the expression of an activity which can be traced to the continuing exercise of that activity under its normal operational conditions, and which can be shown to lead, either immediately or after delay, to deterioration in the expression of that activity, or, more simply, to results within the activity that are not wanted. (Bartlett, 1953 , p. 1)

Identifying the effects of fatigue on performance, however, is not as simple as determining the time at which performance (operationally defined as speed, accuracy, etc.) begins to deteriorate. Frequently, the onset of fatigue is accompanied by continued performance at previous levels or an apparent increase in the level of performance. This is attributable to the fact that an operator can adopt a criterion of acceptable performance and maintain that level for one or more aspects of the task, while other aspects of performance deteriorate (Singleton, 1953). To the extent that the performance attribute emphasized by the operator is that which is being monitored, performance levels may be maintained in the presence of fatigue. Previous studies have asserted that performance decrements resulting from fatigue may be masked by augmented efforts by the operator (Goldmark, 1912; Wells, 1912). As Welford (1953) stated:

> When the task is such that it can be carried out in several different ways, and is not rigidly constrained to one, it would appear that the decline of overall achievement is preceded by changes of method which compensate for the growing impairment of one part of the system by shifting the burden on to another....
> ...it seems safe to assume [that analogous changes could be] demonstrated for fatigue if performance were studied in sufficient detail (p. 189).

Thus, the probability of effectively identifying a fatigue effect might increase as the number of relevant dependent measures of performance which are monitored increases.

In certain tasks, specifically those where dependent measures of fatigue can vary independently and where performance is repetitive rather than serial, fatigue results in a relatively straightforward decrement in performance, preceded by a temporary improvement of overall achievement (Welford, 1953). This performance improvement, however, is typically short-lived. Welford explained that the improvement is associated with a substitution of methods, or an alternative strategy, for accomplishing the task. Such alternatives are seldom as efficient as those they replace and may in fact require greater effort to sustain. As a result, performance eventually deteriorates due to fatigue.

Thus, the performance effects of fatigue may elude identification and quantification unless the dependent measures include the specific performance component which changes with fatigue. In instances where a subject is specifically instructed to maintain certain performance criteria (e.g., speed or accuracy), the performance component that is impacted by fatigue will likely be a less direct and obvious one. The primary performance criterion may be maintained at near-constant levels; what may change is the strategy or method (or some subtle aspect thereof) used in carrying out the task.

*Cumulative Trauma Disorders, Keying Tasks, and Force*

Much research has been devoted to the study of fatigue and cumulative trauma disorders (CTD) in keying. Keyboard users have been identified as be-

ing at high risk for CTD. Pre-existing conditions which impair circulation, result in edema of the upper extremities, or otherwise impact various aspects of the circulatory, skeletal, and/or neurological systems of the body have been implicated in provoking or complicating CTD (Cannon, Bernacki, and Walter, 1981). Keyboard design, workstation design, work methods, working conditions, and demographic variables have been cited as factors which contribute to CTD and fatigue among keyboard users. (Kroemer, 1972; Tichauer, 1978). CTD has also been referred to as an *occupational neurosis.* This label stems in part from the demography of its victims, who tend to be young to middle-aged, predominantly female workers in low-paying, monotonous occupations, for whom there is little financial reward for productivity, but rather where job security rests upon a stated level of productivity (Ireland, 1986). Still, forensic pathological examinations of the carpal tunnel (e.g., Armstrong, Castelli, Evans, and Diaz-Perez, 1984) and other research findings overwhelmingly support the existence of CTDs.

CTDs appear to be induced more by the the repetitive nature of tasks than the force levels (Armstrong, Fine, and Silverstein, 1985; *Hettinger's Hypothesis* (Hettinger, 1958, cited in Kroemer, 1972). However, force has been identified as a contributing factor in CTDs in general (Silverstein, Fine, and Armstrong, 1986), and in keying tasks in particular (M. Laidlaw, personal communication, July 1988).

Haaland, Wingert, and Olsen (1963, cited by Alden et al., 1972) studied the amount of force that could be applied by the various fingers. They found decreasing strength from the thumb to the smallest finger and determined that

anatomical differences in the fingers themselves accounted for the effect. It was also found that the position of the finger affected the amount of force that could be applied. When the finger is held rigidly, it can exert a greater force than if it is permitted to hyperextend at the distal interphalangeal joint.

Practice has been implicated in the ability to perform finger tapping motions. Jackson (1953) found tapping rates of typists to be faster than non-typists. This seems to indicate that the speed achieved by an expert typist is not simply a result of learning the locations of keys on the keyboard, but also that there is a degree of motor learning and dexterity which develop. Jackson also found differences among tapping rates by finger, the index and middle finger being able to tap faster than the thumb, ring, and little fingers (Table 4).

Creamer and Trumbo (1960) studied the relationship between multiple-finger tapping performance and the angle of orientation of the two halves of a keyboard. An effect of orientation was found, such that ulnar deviation, which Kroemer (1972) noted is necessitated in the use of keyboards of one-piece design, resulted in a decrease in the maximum force which could be exerted.

Haaland et al. (1963) determined that the orientation of finger pressing affected not only the amount of force that could be applied, but also the rate of fatigue, with lateral forces resulting in more rapid fatigue than downward forces. It was also found that the resistance to fatigue varied from finger to finger, with the resistance highest for the index finger and lower for each successive finger, the little finger being most susceptible to fatigue. However, it was noted that practice increased the capacity for sustained contraction without fatigue.

Table 4. Mean Tapping Rates per Second (Jackson, 1953).

| | No. of Subjects | Wrist | Thumb | Index | Middle | Ring | Little |
|---|---|---|---|---|---|---|---|
| Men overall | 10 | 6.20 | 4.95 | 5.53 | 5.59 | 5.39 | 4.87 |
| Women overall | 10 | 5.92 | 5.50 | 5.73 | 5.77 | 5.54 | 5.20 |
| Whole group | 20 | 6.02 | 5.23 | 5.63 | 5.68 | 5.47 | 5.04 |
| Women non-typists | 5 | 5.78 | 5.29 | 5.56 | 5.41 | 5.18 | 4.90 |
| Women typists | 5 | 6.06 | 5.70 | 5.89 | 6.12 | 5.89 | 5.51 |

The characteristics of the keyboard have an impact on the amount of trauma or fatigue to the hands and wrists. The foregoing discussion of force may seem to imply that the resulting trauma or fatigue is limited to keyboards which require higher forces for actuation. This, however, is not always the case. Brunner and Richardson (1984) asserted that it is virtually impossible to type successfully on an "instable key action" (i.e., one with a low RAF), without exercising some form of muscular or kinesthetic compensation. In their study, typists reported localized wrist fatigue after using a low resistance, low feedback keyboard. The fatigue is believed to arise out of the compensatory contractions required to overcome gravitational forces and refrain from entering spurious input.

Keyers are at increased risk for cumulative trauma disorders and fatigue. In addition to frequency, undesirable hand/wrist postures, actuation forces which are too high or too low (or applied forces that are too high), static muscular loading, various characteristics of the keyboard, and certain medical conditions have been identified as contributors to CTD. Practice, keying strategy, and keyboard orientation have been found to influence speed of entry and susceptibility to fatigue.

*Measurement of keying force.* The amount of force applied to a keyboard by a user has, to a limited extent, been studied subjectively and objectively. Young and Barton (1983) developed a means for measuring the amount of force exerted on a keyboard. Their objective was to develop a technique for recording which keys were pressed and the time at which they were pressed. They saw the need for a simple, semi-automated technique for accomplishing

these measurements, noting that photogrammetry, a commonly-used technique in kinesiological studies, did not provide a high level of precision, was time-consuming to analyze, and provided no information on the forces applied, a variable which might be of interest. Young and Barton developed a force-platform concept which enabled them to obtain the location and timing of key presses on a calculator. The force platform could be used with virtually any calculator without further instrumentation or modification of the calculator itself, permitting them to measure subjects' performance on their own personal calculators.

Young and Barton's system used seven thin film cantilever beam force transducers, four of which measured vertical forces, two longitudinal, and one which measured lateral forces. The platform was calibrated by pressing the extreme keys in the keyboard matrix (the corners), which enabled mapping of subsequent key presses based on a combined forces measured algorithm.

While the Young and Barton system is a force measurement device per se, the data actually collected using it were *based* on the forces measured, but did not make direct use of the actual force measurements. The transducer outputs were used to calculate x-y coordinates of a keypress based on a differential-forces algorithm, but the authors did not report applied forces data.

In a more recent study, Carr (1988) used strain gauge force transducers to measure the forces exerted on a hand calculator. This system entailed modification of the calculators used, inserting aluminum plungers through holes in the back of the calculator. When the keys were pressed, the plungers transmitted forces to a strain gauge located below. Seven keys of the calculator were

instrumented in this manner, and peak forces applied to each key during a keying task were compared. It was found that the maximum forces applied varied as a function of key location and subject. A tendency toward a decrease in force after several repetitions of a given key was found. Furthermore, a significant effect of gender was found with regard to the percentage of maximum force capacity exerted.

Two problems are inherent in Carr's instrumentation and methodology: first, the relatively complex and invasive plunger system may have altered the fundamental characteristics of keypad function and feel, thereby confounding idiocyncracies of the force measurement system with the force measures obtained. Secondly, subjects began the experimental session by exerting their maximum pushing force on a key of the same, or similar, design as those used on the calculator; thus, it is likely that subjects were aware that force was being measured as a part of the study. Such knowledge might have biased their keying behavior and hence, the forces applied.

In addition to the quantitative techniques used by Young and Barton and by Carr, qualitative measures of applied force have been used to assess keying behavior. In her studies evaluating the conditions surrounding CTD in VDT keyboard operators, Laidlaw (M. Laidlaw, personal communication, July 1988) relied on the ratings of third-party observers to determine the amount of force exerted on the keyboard. Observers classified keyboardists as "high-", "medium-", or "low-force" keyers based on visual observation. These force ratings were positively correlated with the existence of CTD (i.e., high-force keyers demonstrated a higher instance of CTD). Perhaps third-party

observation may be regarded as another method for qualitatively assessing the forces applied at the finger/keyboard interface. These observations are subjective, however, even though correlated with objective data, the existence of CTD. Third-party observation at least permits the utilization of a standard criterion, which is not afforded by first-party users' subjective opinions.

*Subjective Preference and Performance Measures*

Typists' perceptions of their performance appear to be fairly accurate. When asked to judge their overall performance, subject ratings for four keyboards coincided with objective measures of performance, at least on an ordinal basis (Brunner and Richardson, 1984). Such findings seem to indicate that where objective measures are impractical or impossible, subjective measures may be used to at least get a general idea as to performance variables.

Where preference data are at issue, however, much care must be exercised to ensure that transient preferences are not accepted and acted upon. As Alden, Daniels, and Kanarick (1972) pointed out:

> Anecdotal evidence suggests that typists frequently report that they prefer the machine they are accustomed to using, but will change their preference after using a new machine for some period of time. Therefore, one may conclude that preference ratings must be interpreted very cautiously and should seldom, if ever, be the sole basis for design recommendations (p. 289).

In addition to typists' preference for keyboards similar to what they are accustomed to, there is also the potential for the novelty of a given alternative to influence immediate preference. These preferences may change as the novelty wears off, resulting in a return to pre-exposure preferences.

Furthermore, the confounding of the variables being measured with changes in visual appearance of the keyboard may bias subjective responses. While objective force measures can ignore such influences, subjective assessments are biased by them. Thus, subjective preferences must be used with care and, as suggested above, in conjunction with other, objective measures wherever possible.

*Stimulus Presentation and Keying Technique*

Different mental encoding strategies used by subjects also have an impact on keying time. Subjects may encode the entire sequence and then key it, or they may encode part of the sequence, key it, then return to the displayed stimulus and encode the remaining portion of the sequence before keying it. These differing keying strategies have a significant effect on keying time, although no effect on accuracy (Deininger, 1960). The encoding strategy used was found to be the most important factor influencing performance. However, the effects were found to be consistent across sessions and keyboards. Thus, within-subjects variability due to altering keying strategies is not a real concern, even across different keyboard configurations or sessions; however, between-subjects effects may be significant as a result of differing keying strategies. For maximizing entry speed in general, Klemmer (1969) recommends that digits be presented in groups of three or four. This stimulus length also minimizes between-subjects variability by virtually eliminating the necessity for repeated reference to the displayed stimulus, hence, differences in encoding strategy.

*Summary*

The amount of force required to actuate a membrane switch varies as a function of the switch construction. The membrane thickness, spacer thickness, and spacer aperture diameter may be manipulated to achieve a given RAF. Different combinations of these three parameters can yield the same or different RAF. Whether a membrane touchpanel user can perceive these differences in construction has not been investigated. Furthermore, guidelines for acceptable force/displacement characteristics have not been clearly established.

Membrane switches exhibit negligible displacement and as such are lacking in kinesthetic feedback. Feedback is considered important in control actuation. Users must have some indication as to when the switch is actuated, so that they may discontinue the application of force. Kinesthetic feedback also plays an important role in the detection and correction of errors. Because of their flat design, membrane touchpanels are also lacking in tactual feedback, unless options such as embossing are employed. The provision of supplemental visual and aural feedback has been shown to improve performance and preferences slightly, depending on the task and what other feedback is provided.

Touchpanel aesthetics have been identified as affecting the feel of the touchpad as well as the user's perception of the product. The graphic overlay also serves to provide the user with operational information, such as key location and function. The utility of various measures for designating key location,

such as embossing, recessing through the use of an escutcheon overlay, or the use of surface key caps, has not been studied previously.

With regard to keypad design in general, slight changes in the angle of orientation of the keypad surface (fore/aft slope) appear to have no effect on performance for angles less than 40 degrees from the horizontal (distal edge of keypad elevated), although some studies suggest that users prefer keypads oriented at 10 to 15 degrees (Table 2). Perceived fatigue is greater for forward as opposed to downward keying motions, suggesting that keypads oriented on a horizontal (or nearly horizontal) work surface, such as a desk top, are superior to those oriented on vertical work surfaces, such as a wall. With regard to keypad height, users in studies conducted in the United States prefer and perform better on heights which exceed the DIN standard of 30 mm, but just how high the keypad should be is unclear. Performance differences between numeric key logics are relatively small compared to the performance decrements associated with switching between key logics. Selection of the telephone or calculator key logic is still primarily application-dependent.

The keying task takes its toll on users who perform it continuously and forcefully while maintaining poor arm/wrist postures and/or static loading of the hand or wrist, or who are predisposed to occupational injury due to other risk factors. Cumulative trauma disorders, fatigue, and discomfort are reported by keyboard users under such conditions. Keyboard redesign has been proposed as one means for potentially reducing these problems. While users can generally learn to use any keyboard regardless of how poorly designed it may be (Klemmer, 1971), the implications for the health and productivity of the user

mandate responsible design. To gather valid data upon which to base design decisions, a combination of objective and subjective measures of performance and preference is required. Controlling for the contaminating effects of novelty and perceptual differences is also important.

*Research Needs*

In studies comparing conventional full-travel and membrane touchpads (e.g., Loeb, 1983; Pollard and Cooper, 1979), the full-travel varieties were found to be superior in terms of performance, preference for use, and quality perception. In the design of control panels for hostile environments, however, membrane touchpads are the only feasible alternative. Thus, there is a need for further study of the inferior membrane touchpad which would lead to improvements in its design.

Although there are no standardized test methods for evaluating membrane touchpanel performance and operation, tests such as those outlined in Oak Switch's Testing Handbook (1982) and in other sources are used selectively throughout industry (Ford, 1983; VanZeeland, 1984). In these test procedures, performance and reliability measures depend on conditions found only in the laboratory, in which contact testing and life testing of touchpanels using the minimal RAF for contact closure can be performed. Because the RAF and the force exerted by the user are not necessarily the same, unless the user accurately perceives the level of force required, he or she may exert a force which is unnecessarily strong or inadequate for actuation. Insufficient force will result in omitted input, while excessive force will lead to structural fatigue of the membrane and may contribute to user fatigue.

Acknowledging that excessive forces contribute to premature switch failure, the results of tests based on minimum forces would grossly overestimate the expected life for a switch used in a normal setting. A review of the literature fails to reveal any studies which have measured forces applied to membrane touchpads during normal use. Because this information is necessary to effectively assess expected switch life, it is desirable to know the range of forces applied to membrane keys by users and also how changes in switch construction and appearance may alter applied forces.

Furthermore, assuming that force is a factor in user fatigue and cumulative trauma disorders associated with keying, identifying those factors, if any, that tend to elicit greater forces may enable the reduction of excessive applied forces in extended-use applications through effective design. Hence a potential reduction in the incidence of fatigue and CTD among membrane switch touchpanel users could result.

In summary, there are certain relationships with respect to the amount of force exerted on a membrane touchpad which have not been addressed, as illustrated in Figure 12. Whether the RAF influences the force which is applied to a membrane touchpad by the user is unknown. Furthermore, there are alternate means for achieving a given RAF. How differing constructions affect the applied force has not been investigated. And, while an effect of aesthetics has been suggested as having an impact on the feel of the touchpad and on the user's perception of the product, these and the relationship between aesthetics and applied force have not been investigated, nor has the role of excessive

applied forces in eliciting subjective fatigue and performance decrements been assessed.

The objectives of this research are:

(1) to assess the amount of force applied to membrane switches by typical users;

(2) to determine the effect of switch construction on performance and on the amount of force applied;

(3) to evaluate the impact of various aesthetic overlays on users' perception of required force, quality, and on performance; and,

(4) to evaluate the relationship among excessive applied forces, subjective reports of fatigue, and objective measures of performance.

These objectives were addressed in two experiments which investigated the effect on applied forces of various means for achieving a given RAF through design and the relationship between RAF and the applied force. The first experiment investigated the effect of manipulations of the structural components of the membrane switch. The second experiment evaluated the influence of aesthetic overlay variations on applied force and preference.

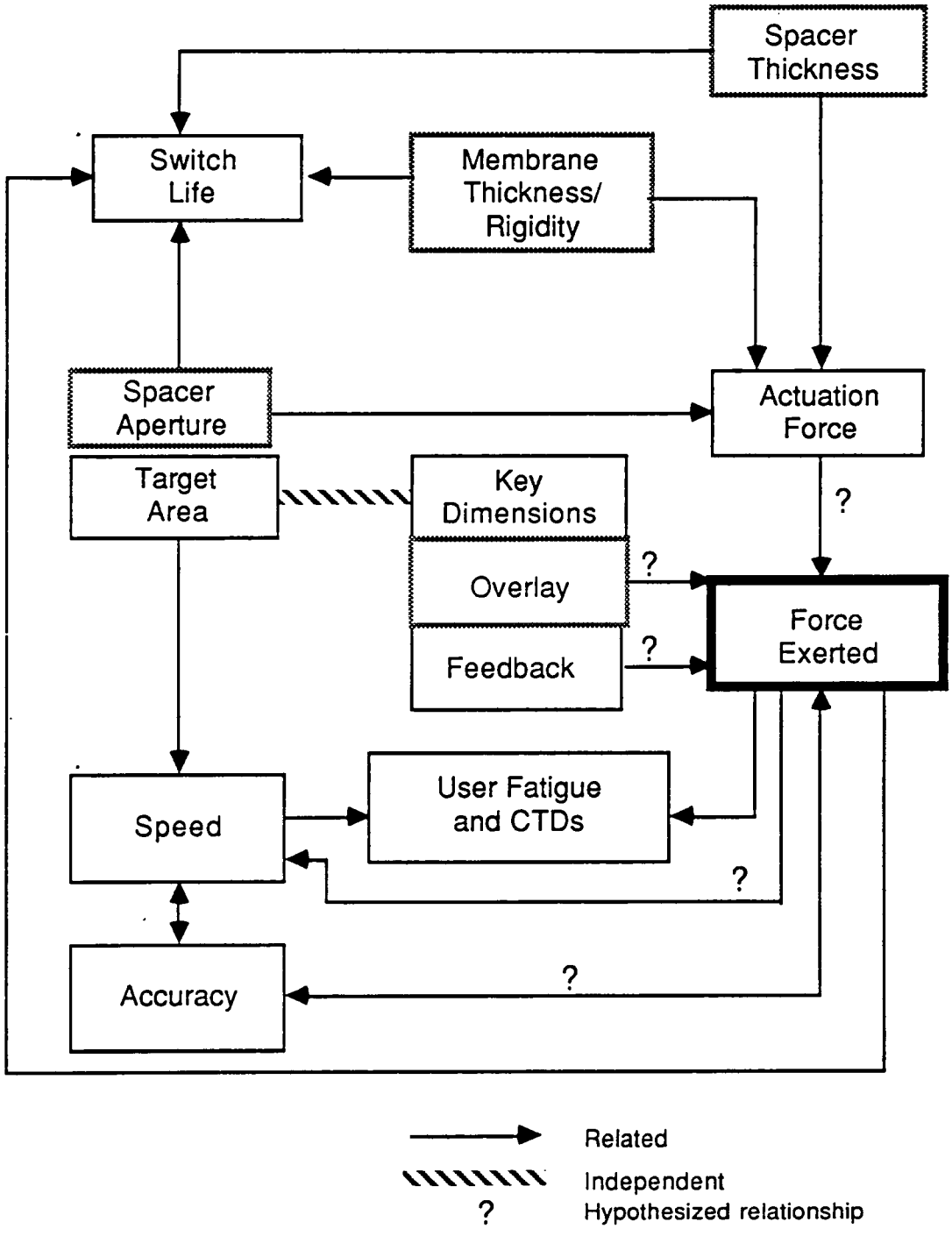



Figure 12. Relationship of variables in membrane switch research.

## EXPERIMENT I: SWITCH CONSTRUCTION

This experiment investigated the effect of membrane switch construction on performance. The three construction variables of spacer thickness (two levels), aperture diameter (three levels), and membrane thickness (two levels) were manipulated, and the 12 resulting configurations (which yielded 12 distinct RAFs) were tested.

### *Subjects*

Twenty-four persons, 12 male and 12 female, participated in this experiment. Subjects were volunteers, employees from Eastman Kodak Company, who participated during their normal working hours. All were novice keyers, although most indicated having used both 1-2-3 and 7-8-9 key logic input devices and membrane switch touchpads previously. None, however, performed numerical data entry using a 10-key input device in their primary job role.

### *Apparatus*

*Force measurement instrumentation.* The force measurement system was based on the one developed by Young and Barton (1983) and consisted of a rigid platform supported at each of its four corners. Seven miniature strain-gauge load cell force transducers (A.L. Design, Amherst, NY: Model ALD-Mini) were configured to measure the key presses, four vertically, two longitudinally, and one laterally. In this manner, forces about the axes of movement could be measured. The force measurement platform is pictured in Figure 13. The

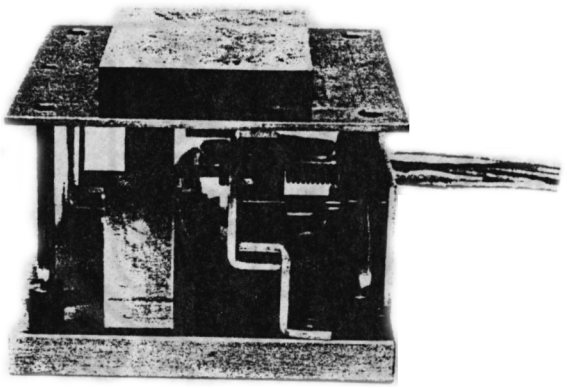


Figure 13. The force measurement system.

outputs from the transducers were each connected to a 60 dB differential amplifier. Outputs from the seven amplifiers were each fed to a 12-bit analog-to-digital converter (Burr-Brown, Model PCI-20089-1) interfaced with a Compaq 286 (14 MHz) microcomputer. A block diagram of the equipment is shown in Figure 14.

Strain-gauge load cell force transducers were selected due to their robust linearity and negligible hysteresis, as described by Wood (1987) and substantiated in the ALD-Mini product specifications.

Based on the maximum tapping rate determined by Jackson (1953), the Nyquist frequency for sampling was determined. Pilot studies indicated that sampling at this rate was insufficient as there was a desire to grossly characterize the force function of a keypress, rather than simply record the occurrence of an event. Thus, a sampling rate of not less than 100 Hz was determined necessary. A square wave signal from a function generator (Wavetek, Model 110b) controlled the sampling rate, configured as an external clock source to the A/D Board, as outlined in the PCI-20089-1 hardware manual (Burr-Brown, 1988). (During the course of the experiment, two function generators were used. While the first function generator was calibrated prior to the onset of testing, the second function generator was not. Post-testing calibration revealed that the second function generator was out of calibration. Thus, the effective sampling rate for some sessions was not 100 Hz, but 167 Hz. Since this was a higher sampling rate, it did not result in a loss of information. Subsequent handling of the data took into account which function generator had been used and adjusted time-based information accordingly.)

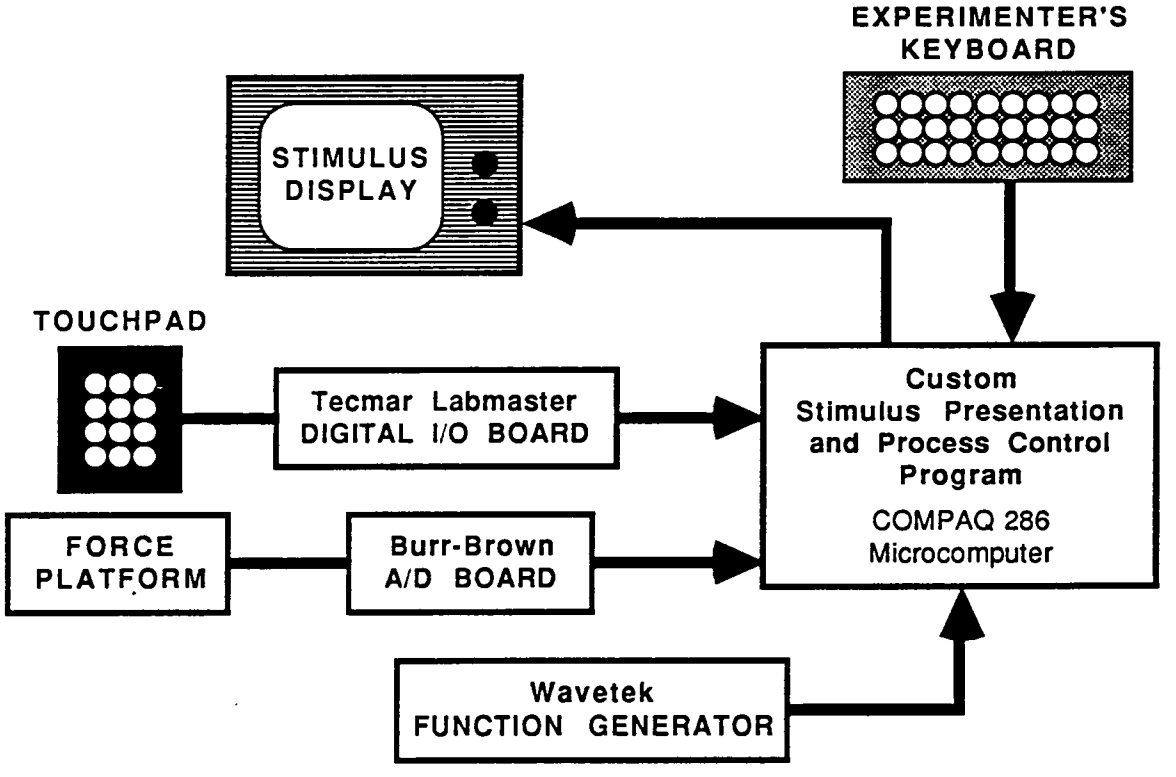



Figure 14. Block diagram of equipment used in Experiments I and II.

*Stimulus presentation and process control software.* A custom stimulus presentation and process control program was used. The program permitted logging of all subject demographic data, performed a self-calibration procedure, presented instructions to subjects, displayed the stimuli, controlled sampling of the load cells, monitored input from the keypad, administered auditory feedback, presented a questionnaire to the subject after testing on each touchpad was completed, and logged all data to a disk file. The program was written in compiled BASIC (QuickBASIC 4.5), incorporating the Burr-Brown PCI-20090S-1 software drivers. A listing of the program may be found in Appendix A.

The self-calibration procedure consisted of sampling the load cells at 1 Hz for 60 seconds before recording the mean A/D value and the variance, and setting a threshold value for sampling. The threshold value was set at four more than the maximum digital bit value (DBV) encountered during the calibration period, that is:

$$\text{Threshold} = DBV_{max} + 4. \tag{1}$$

This threshold was used to trigger the onset of a sampling interval. When the subject applied force to the platform (via the touchpad), data collection began once the threshold was exceeded. In terms of force, the threshold was equivalent to 1.08 N. Pilot testing demonstrated that the threshold level was well below typically applied force levels, and that no perceptivel change in touchpad function occurred upon implementation of the threshold/lockout algorithm.

Sampling continued until two conditions were met: (1) the force exerted fell below the threshold value and (2) a valid keypress had been recorded. The software incorporated an absolute lock-out mechanism to control switch bounce. This was accomplished by requiring that the measured force fall below the threshold value after a valid keypress, before another keypress would be accepted. A valid keypress resulted in the presentation of a 1000 Hz, 50 ms tone. Depression of an incorrect key, even if sufficient to make contact, did not result in presentation of the tone.

Because of microcomputer memory and array size limitations, a maximum sampling duration of 0.5 s per depressed key could be achieved. While this was sufficient for most presses, some presses exceeded this limit, particularly where the subject pressed the incorrect key. To overcome this limitation, the array was cleared and an array iteration flag was incremented and recorded, noting each time the 0.5 s limit was exceeded. Thus, data were collected for the last 0.5 s period of a keypress (when the valid actuation occurred) and the total duration of the keypress was known.

Information recorded included the array overflow counter described above, a time stamp at the beginning and end of each five-key sequence (four digits plus an "enter" key press), trial number (each trial consisted of one five-key sequence), stimulus, channel number, and time-stamped digital bit values for each of the seven load cells.

*Membrane touchpads.* Twelve three-by-four key matrix custom flat membrane numerical touchpads were used (Lucas-Duralith Corp.: Millville, NJ).

The membranes were vented and ESD/EMI/RFI shielded. The shielding mechanism entailed a trace printed in conductive ink around the perimeter of the touchpad and connected to ground via the pin-out connector, as described by Munson (1984). This construction is in contrast to other shielding methods (such as the incorporation of a foil layer beneath the overlay) which increase the RAF of the switch. The construction parameters for each of the 12 touchpads are presented in Table 5. All were identical in terms of key size, shape, labeling, and layout, utilizing the standard telephone layout (1-2-3 key logic with two function keys, Figure 15).

The touchpads were connected to a digital I/O board (Tecmar Labmaster, Model No. 200009) in the microcomputer, via a custom interface circuit .

*Stimulus display.* The stimuli were presented with white text on a dark blue background, within a red and yellow graphic box. Instructions to the subject were presented at the top of the screen and remained present throughout the session. The CRT was adjusted by the subject to preferred contrast and luminance levels.

*Workstation.* The touchpad was oriented horizontally, the top of the touchpad resting flush with the work surface, a vinyl-covered desktop (Figure 16). The desktop surface was supported independently of the force platform. Thus, only the area directly beneath the touchpad was force-sensitive, allowing subjects to rest one or both hands on the desk top while keying, without interfering with force measurements. The keypads were mounted on the force platform with a uniformly thin layer of adhesive (Scotch Brand Transfer Adhesive 924, 2 inch Tape) to permit proper and expedient location of all

Table 5. Construction Parameters for Touchpads used in Experiment I

Flat, non-tactile, non-embossed, channel-vented, ESD/EMI/RFI shielded 3 x 4 matrix numerical keypads. No rigid base plate. "Velvet finish" textured-surface polycarbonate overlay with polyester membrane, spacer, and substrate layer.

*Overlay graphics:* Background: black; Numbers and symbols: black, 18 pt. Helvetica Medium on white keypads.

| Touchpad Number | Overlay Thickness | Spacer Thickness | Spacer Aperture Diameter |
|---|---|---|---|
| 1 | 0.127 | 0.127 | 6.350 |
| 2 | 0.127 | 0.127 | 9.525 |
| 3 | 0.127 | 0.127 | 12.70 |
| 4 | 0.127 | 0.254 | 6.350 |
| 5 | 0.127 | 0.254 | 9.525 |
| 6 | 0.127 | 0.254 | 12.70 |
| 7 | 0.254 | 0.127 | 6.350 |
| 8 | 0.254 | 0.127 | 9.525 |
| 9 | 0.254 | 0.127 | 12.70 |
| 10 | 0.254 | 0.254 | 6.350 |
| 11 | 0.254 | 0.254 | 9.525 |
| 12 | 0.254 | 0.254 | 12.70 |

(all dimensions are mm)

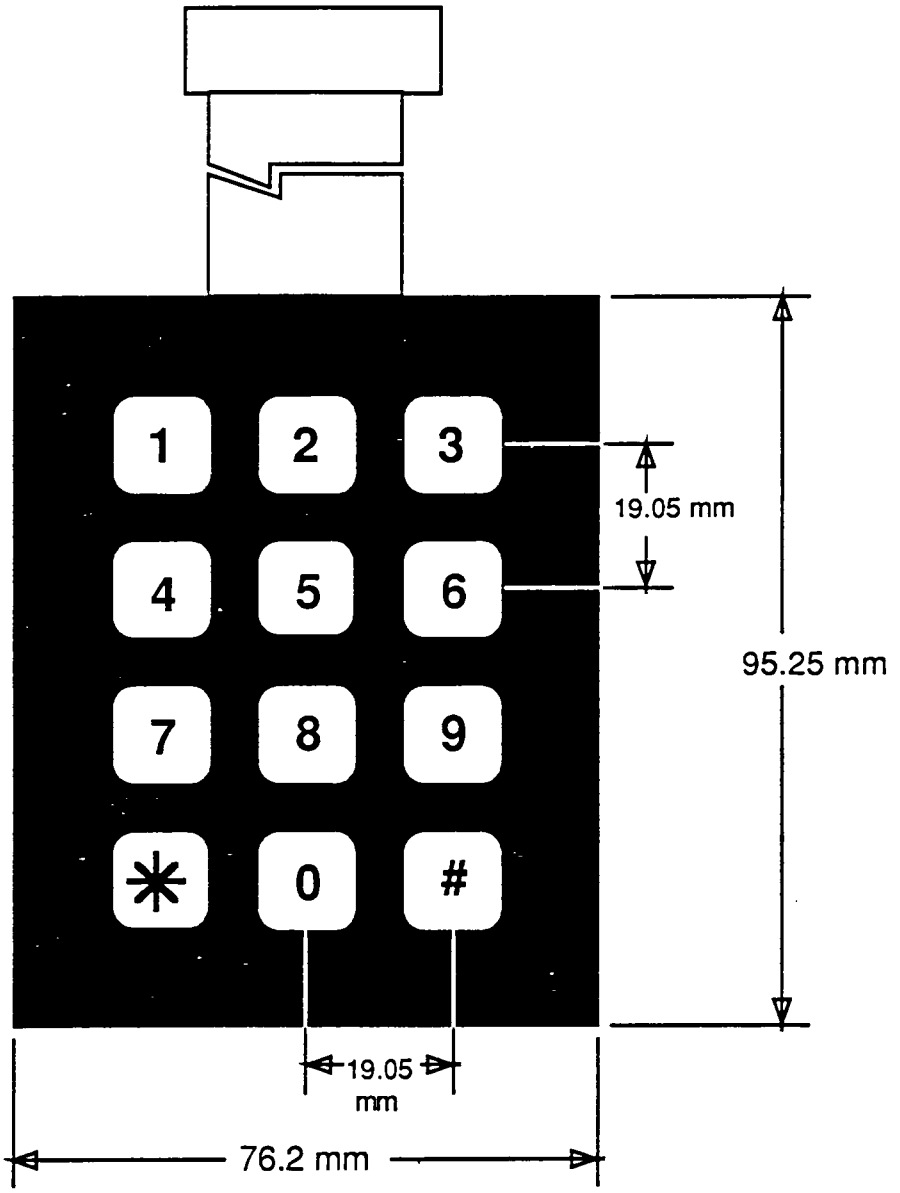



Figure 15. Size, shape, labeling, and layout of touchpads used in Experiments I and II

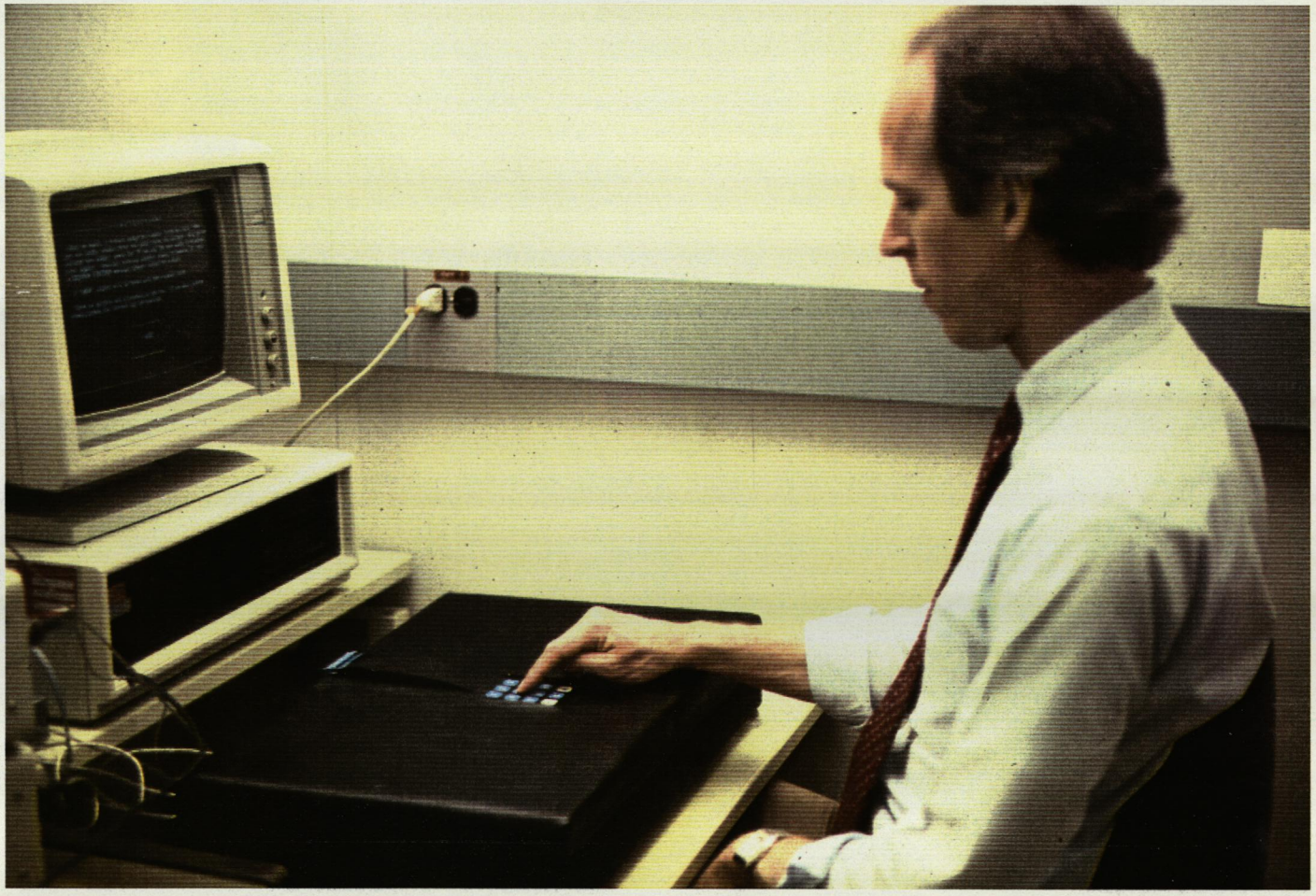


Figure 16. Instrumented touchpad workstation.

keypads during the experiment. Pilot studies confirmed this adhesive bond held the touchpads firmly in place and did not perceptibly distort or alter the fundamental touchpad characteristics.

The work surface was adjustable in height from 77.5 to 100 cm with 63 to 86 cm knee-hole clearance. A color EGA monitor was located in front of the subject, with an approximate eye-to-display distance of 46 cm. Display height was adjustable within a 20-cm range, permitting the center of the screen to be located 107 to 127 cm from the floor. The subject was seated in an adjustable chair with compressed seat height of 40.6 to 56 cm and adjustable seat pan angle and lumbar support. This enabled seating of the subject in accordance with the recommendations of the ANSI VDT Standard (1988).

*Experimental Design*

A mixed nested hierarchical factorial design (Figure 17) employing four repetitions of a complete 6 x 6 Latin square to control for presentation order and stimulus set effects was used for this study. Subjects were blocked by the variable Membrane Thickness and thus tested on 6 of the 12 touchpads, with Membrane Thickness a between-subjects factor. An equal number of males and females were assigned to each condition.

Touchpad was a within-subjects factor, incorporating the construction parameters of spacer thickness and aperture diameter. Two additional repeated factors, Period and Digit, completed the model. There were 10 periods per session, with each period consisting of 50 keypresses. The digits 0

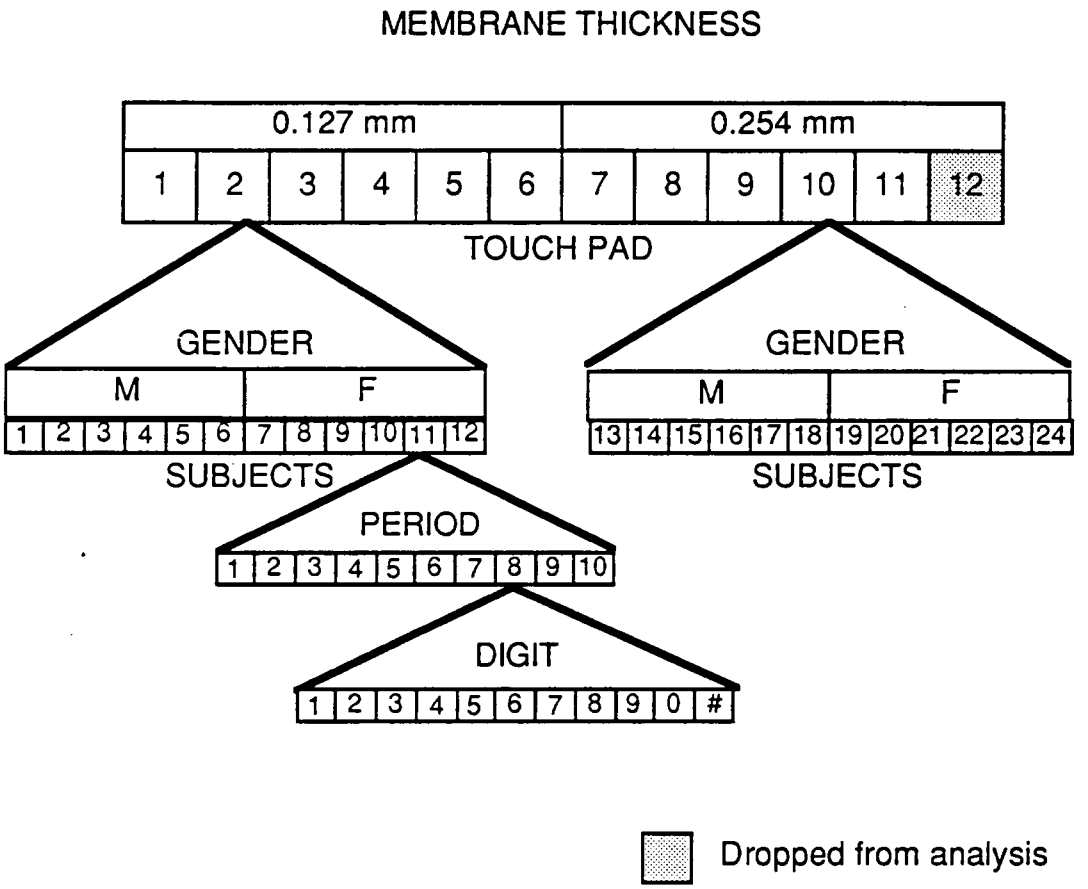



Figure 17. Experimental design for membrane switch construction study.

## STRUCTURE NESTED WITHIN MEMBRANE

SPACER THICKNESS

| 0.127 mm | | | | | | 0.254 mm | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 7 | 8 | 9 | 4 | 5 | 6 | 10 | 11 | 12 |

APERTURE DIAMETER

| 12.70 mm | | | | 9.525 mm | | | | 6.350 mm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 7 | 10 | 2 | 5 | 8 | 11 | 3 | 6 | 9 | 12 |

Dropped from analysis

Figure 17 (continued).

through 9 and the "#" key comprised the stimuli, hence there were 11 levels. This variable, Digit, was an indicator of the effects of key location.

The dependent variables included two measures of applied force, duration of a keypress, and two measures of excessive applied force, computed as the difference between touchpads RAFs and the forces actually applied. All dependent variables are described below.

*Procedure*

*Equipment calibration.* A fixture for applying a known force to the platform was developed. The fixture consisted of a 0 - 1000 gm spring gauge mounted to a block which vertically transversed a threaded column and was controlled by a synchronous 5 rpm motor with effective vertical displacement of 1.0 mm/s (Figure 18). The platform was calibrated by applying forces at 100 gm increments (ascending and descending) at each of the four corners of the platform. Least-squares regression lines of best fit were developed for each of the four locations measured across the force range and an overall transfer function was developed based on the correlation between applied force and output voltage. The calibration results are shown in Figures 19 and 20. The regression line for each location calibrated accounted for 99.6% or more of the voltage variability. A regression line of composite data accounted for 97.8% of the total variance. Due to the minimal improvement in predictability by using different equations for different locations, the regression line of the composite data was used for subsequent voltage to force transformations. Thus, the

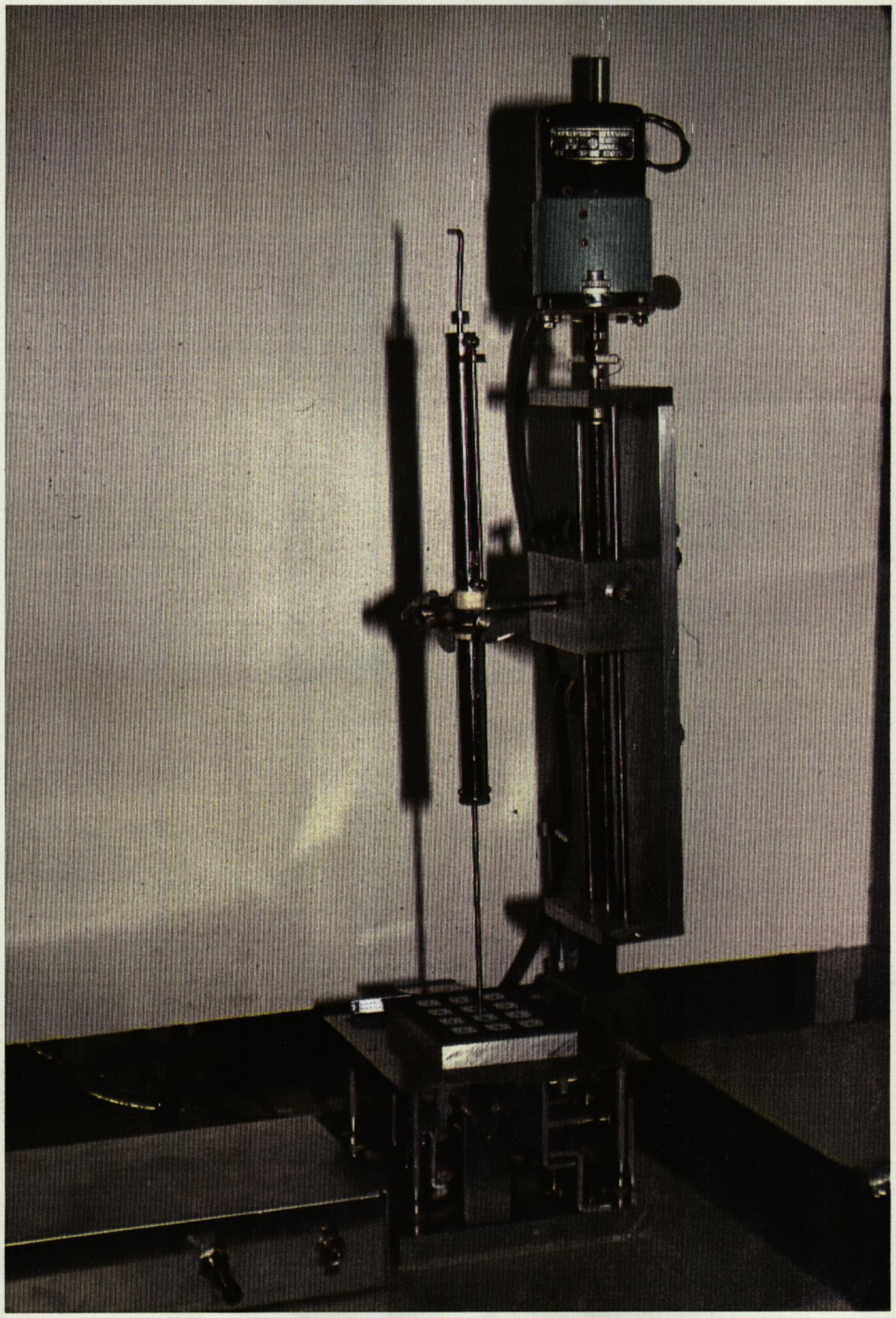


Figure 18. The calibration apparatus.

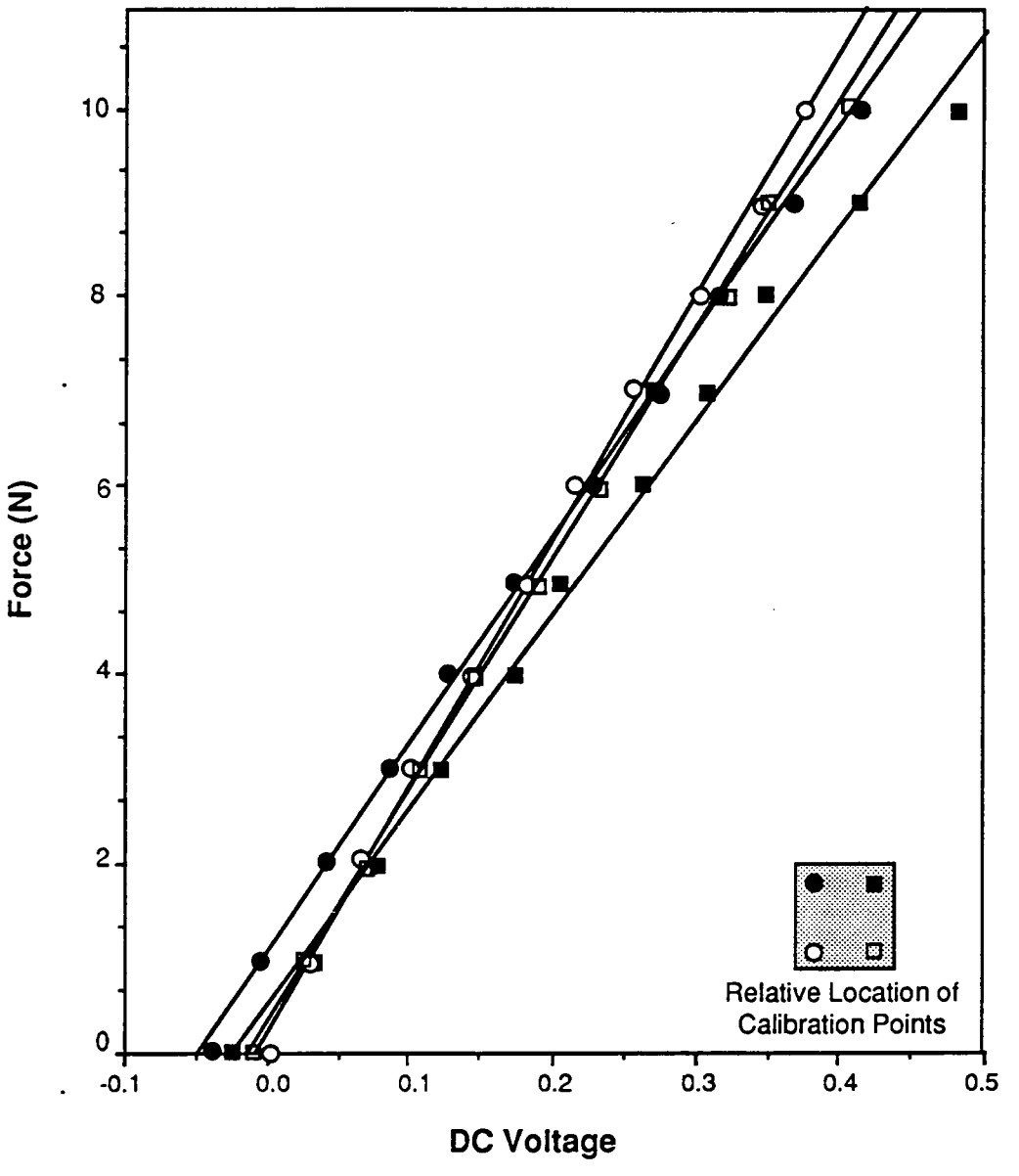



Figure 19. Least-squares regression lines of best fit for each of the four locations calibrated.

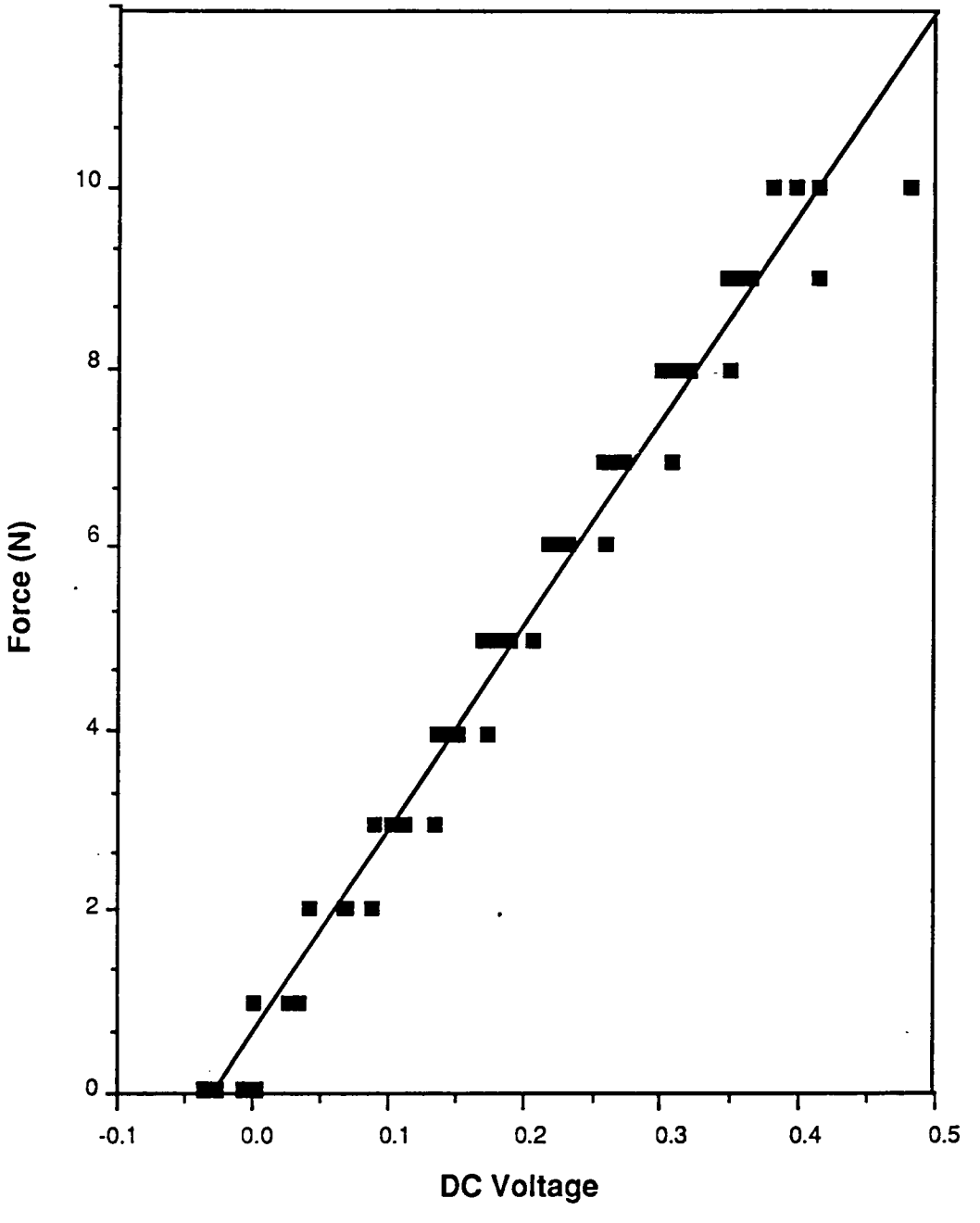



Figure 20. Composite least-squares regression line of best fit used for force platform calibration

relationship between DC voltage and force (N) may be expressed as:

$$\text{Force} = (66.493 + 2259.7\ V)\ 9.80665 \times 10^{-3} \qquad (2)$$

This fixture was also employed to determine the minimum RAF for each of the 12 touchpads used in the study. Industry standards for determining the minimum RAF provide little, if any, guidance in producing measures which are transferable and understood between manufacturers. The American National Standards Institute/Electronic Industries Association Standard specification for measuring the operating characteristics of keyboard switches, including the RAF, states "The specified operating characteristics shall be measured by any appropriate means" (ANSI, 1985, p. 9). Oak Switch Systems (1982) specifies (albeit in general terms) the method for determining the minimum RAF for *full-travel* membrane switch keys. However, techniques used for full-travel versus flat panel membrane switches would differ, recalling that membrane switches are *strain-dependent* displacement devices. Strain, being proportional to stress, which is the force per unit area, then is dependent upon the contact area. Thus, the contact area of the actuating device is relevant when measuring flat panel membrane switches, although this factor is irrelevant with full-travel membrane switches. With full-travel membrane switches, it is the area of the contact mechanism of the key cap which is relevant in eliciting strain. Therefore, in the absence of a standard means for measuring the RAF of flat panel membrane switches, the apparatus and methods described herein were developed and employed.

The contact area of the spring gauge actuator used to calibrate the touchpads was approximately 7.9 $mm^2$. Since this is a significantly smaller dimension than the area of the finger tip, the RAFs determined using this method will be the *minimum* RAFs, rather than the typical RAFs when actuated with a fingertip. As there are individual differences with regard to fingertip anthropometry, and given that subjects used different parts of the finger to actuate the membrane switches (e.g., fingertip, volar surface, fingernail, knuckle), any attempt to measure the typical RAF would necessarily require multiple measures and still require that the results be specified as ranges. Furthermore, since the purpose of this measure was to enable calculation of the excessive applied force, using a range or mean would unnecessarily complicate the measure and any conclusions which could be made from it. Thus, the minimum RAF specified herein is a meaningful and reliable, but relative, measure and not necessarily directly transferable to manufacturers' specifications of RAFs.

Four keys were randomly selected and measured on each of the 12 touchpads. The spring gauge actuator tip was carefully located 0.5 mm above the surface of the center of the touchpad key area. The actuator tip was lowered and increasing force was applied to the touchpad as the spring gauge, mounted to the block which transversed the threaded column, was lowered by the motor. At the point of actuation (which was signalled by an auditory tone), the motor was stopped and the gauge reading was recorded. The procedure was repeated a minimum of three times on each of the four keys measured on each

touchpad. The average minimum RAF for each touchpad was calculated and is presented in Table 6.

*Experimental protocol.* Each subject was tested on six configurations, two configurations per session. Subjects completed three sessions within a 10-day period.

The general purpose of the study, obtaining performance data for membrane touchpads, was explained to subjects. Subjects were not told that applied force was being monitored. Subjects were seated and given assistance in adjusting the chair height, desktop height, and display height, angle, and contrast. Comfort of the subject was the main criterion in adjusting the workstation, within the available range. Appendix B details the verbal instructions given to subjects.

Specific task instructions were presented to subjects via the CRT; those instructions are detailed in Appendix C. Subjects entered a series of 100 four-digit sequences which were displayed serially on a CRT. For this purpose, six sets of previously-generated random numbers were used. The six stimulus sets were presented in the same order to all subjects; hence, if any differences existed between the sets, such effects were confounded with order. (Thus stimulus set and presentation order, both nuisance effects, were confounded. The Latin squares were used to balance these effects across the experimental conditions.) Subjects concluded each four-digit sequence entered by pressing the "#" key, which prompted updating of the display with the next sequence to be entered. Supplemental auditory feedback for correct actuations was

Table 6. Minimum Required Actuation Forces for Touchpads used in Experiment I.

| Touchpad | Membrane Thickness | Spacer Thickness | Spacer Aperture | Minimum RAF |
|---|---|---|---|---|
| 1 | 0.127 | 0.127 | 12.70 | 0.637 N |
| 2 | 0.127 | 0.127 | 9.525 | 1.030 N |
| 3 | 0.127 | 0.127 | 6.350 | 1.961 N |
| 4 | 0.127 | 0.254 | 12.70 | 1.765 N |
| 5 | 0.127 | 0.254 | 9.525 | 2.991 N |
| 6 | 0.127 | 0.254 | 6.350 | 3.923 N |
| 7 | 0.254 | 0.127 | 12.70 | 1.079 N |
| 8 | 0.254 | 0.127 | 9.525 | 1.716 N |
| 9 | 0.254 | 0.127 | 6.350 | 3.530 N |
| 10 | 0.254 | 0.254 | 12.70 | 3.334 N |
| 11 | 0.254 | 0.254 | 9.525 | 5.198 N |
| 12 | 0.254 | 0.254 | 6.350 | 9.758 N |

provided, as previously described. No supplemental visual feedback was given (i.e., characters pressed were not displayed on the CRT).

At the conclusion of the final session, the six configurations were presented serially to the subject, who was asked to use each briefly and then to rate the touchpads in terms of his/her preference for the individual configurations using an unanchored magnitude estimation scaling techique. Subjects' instructions for the magnitude estimation scaling technique may be found in Appendix D. After completing the scaling procedure, the subject was debriefed and given a token gift (a Kodak Fling 35™ single-use camera) in exchange for completing the experiment.

*Data Collection and Analysis*

Data were collected using the Compaq 286 microcomputer and software previously described. At the end of each day of testing, the data collected were converted to archive files using a compression utility (PKARC, version 3.6; PKWARE, Inc., Glendale, WI) and stored on floppy disks.

In order to analyze the force and duration data (which consisted of digital bit values and clock values), it was first necessary to expand the archived data and transform them to a meaningful form. The program written and used to transform the raw data is presented in Appendix E. The transformation procedure was carried out using several IBM PS-2 microcomputers. The data were uploaded to a mainframe IBM system and additional transformations were carried out using SAS (version 5.1) routines.

Outputs in the form of digital bit values from the seven load cells were summed to yield the net force applied. The summed values were converted to voltages and then to force based on the results of the calibration procedures previously described. The equation used for this transform incorporates the relationship between DC voltage and force given in Equation (2). The force, expressed in Newtons, is:

$$\text{Force} = 9.80665 \times 10^{-3}\left[66.493 + 2259.7\left(\sum_{i=1}^{7} LC_i \frac{7\left(\frac{20}{4096} - 10\right)}{K}\right)\right], \qquad (3)$$

where $LC_i$ is the digital bit value for a load cell and K, the gain, is equal to 1.0.

Due to the random selection of stimuli, unequal frequencies by Digit existed within each Period. To correct for this, force data within each Period were collapsed within each Digit using two signal-averaging algorithms. These two algorithms differed in their treatment of force data as a function of keypress duration. A discussion of the properties of the two measures yielded by the signal-averaging techniques follows.

*Duration Weighted Mean Force.* The duration-weighted mean force (DWMF) represents the mean force as a function of time and also as a function of keypress duration. All force outputs at time $T_i$ were summed and the divisor used for signal-averaging was the number of keypresses at $T_1$ (i.e., the total number of keypresses for that Digit in that Period). Thus, when keypresses of unequal duration were averaged using this technique, the composite waveform was representative of modal keypresses. Error keypresses, where the subject pressed the key two or more times before a valid actuation, resulted in a

keypress of sustained duration. This signal-averaging technique corrected for error keypresses by decreasing their amplitude as an inverse function of the proportion of total keypresses they comprised. Thus, the DWMF is biased toward correct, typical keypresses.

*Absolute Amplitude Mean Force.* The absolute amplitude mean force (AAMF) represents the mean force as a function of time, irrespective of the duration of the keypress. All force outputs for all keypresses for a Digit at $T_i$ were summed and the divisor used for signal-averaging was the number of active keypresses at $T_i$ (i.e., those which remained above threshold). Thus, when keypresses of unequal durations were averaged using this technique, keypresses of shorter durations, once completed, were dropped from the equation (i.e., once actuation had occurred and the application of force had ceased). Thus, the AAMF does not adjust the amplitude to more accurately represent typical keypresses. Instead, the AAMF is biased toward keypresses of longer duration (i.e., error keypresses). A comparison of the DWMF and AAMF signal-averaging functions is shown in Figure 21. The peak values for each composite waveform were determined and used in the analyses.

Despite the use of the preceding signal-averaging procedures to reduce the number of missing data points, the random selection of stimuli resulted in some Digits not being represented within each Period. Furthermore, as a result of equipment failures and some subjects refusing to finish a session due to strong dislike for, or inability to use, a particular touchpad, additional incomplete data existed for some subjects. As no subject completed Touchpad 12, this touchpad was dropped from the analysis, resulting in an unbalanced design.

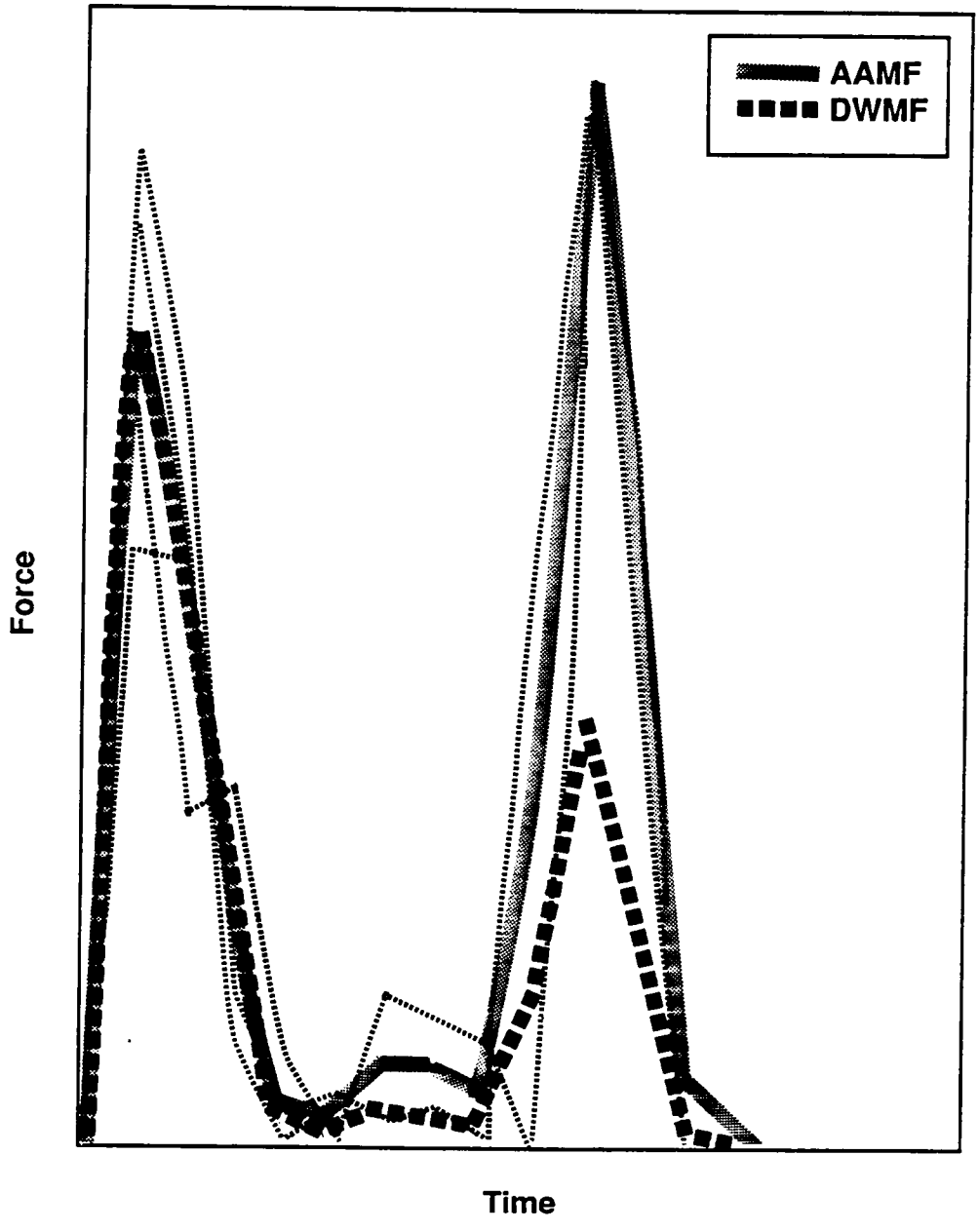



Figure 21. Duration-weighted mean force versus absolute amplitude mean force signal averaging functions.

The cell means were used to estimate all other lost data. Cell means were substituted for missing data and the degrees of freedom of the affected variance terms were reduced by one for each lost datum.

*Results and Discussion*

For the force data, two separate analyses of variance for each of the five dependent measures, DWMF, AAMF, excessive applied forces (DWMF and AAMF metrics), and duration, were performed. The first collapsed across membrane switch structure to determine the effects of varying RAFs among touchpads. Although applied forces were found to be significantly correlated with RAF, analysis of the effects of varying RAFs did not account for all differences in the dependent measures. Therefore, a second analysis was conducted which separated the construction parameters and analyzed the effect of structure on the dependent measures.

Because the elimination of Touchpad 12 from the analysis resulted in an unbalanced design, it was not possible to analyze the experimental model using the SAS ANOVA procedure. Instead, the General Linear Model (GLM) procedure was required. Because GLM utilizes an extremely large portion of computer (RAM) memory in the creation of X'X arrays for the data, it was impossible to analyze the experimental model in its entirety, using a mainframe computer sytem. Thus, sums of squares for the higher-order effects which could not be analyzed were added to the residual error. In general, the effects that were not analyzed were deemed less important than those presented, as the

performance relationships sought could be adequately addressed by way of the main effects and those interactions analyzed and presented herein.

Significant findings were evaluated with post-hoc Newman-Keuls multiple comparisons of means. The Newman-Keuls test is a moderately sensitive test which offsets a slight loss of power by controlling for experiment-wise Type I error. For all ANOVAs and post hoc tests, the criterion for rejection of the null hypothesis was $p < 0.05$.

*Required Actuation Force Analysis: Duration-Weighted Mean Force.* The results of the ANOVA for peak DWMF are shown in Table 29, Appendix F. A significant interaction of Membrane Thickness and Period was found ($F_{(8,180)} = 10.69$, $p < 0.0001$) and is shown graphically in Figure 22. Mean applied force and post-hoc comparisons are shown in Table 7.

Overall, DWMFs were found to be greater for touchpads with 0.254 mm membranes ($F_{(1,20)} = 6.16$, $p = 0.0221$). Mean DWMFs for touchpads with 0.127 mm thick membranes were not significantly different for the first two periods, but the mean DWMF for Period 1 was significantly less than that for Periods 3 through 10. For touchpads with a membrane thickness of 0.254 mm, mean DWMFs for Periods 8 and 9 were significantly greater than those for Periods 1 through 4. The mean DWMF for Period 1 was significantly less than those for all subsequent periods.

For touchpads with a 0.127 mm thick membrane, there is a general trend toward decreasing mean DWMFs over periods, while membranes with a 0.254 mm thick membrane show increasing DWMFs for subsequent periods. The

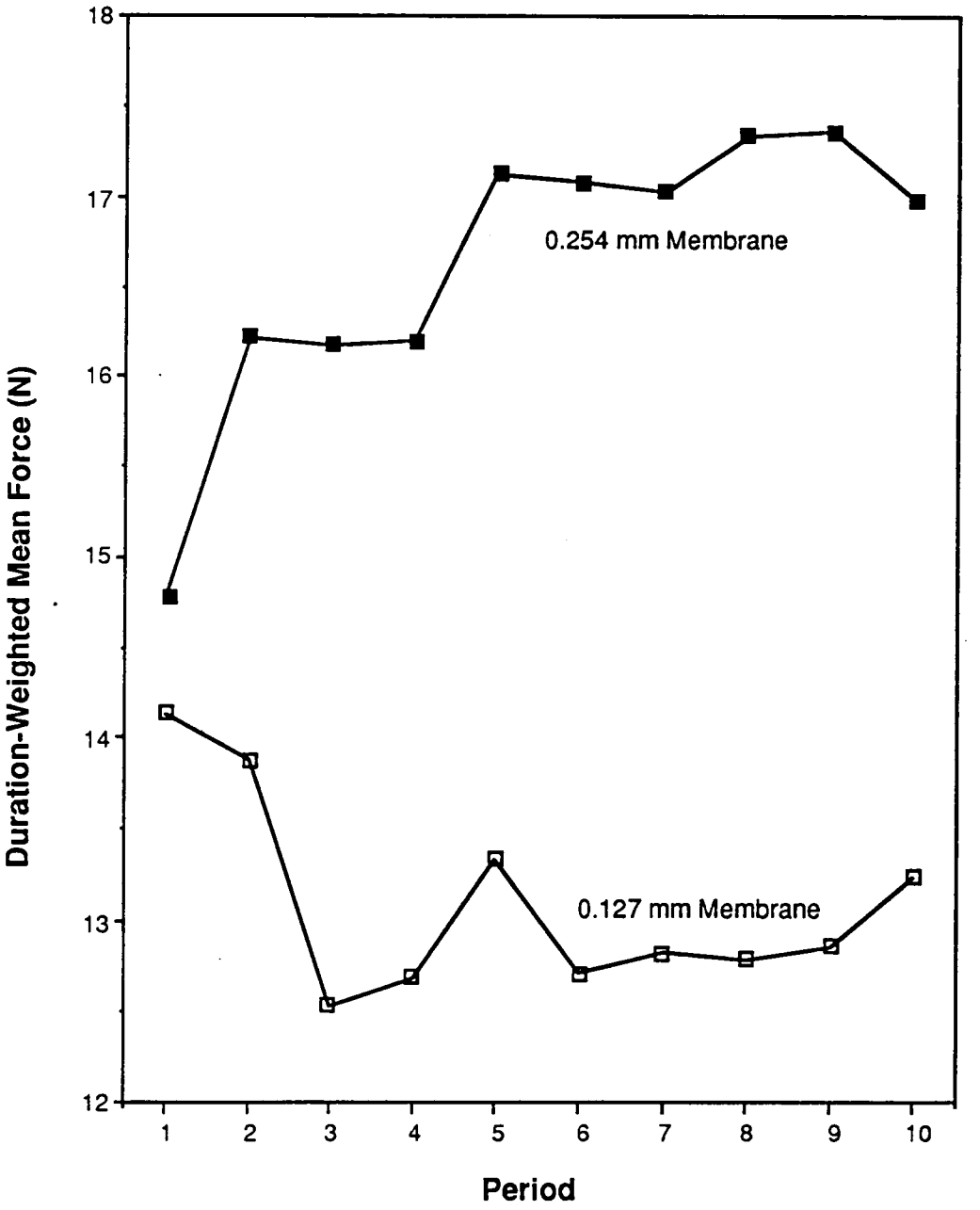



Figure 22. Interaction of Membrane Thickness and Period for the dependent measure duration-weighted mean force.

Table 7. Newman-Keuls Comparison of Means for Duration-Weighted Mean Force: Membrane Thickness by Period Interaction

| Membrane | Period | Mean (N) |
|---|---|---|
| 0.127 | 3 | 12.517 |
| 0.127 | 4 | 12.691 |
| 0.127 | 6 | 12.707 |
| 0.127 | 8 | 12.785 |
| 0.127 | 7 | 12.814 |
| 0.127 | 9 | 12.855 |
| 0.127 | 10 | 13.233 |
| 0.127 | 5 | 13.335 |
| 0.127 | 2 | 13.884 |
| 0.127 | 1 | 14.128 |
| 0.254 | 1 | 14.797 |
| 0.254 | 3 | 16.177 |
| 0.254 | 4 | 16.206 |
| 0.254 | 2 | 16.219 |
| 0.254 | 10 | 16.984 |
| 0.254 | 7 | 17.032 |
| 0.254 | 6 | 17.089 |
| 0.254 | 5 | 17.131 |
| 0.254 | 8 | 17.336 |
| 0.254 | 9 | 17.370 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

significant changes in mean DWMF between periods can be seen between Period 1 and 2 for those touchpads with a 0.254 mm thick membrane, and between Period 2 and 3 for those touchpads with 0.127 mm membranes.

A main effect of Period ($F_{(9,180)} = 2.75$, $p = 0.0049$) demonstrates significant changes in applied force as a function of time. Means and multiple comparisons for the main effect of Period are shown in Table 8. Only Periods 4 and 5 showed significantly different mean forces applied. Figure 23 illustrates the effect. For both the main effect of Period, and hence the interaction of Membrane Thickness and Period, the variability among means is much greater among the first five periods than the last five. As illustrated in Figure 23, the Period effect is heavily influenced by the Membrane Thickness by Period Interaction.

A main effect of Touchpad ($F_{(9,90)} = 60.61$, $p < 0.0001$) was found for the dependent measure DWMF. Means and multiple comparisons are presented in Table 9. .Mean DWMFs varied significantly as a function of Touchpad, with Touchpads 1, 2, 4, and 7 being pressed least hard, and Touchpads 6, 9, and 11 eliciting the greatest applied forces. Moderate levels of force were applied to Touchpads 3, 5, 8, and 10. Given the RAFs for the individual touchpads, such a finding is unremarkable. Touchpads 6, 9, and 11 had the highest RAF and Touchpads 1, 2, 4, and 7 were among the lowest RAFs.

An analysis of the relationship between RAF and the dependent measure DWMF supports the relationship between RAF and applied force. A moderately high correlation between RAF and DWMF was found ($r = 0.89$, $p < 0.01$). Figure

Table 8. Newman-Keuls Comparison of Means for Duration-Weighted Mean Force: Main Effect of Period

| Period | Mean (N) |
|---|---|
| 4 | 14.180 |
| 3 | 14.289 |
| 1 | 14.432 |
| 6 | 14.699 |
| 7 | 14.731 |
| 8 | 14.854 |
| 9 | 14.907 |
| 10 | 14.938 |
| 2 | 14.946 |
| 5 | 15.061 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

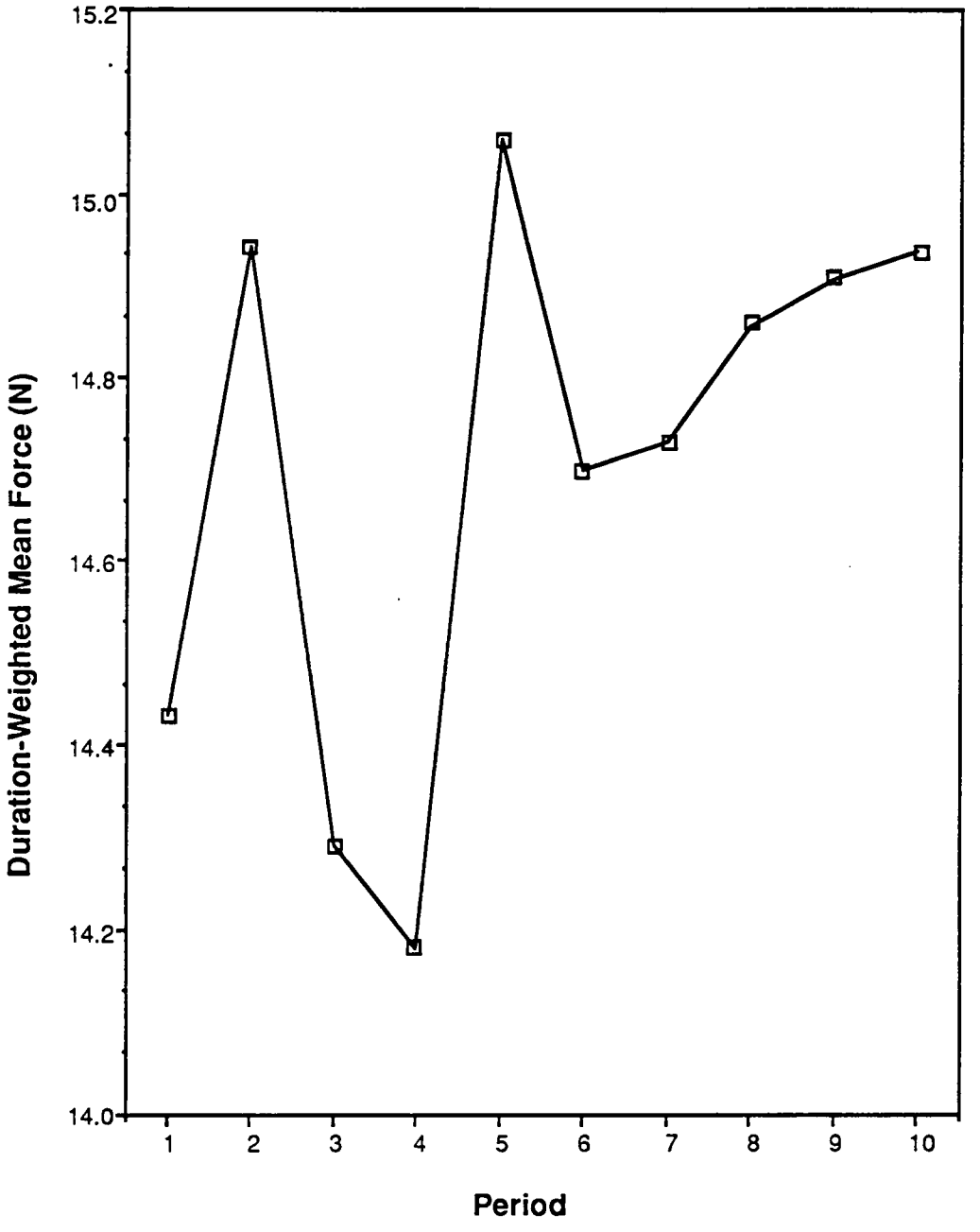



Figure 23. Main effect of Period for the dependent measure duration-weighted mean force.

Table 9. Newman-Keuls Comparison of Means for Duration-Weighted Mean Force: Main Effect of Touchpad

| Touchpad | Mean (N) |
|---|---|
| 1 | 5.871 |
| 2 | 7.340 |
| 7 | 7.651 |
| 4 | 9.599 |
| 8 | 12.064 |
| 10 | 13.445 |
| 3 | 14.786 |
| 5 | 15.655 |
| 11 | 23.576 |
| 6 | 25.318 |
| 9 | 26.434 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

24 illustrates the relationship between RAF and DWMF. Although Touchpads 3, 4, and 8 have nearly the same RAFs, Touchpad 4 elicited significantly less force. Likewise, although the RAFs of Touchpads 5, 9, and 10 were very similar, Touchpads 5 and 10 elicited significantly less force than Touchpad 9. Touchpad 4 is constructed of a 0.127 mm membrane and a 0.254 mm spacer, with a spacer aperture diameter of 12.7 mm. Touchpad 10 is constructed of a 0.254 mm membrane and a 0.254 mm spacer, with a spacer aperture diameter of 12.7 mm. Thus, both Touchpads have the same spacer thickness and aperture diameter. Touchpad 3 is constructed of a 0.127 mm membrane and a 0.127 mm spacer, with a spacer aperture diameter of 6.35 mm. Touchpad 9 differs from Touchpad 3 in that its construction incorporates a 0.254 mm membrane. Thus, in addition to the RAF, structure appears to play a role in influencing the applied force. The combination of spacer thickness and aperture diameter appears to impact the forces that are applied, with the thicker spacer and larger aperture diameter eliciting the least force.

A main effect of Digit was identified ($F_{(10,200)} = 20.78$, $p < 0.0001$), such that the mean DWMFs for the 2, 3, and 6 key locations were greater than those for all other keys (Table 10). Greater DWMFs were found for the 1, 5, and 9 keys, compared with the 0, 7, and Enter (#) keys. Other differences between mean DWMFs were not significant. Thus, greater forces were exerted on key locations in the far left corner than along the near edge.

Membrane thickness is related to a touchpad's RAF. Touchpads with a membrane thickness of 0.254 mm exhibited higher RAFs than those with a membrane thickness of 0.127 mm and equivalent spacer thickness and

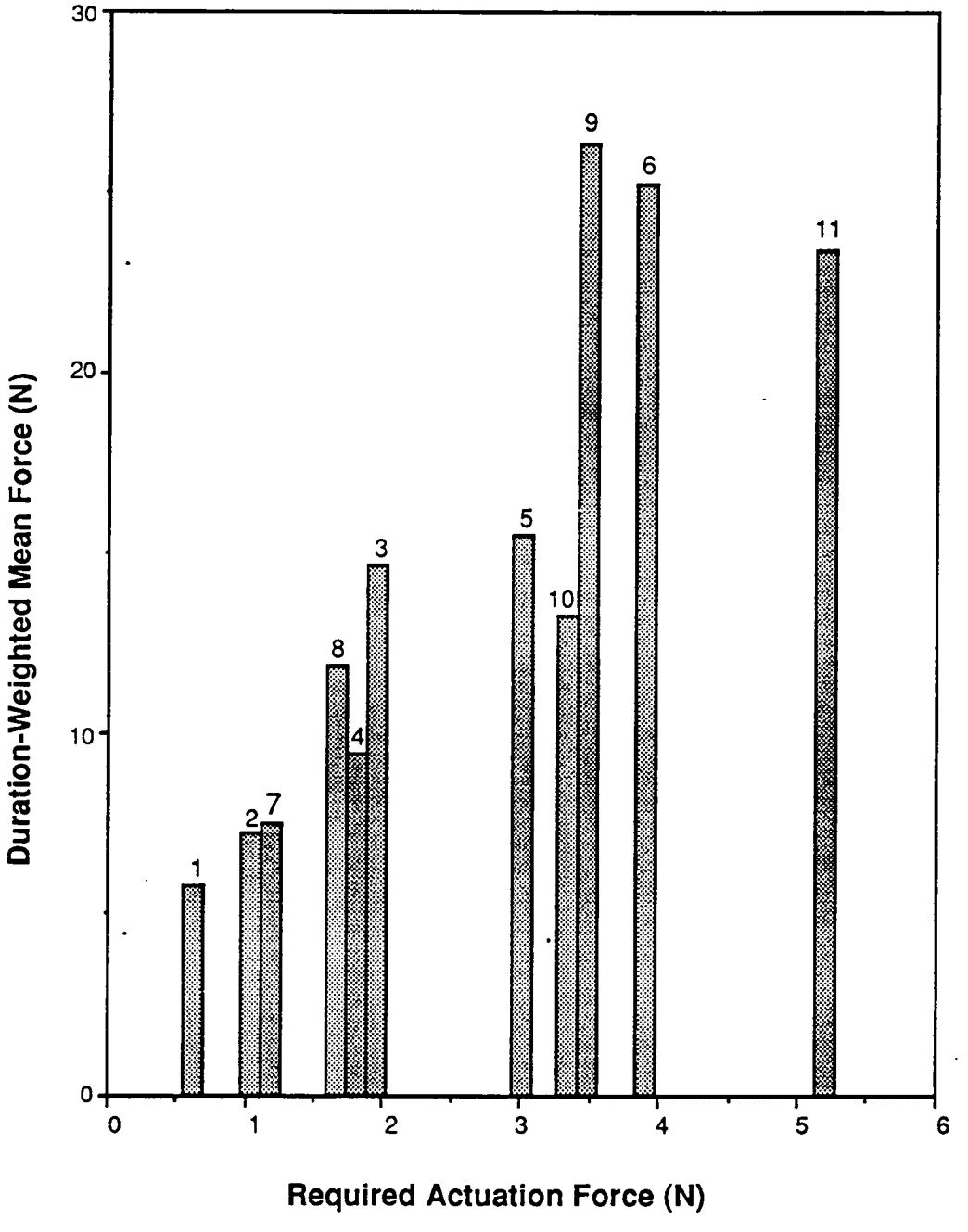



Figure 24. Required actuation force versus applied force as measured by the DWMF metric.

Table 10. Newman-Keuls Comparisons of Means for Duration-Weighted Mean Force: Main Effect of Digit

| Digit | Mean (N) |
|---|---|
| # | 13.959 |
| 7 | 13.968 |
| 0 | 14.007 |
| 4 | 14.297 |
| 8 | 14.473 |
| 1 | 14.651 |
| 5 | 14.698 |
| 9 | 14.845 |
| 2 | 15.492 |
| 6 | 15.503 |
| 3 | 15.847 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

aperture dimensions. Differences in thicker spacer and aperture dimensions also directly impact the RAF. Given a moderately high correlation between RAFs and DWMF, the main effects of Membrane Thickness and Touchpad are to be expected. The interaction between Membrane Thickness and Period suggests differences in keying behavior that are related either to differences in RAF and/or differences in the structure of the membrane switch itself.

*Required Actuation Force Analysis: Absolute Amplitude Mean Force.* The AAMF metric yielded similar results to those of the DWMF. The results of the ANOVA for peak AAMF are shown in Table 30, Appendix F. A significant interaction between Membrane Thickness and Period ($F_{(9,180)} = 4.57$, $p <$ 0.0001) and a main effect of Membrane Thickness ($F_{(1,20)} = 4.99$, $p = 0.0371$) were found. Greater forces were applied to touchpads with 0.254 mm membranes. Means and multiple comparisons for the Membrane Thickness by Period interaction are found in Table 11. Forces exerted on touchpads with 0.127 mm thick membranes were greater during the first two periods than those during the last period (Period 10). Other differences between periods were not significant for touchpads with a membrane thickness of 0.127 mm. For touchpads with 0.254 mm thick membranes, the mean AAMF for the first period was significantly less than those applied during subsequent periods. AAMFs for Period 1 were not significantly different between the two membrane thicknesses, although the mean AAMF differed significantly between membrane thicknesses for all other periods.

The interaction of Membrane Thickness by Period is shown graphically in Figure 25. Like the DWMF measure, touchpads with a 0.127 mm thick

Table 11. Newman-Keuls Comparison of Means for Absolute Amplitude Mean Force: MembraneThickness by Period Interaction

| Membrane | Period | Mean (N) |
|---|---|---|
| 0.127 | 10 | 15.093 |
| 0.127 | 3 | 15.460 |
| 0.127 | 8 | 15.512 |
| 0.127 | 9 | 15.703 |
| 0.127 | 7 | 15.736 |
| 0.127 | 6 | 15.752 |
| 0.127 | 5 | 15.783 |
| 0.127 | 4 | 15.960 |
| 0.127 | 1 | 16.882 |
| 0.127 | 2 | 16.945 |
| 0.254 | 1 | 17.785 |
| 0.254 | 2 | 19.822 |
| 0.254 | 4 | 19.911 |
| 0.254 | 3 | 19.916 |
| 0.254 | 6 | 20.019 |
| 0.254 | 9 | 21.192 |
| 0.254 | 7 | 20.301 |
| 0.254 | 10 | 20.339 |
| 0.254 | 8 | 20.452 |
| 0.254 | 5 | 20.629 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

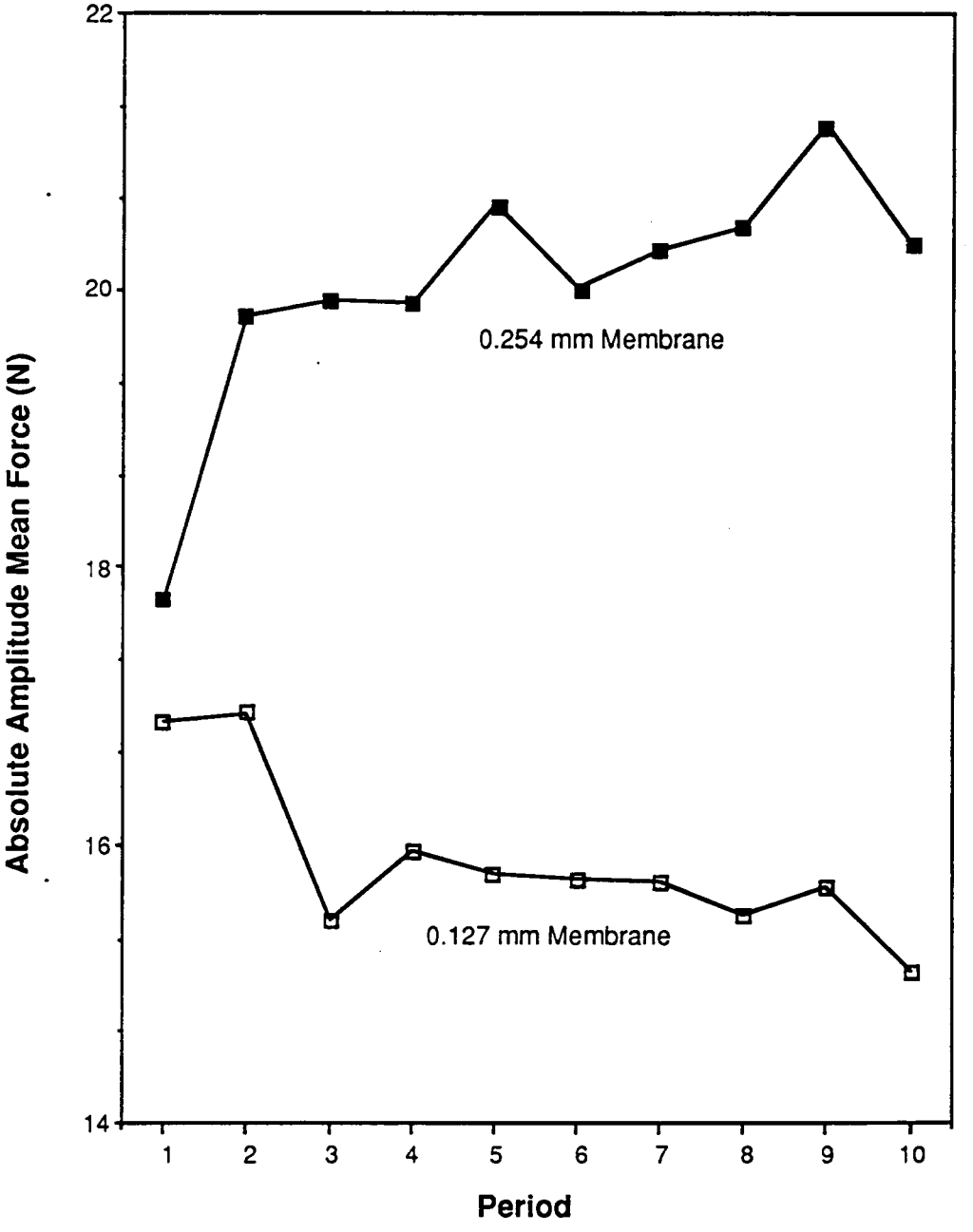



Figure 25. Interaction of Membrane Thickness by Period for the dependent measure absolute amplitude mean force.

membrane showed decreasing applied forces over periods, while those with 0.254 mm membranes showed an increase in applied forces during subsequent periods. No significant main effect of Period was demonstrated for the dependent variable AAMF.

The effect of membrane thickness is unsurprising in that touchpads with 0.254 mm membranes exhibited higher RAFs than those with 0.127 mm membranes; hence, the higher exerted forces might be attributable to RAF differentials.

A main effect of Touchpad ($F_{(9,90)} = 49.75$, $p < 0.0001$) resulted in rejection of the null hypothesis that users exert the same force to all touchpads, regardless of RAF differentials. Touchpads 6, 9, and 11 elicited significantly greater forces than all other touchpads. Mean applied forces and post-hoc comparisons are shown in Table12. Touchpads 1, 2, and 7 elicited significantly lesser forces than Touchpads 3, 5, 8, and 10. Forces applied to Touchpad 4 were less than those applied to Touchpads 3, 5, 6, 9, 10, and 11. These results are similar to those for DWMF as touchpads with virtually equivalent RAFs (i.e., Touchpads 3 and 4, and Touchpads 9 and 10) elicited significantly different applied forces.

An interaction of Digit and Gender ($F_{(10,200)} = 2.16$, $p = 0.0217$) as well as the main effect of Digit ($F_{(10,200)} = 6.00$, $p < 0.0001$) are significant. Means and post-hoc comparisons are presented in Tables 13 and 14. The mean AAMFs for Digits 2 and 3 were significantly greater than those for Digits 0, 4, 7, and the enter key (#), as shown by the comparison of means. Other differences

Table 12. Newman-Keuls Comparison of Means for Absolute Amplitude Mean Force: Main Effect of Touchpad

| Touchpad | Mean (N) |
|---|---|
| 1 | 8.249 |
| 2 | 9.037 |
| 7 | 10.030 |
| 4 | 11.954 |
| 8 | 14.938 |
| 10 | 16.576 |
| 3 | 17.582 |
| 5 | 18.989 |
| 11 | 27.671 |
| 9 | 30.467 |
| 6 | 30.684 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 13. Newman-Keuls Comparison of Means for Absolute Amplitude Mean Force: Gender by Digit Interaction

| Gender | Digit | Mean (N) |
|---|---|---|
| F | 5 | 16.204 |
| F | 0 | 16.219 |
| F | 4 | 16.246 |
| F | # | 16.358 |
| F | 7 | 16.508 |
| F | 1 | 16.555 |
| F | 8 | 16.562 |
| F | 2 | 16.909 |
| F | 6 | 16.929 |
| F | 3 | 17.415 |
| F | 9 | 17.587 |
| M | # | 18.181 |
| M | 0 | 18.494 |
| M | 7 | 18.586 |
| M | 4 | 18.714 |
| M | 8 | 18.717 |
| M | 1 | 18.789 |
| M | 9 | 18.917 |
| M | 5 | 19.276 |
| M | 3 | 19.436 |
| M | 6 | 19.692 |
| M | 2 | 20.059 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 14. Newman-Keuls Comparison of Means for Absolute Amplitude Mean Force: Main Effect of Digit

| Digit | Mean (N) |
|---|---|
| # | 17.269 |
| 0 | 17.357 |
| 4 | 17.480 |
| 7 | 17.547 |
| 8 | 17.639 |
| 1 | 17.672 |
| 5 | 17.740 |
| 9 | 18.252 |
| 6 | 18.311 |
| 3 | 18.426 |
| 2 | 18.484 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

between mean AAMFs were not significant. Figure 26 shows a comparison of the AAMF and DWMF metrics for the main effect of Digit. While the mean AAMFs are higher than mean DWMFs, the effects are generally similar.

With regard to gender, females exerted less force than males. Most comparisons of means were not significant. Males applied greater forces to the digit *2* than they did to all others except *3*, *6,* and *5*. Females applied less force to the digit *5* than to all others. The interaction of Gender by Digit is not truly of practical interest and is perhaps attributable in part to the high power attained through the large number of observations and thus the many degrees of freedom in the test of the Gender by Digit interaction.

*Required Actuation Force Analysis: Excessive Applied Force.* Excessive applied force measures were computed by subtracting the minimum RAF for each touchpad from the DWMF and AAMF data. Hence, a measure of excessive force beyond that necessary to effectuate an actuation of the key switch, was derived. The results of ANOVAs for the excessive applied force for the DWMF and AAMF metrics may be found in Tables 31 and 32, Appendix F. Because the computation of the excessive applied force metrics involved the subtraction of the RAFs for touchpads from the applied force metrics, only the sums of squares for the main effect of Touchpad were different from those for the other measures previously described. For the applied force metrics, as well as both excessive applied force metrics, the main effect of Touchpad was significant.

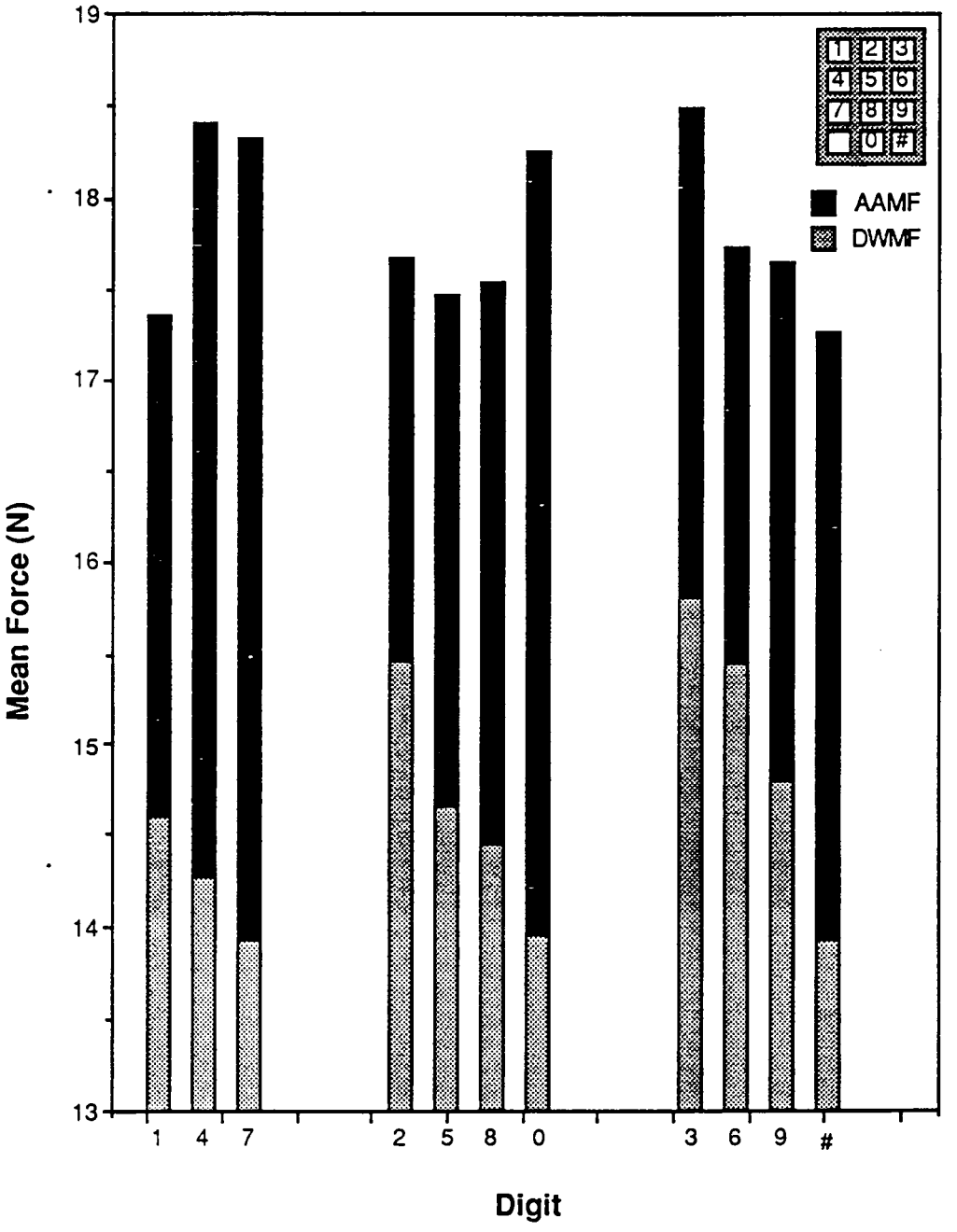



Figure 26. Mean applied force: Main effect of Digit for AAMF and DWMF metrics.

The means and multiple comparisons for excessive applied DWMF (EDWMF) are shown in Table 15. EDWMFs for Touchpads 6 and 9 were not significantly different, but were greater than those for all other touchpads. EDWMFs were significantly less for Touchpads 1, 2, and 7 than all other touchpads except Touchpad 4. Although these results are very similar to the results for the DWMF metric, there are some differences. While the mean DWMFs applied to Touchpads 6, 9, and 11 were not significantly different, Touchpads 6 and 9 elicited significantly greater EDWMFs than Touchpad 11. DWMFs for Touchpads 3, 5, 8, and 10 were not significantly different; however, EDWMFs for Touchpads 3 and 5 were significantly higher than those for Touchpads 8 and 10. Neither the DWMFs nor the EDWMFs differed significantly among Touchpads 1, 2, 7, and 4. The implications of these differences are discussed following presentation of the excessive AAMF results.

Table 16 shows the means and post-hoc comparisons for excessive applied AAMF (EAAMF). Like EDWMF and DWMF, the results of the comparisons for the EAAMF differed slightly from those of the AAMF for some Touchpads and were virtually the same for others. Neither the EAAMF nor the AAMF differed significantly among Touchpads 1, 2, 4, and 7. While Touchpads 6, 9, and 11 AAMFs were not significantly different, the EAAMF for Touchpad 11 was significantly less than that for Touchpads 6 and 9. AAMFs were not significantly different among Touchpads 3, 5, 8, and 10, but EAAMFs were significantly greater for Touchpads 3 and 5 than for Touchpad 8. AAMFs for Touchpad 4 were significantly less for than those for Touchpad 10 although EAAMFs for these two touchpads were not significantly different.

Table 15. Newman-Keuls Comparison of Means for Excessive Applied Force (DWMF Metric): Main Effect of Touchpad

| Touchpad | Mean (N) |
|---|---|
| 1 | 5.234 |
| 2 | 6.310 |
| 7 | 6.572 |
| 4 | 7.834 |
| 10 | 10.111 |
| 8 | 10.348 |
| 5 | 12.664 |
| 3 | 12.825 |
| 11 | 18.378 |
| 6 | 21.395 |
| 9 | 22.904 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 16. Newman-Keuls Comparison of Means for Excessive Applied Force (AAMF Metric): Main Effect of Touchpad

| Touchpad | Mean (N) |
|---|---|
| 1 | 7.612 |
| 2 | 8.007 |
| 7 | 8.951 |
| 4 | 10.189 |
| 8 | 13.222 |
| 10 | 13.242 |
| 3 | 15.621 |
| 5 | 15.998 |
| 11 | 22.473 |
| 6 | 26.761 |
| 9 | 26.937 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Touchpads 6 and 9, those with 0.254 mm thick spacers and small aperture diameters (6.35 mm) elicited greater forces than Touchpad 11, which incorporated the same spacer thickness but a larger aperture diameter. Because these differences relate to RAFs as well as to structural changes, which factor (RAF or structure) is responsible is difficult to interpret. Likewise for Touchpads 3, 5, 8, and 10, which varied in membrane thickness.

*Required Actuation Force Analysis: Duration.* The ANOVA summary table for the the dependent measure Duration may be found in Table 33, Appendix F. A main effect of Touchpad ($F_{(9,90)} = 8.78$, $p < 0.0001$) was found. Mean keypress durations ranged from 0.148 to 0.301 s (Table 17). Keypress durations for Touchpad 6 were significantly longer than for all other touchpads. Keypress durations for Touchpad 9 were significantly longer than those for Touchpads 1, 2, 4, 7, 8, and 10. As with the force measures, a relation to RAFs is apparent. Touchpads with high RAFs elicit longer keypress durations than touchpads with lower RAFs.

A significant effect of Period ($F_{(9,180)} = 72.55$, $p < 0.0001$) demonstrates changes in the duration of keypresses over time. Keypress duration increased monotonically over periods, as can be seen in Figure 27. Mean durations and results of the multiple comparisons are shown in Table 18. Significant increases in duration occur between Periods 1 and 2, and between Periods 2 and 3. Other increases between successive periods are not significant. Furthermore, increases over Periods 4 through 6 and over the last four periods are not significant.

Table 17. Newman-Keuls Comparison of Means for Duration: Main Effect of Touchpad

| Touchpad | Mean (s) |
|---|---|
| 7 | 0.148 |
| 1 | 0.155 |
| 8 | 0.157 |
| 2 | 0.158 |
| 4 | 0.169 |
| 10 | 0.177 |
| 5 | 0.205 |
| 3 | 0.210 |
| 11 | 0.213 |
| 9 | 0.237 |
| 6 | 0.301 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

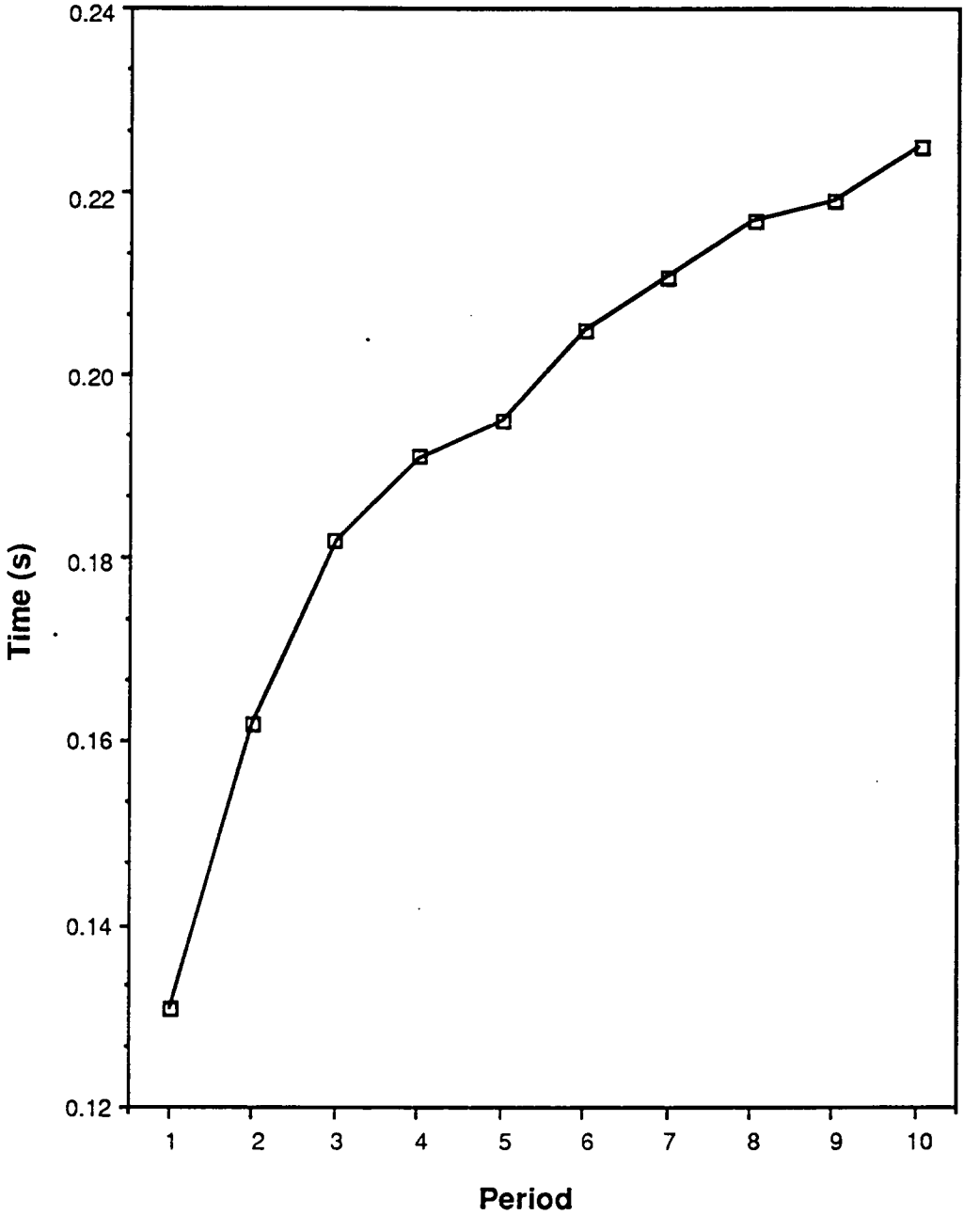



Figure 27. Main effect of Period for the dependent measure duration.

Table 18. Newman-Keuls Comparison of Means for Duration: Main Effect of Period

| Period | Mean (s) |
|---|---|
| 1 | 0.131 |
| 2 | 0.162 |
| 3 | 0.182 |
| 4 | 0.191 |
| 5 | 0.195 |
| 6 | 0.205 |
| 7 | 0.211 |
| 8 | 0.217 |
| 9 | 0.219 |
| 10 | 0.225 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Changes in keypress duration might be an indicator of changes in keying strategy, as different onset-to-peak-force latencies would be expected depending on the technique a subject used, such as ballistic tapping versus a more controlled keying motion. Such changes in keying strategy might signify an adaptation or fatigue effect. The potential implications of the changes in keying strategy and keypress duration are presented in the discussion.

Keypress duration varied as a function of key location ($F_{(10,200)} = 39.10$, $p < 0.0001$). The comparison of mean keypress durations by digit is shown in Table 19. The # key, which was the concluding key in a five-key sequence (the *enter* key) was pressed for a significantly longer duration than other keys. Differences among numerical keys were not significant.

This finding is likely to have practical significance for the switch life of the enter key, as that key is pressed (stressed) for longer periods of time. It is known that greater exerted forces contribute to the deterioriation of switch life and that when membrane switches are held in their closed (actuated) position for an extended period of time, as occasionally happens during storage of membrane switches with full-travel keycaps that are not packaged properly, structural fatigue of the membrane may occur and impair switch life (Matsunaga, 1985). Whether the differences observed in keypress duration herein are sufficient to seriously degrade switch life remains to be investigated.

The reason for studying the effect of digit was to assess the force differentials between numerical keys and the enter function key. Anecdotal observations of keyboard users in general suggests that users exert greater

Table 19. Newman-Keuls Comparison of Means for Duration: Main Effect of Digit

| Digit | Mean (s) |
|---|---|
| 8 | 0.186 |
| 6 | 0.187 |
| 7 | 0.187 |
| 2 | 0.188 |
| 4 | 0.188 |
| 0 | 0.190 |
| 1 | 0.192 |
| 5 | 0.193 |
| 9 | 0.194 |
| 3 | 0.195 |
| # | 0.230 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

forces on the enter key. The preceding analyses failed to support such observations. The duration differences, however, may be relevant. If keying behavior varied significantly as a function of which key was pressed, increasing switch life of the touchpanel may require structural changes to only one keyswitch. For example, if the enter key was known to elicit keypresses of greater force or duration, the enter key could be designed with a slightly smaller aperture diameter. This would have the effect of increasing the RAF for that key over others on the touchpanel, but it would also increase the switch life of that key. While previously stated recommendations for membrane switch design emphasized the need to maintain the same RAF across the panel, findings which suggest some keys will be stressed more than others present the exception to this practice.

Although the results indicate the absence of an effect of key location on applied force, this may not be a universal finding. Recall that the ENTER key on the touchpads used in this experiment was of the same dimensions as all other keys, which is in contrast to the enter key on many other keypad and keyboard devices. Fitt's Law predicts shorter time-to-target intervals for targets of larger size and equivalent distance. This may mean differences in the rate of acceleration with which the finger strikes keys of different dimensions. Greater acceleration would yield a greater force upon contact with the key. Hypothetically, it would follow that exerted forces may vary as a function of key size.

*Required Actuation Force Analysis: Subjective Preference.* The magnitude estimation data were rescaled to allow between-subjects

comparisons. The rescaling algorithm is implemented in a program which may be found in Appendix G. The ANOVA summary table for subjective preference is found in Table 34, Appendix F. A main effect of Touchpad ($F_{(11,109)} = 3.90$, $p > 0.0001$) for the dependent measure of subjective ratings was found. Post-hoc comparisons determined that Touchpad 7 was significantly preferred over others, although differences among other ratings were not significant.

However, due to the fact that the force measurement system imposed a minimum threshold of 1.08 N, although the RAFs for Touchpads 1 and 2 were below this threshold, their effective RAF was equivalent to that of Touchpad 7. Thus, conclusions emanating from the structural differences among Touchpads 1, 2, and 7 must be approached with caution, as the measurement system altered the effective RAF and likely affected the operating characteristics of the switch as well. However, it can be concluded that, when switch de-bounce techniques are employed, users prefer a switch with an RAF of 1.08 N (or perhaps less) over those with higher RAFs. Furthermore, since other touchpads with structural elements simlar to Touchpad 7 were not also preferred, it is likely that the driving force of this effect is the RAF.

This is of particular interest in that increased resistance in a switch is frequently used to reduce spurious input and eliminate key bounce. Given that these ill effects of low RAF switches were impossible with the apparatus used in this study, this finding suggests that striving to attain the lowest possible RAF is unnecessary for preference. Furthermore, since other touchpads with similar structural elements were not also preferred, it is likely that the driving force of this effect is the RAF.

*Summary of the Results regarding Required Actuation Force .* All of the preceding measures demonstrate significant effects of RAF differentials among touchpads. The results of the EDWMF and EAAMF metric analyses suggest that in addition to different RAFs influencing the forces exerted on membrane touchpads, some other influential factor is present; even when RAF differentials are accounted for, significant differences among touchpads exist. It is hypothesized that touchpad structure may be partially responsible for these differences. Therefore, the force measures were re-analyzed and the effects of structure were investigated.

Due to the elimination of Touchpad 12 from the analysis, a full factorial model of the membrane switch structure could not be completed. Since the main effect of Membrane Thickness has been previously defined in the preceding analyses, only the effects of the two remaining structural parameters, Aperture Diameter and Spacer Thickness, remain to be defined. Therefore, the dependent measures for the two Membrane Thicknesses were analyzed separately. For the 0.127 mm thick membrane, a full factorial model for Spacer Thickness (2 levels) and Aperture Diameter (3 levels) was possible. For the 0.254 mm thick membrane, the absence of one Spacer Thickness by Aperture Diameter level necessitated the five remaining combinations of spacer thickness and aperture diameter to be analyzed as simple combinations. The results of both analyses are presented by dependent variable.

*Structural Analysis: Duration-Weighted Mean Force.* The ANOVA summary table for the structural analysis of the dependent measure DWMF may be found in Tables 35 and 36, Appendix F. For touchpads with membrane

thicknesses of 0.127 mm, main effects of Aperture and Spacer were found. The interaction of aperture diameter and spacer thickness was also significant ($F_{(2,22)} = 8.26$, $p < 0.0001$). Mean DWMF values for all levels of aperture diameter and both levels of spacer thickness were significantly different, as were all combinations of aperture diameter and spacer thickness.

For touchpads with membrane thicknesses of 0.254 mm, the five combinations of aperture diameter and spacer thickness were also significant. Post-hoc comparisons demonstrated that all pairs were significantly different .

Regardless of membrane thickness, touchpads with thicker spacers (0.254 mm) elicited greater forces than those with thinner spacers (0.127 mm), except when combined with a small spacer aperture (6.35 mm). However, when RAF differentials are taken into account, the effect of Spacer Thickness is reversed. Touchpads 9 and 10, constructed of the same membrane thickness (0.254), exhibited virtually the same RAFs. However, differences in applied forces between these two touchpads were significant. Higher forces were applied to the touchpad with a 6.350 mm diameter aperture in a 0.127 mm spacer (Touchpad 9) than to all others, including the touchpad with a 12.70 mm diameter aperture in a 0.254 mm spacer (Touchpad 10).

*Structural Analysis: Absolute Amplitude Mean Force.* The ANOVA summary tables for the structural analysis of the dependent measure AAMF may be found in Tables 37 and 38, Appendix F. A significant interaction between aperture diameter and spacer thickness was found for touchpads with 0.127 mm membranes ($F_{(2,22)} = 8.88$, $p < 0.0001$) and an effect was found across combinations for touchpads with 0.254 mm membranes ($F_{(4,44)} = 67.61$, $p <$

0.0001). As with the DWMF metric, all combinations of aperture diameter and spacer thickness were significantly different from all others.

*Structural Analysis: Excessive Applied Forces.* The ANOVA summary tables for the structural analysis of the two measures of excessive applied force (AAMF and DWMF metrics) for the two membrane thicknesses may be found in Tables 39 through 42 in Appendix F. Aperture diameter by spacer thickness effects for both metrics at both levels of membrane thickness were significant. Post-hoc comparisons distinguished among all combinations of aperture diameter and spacer thickness except as follows: Mean EDWMF values for touchpads with 0.127 mm membranes were significantly different for all pairs of touchpads except Touchpads 3 and 6. Touchpads 3 and 6 each have a 6.35 mm aperture diameter, with spacer thicknesses of 0.127 and 0.254 mm, respectively.

Differences in mean EAAMF values were not significant for the two touchpads with 6.35 mm diameter apertures. In addition, mean EAAMF values for Touchpad 2 (spacer thickness = 0.127 mm, aperture diameter = 9.525 mm) were not significantly different from those of Touchpad 4 (spacer thickness = 0.254 mm, aperture diameter = 12.70 mm).

For touchpads with 0.254 mm membrane thicknesses, the results were similar for both metrics: Touchpad 1 (spacer thickness = 0.127 mm, aperture diameter = 12.70 mm) was not significantly different from Touchpad 5 (spacer thickness = 0.127, aperture diameter = 9.525 mm). All other pairs were significantly different.

*Structural Analysis: Duration.* As with the force measures, the dependent measure duration exhibited significant effects of the aperture by spacer combinations for both levels of membrane thickness. The ANOVA summary tables for the dependent measure duration are found in Tables 43 and 44, Appendix F. Mean keypress durations for all touchpads with 0.254 mm membrane thickness were significantly different. Of touchpads with 0.127 mm membranes, mean keypress durations were not significantly different between Touchpads 3 and 6 (both having 6.35 mm diameter apertures, with spacer thicknesses of 0.127 and 0.254 mm, respectively) or between Touchpad 2 (aperture diameter = 9.525 mm, spacer thickness = 0.127 mm) and Touchpad 4 (aperture diameter = 12.70 mm, spacer thickness = 0.254 mm).

*Structural Analysis: Subjective Ratings.* The ANOVA summary table for the subjective ratings may be found in Table 45, Appendix F. Effects of spacer aperture diameter ($F_{(2,44)} = 8.41$, $p = 0.0008$) and spacer thickness ($F_{(1,22)} = 6.86$, $p = 0.0157$) were found. Neither membrane thickness nor any of the interactions was significant. Post-hoc analysis determined that subjects preferred touchpads with an aperture diameter of 12.70 mm over those with 9.525 and 6.350 mm diameters. Touchpads with a spacer thickness of 0.127 mm were preferred over those with 0.254 mm spacers.

The highly significant effects in the structural analysis, especially after RAF differentials were accounted for, suggests that structure, in addition to RAF, does play a role in applied force and keypress duration as well as preference for membrane switch touchpads. The larger aperture diameters received higher preference ratings, elicited lower forces, and resulted in keypresses of shorter

duration than the smaller aperture diameters. Membrane thickness did not affect initial differences in applied force; however, after 50 to 100 keypresses (1 to 2 Periods), the force trends for different membrane thicknesses opposed one another. Users of touchpads with 0.127 mm membranes exerted successively decreasing forces as a function of time while users of those with 0.254 mm membranes exerted successively increasing forces over time.

These opposing trends might be explained as a difference in the tactile and kinesthetic characteristics that yield a small degree of feedback. While no general adaptation trend appears to occur, the successive reduction in forces applied to touchpads with membrane thicknesses of 0.127 mm illustrates a small but statistically significant effect which could be explained as an adaptation trend. The user exerts successively lesser forces without a loss of reinforcement of the activity, as previously exerted excessive forces were unnecessary. Although applied force levels still remain substantially higher than required levels, some improvement results.

For touchpads with a membrane thickness of 0.254 mm, an opposite trend occurs. This may indicate that any level of tactile or kinesthetic feedback inherent in the switch structure is less salient or imperceptible with the thicker membrane. Hence, the user does not adapt to the required force levels. Instead, the higher resistance of the membrane results in greater applied forces corresponding to higher RAFs. The increasing trend may be attributable to fatigue. Exerting higher levels of force will be more fatiguing than the lower force levels typically exerted on thinner membranes. As the subject strives to maintain accuracy and speed criteria (which were emphasized in instructions to

the subjects), other measures of the task, in this case applied force, show the influence of fatigue. In addition to fatigue, the greater resistance and corresponding increased difficulty of switch actuation may lead to increased frustration or other psychological effects which impact keying behavior. This might also explain the increasing forces applied over time.

## EXPERIMENT II: OVERLAY

This experiment investigated the effect of membrane switch aesthetic overlays on performance. Six overlays—flat (FL), flat with an escutcheon overlay (ES), embossed key borders (EM), kinesthetic domes (DO), embossed key borders with domes (ED), and keycaps with domes (KC)—were evaluated.

### *Subjects*

Eighteen subjects, nine male and nine female, participated in this experiment. Subjects were similar to those participating in Experiment I with regard to recruitment and experience with touchpad devices. However, individuals who participated in Experiment I did not participate in this experiment.

### *Apparatus*

The force measurement instrumentation and stimulus presentation and process control software previously described and used in Experiment I was also used in this experiment.

*Membrane touchpads.* Six touchpads were used in this experiment. Four touchpads were unmodified, commercially available membrane touchpads (Honeywell Keyboard Division, El Paso, TX). These included a flat touchpad (Part No. TCA131-2), embossed touchpad (Part No. TCA331-2), a touchpad with metallic domes (Part No. TCA231-2), and an embossed touchpad with metallic domes (Part No. TCA431-2). Two additional touchpads were modified for use in this experiment. A touchpad with an escutcheon overlay was

configured by cementing a 0.71 mm thick escutcheon overlay to a flat touchpad, as specified above. A touchpad with tactile keycaps was also constructed, incorporating the three-layer membrane switch base from the flat touchpad specified above, and adding keycaps and domes. The keycaps were made of plastic and were square, with a stem protruding from the underside. To this stem; a dome of the same type used in the domed touchpads specified above, was cemented. The keycaps were mounted within a bezel which was cemented to the membrane switch base. The keycaps and bezel were painted to match the other touchpads. A diagram of the six overlays is shown in Figure 28. Emboss height for the EM and ED touchpads was 0.71 mm and the domes used in the DO, ED, and KC touchpads exhibited nominal displacement of 0.43 mm. All utilized the standard telephone key layout, with 19.1 mm center-to-center spacing as shown previously.

*Experimental Design*

A repeated measures design employing three repetitions of a complete Latin square to control for presentation order and stimulus set effects was used. Within-subjects factors were Touchpad, Period, and Digit. A diagram of the experimental model is shown in Figure 29. Dependent variables included DWMF, AAMF, EDWMF, EAAMF, and keypress duration, as defined in Experiment I.

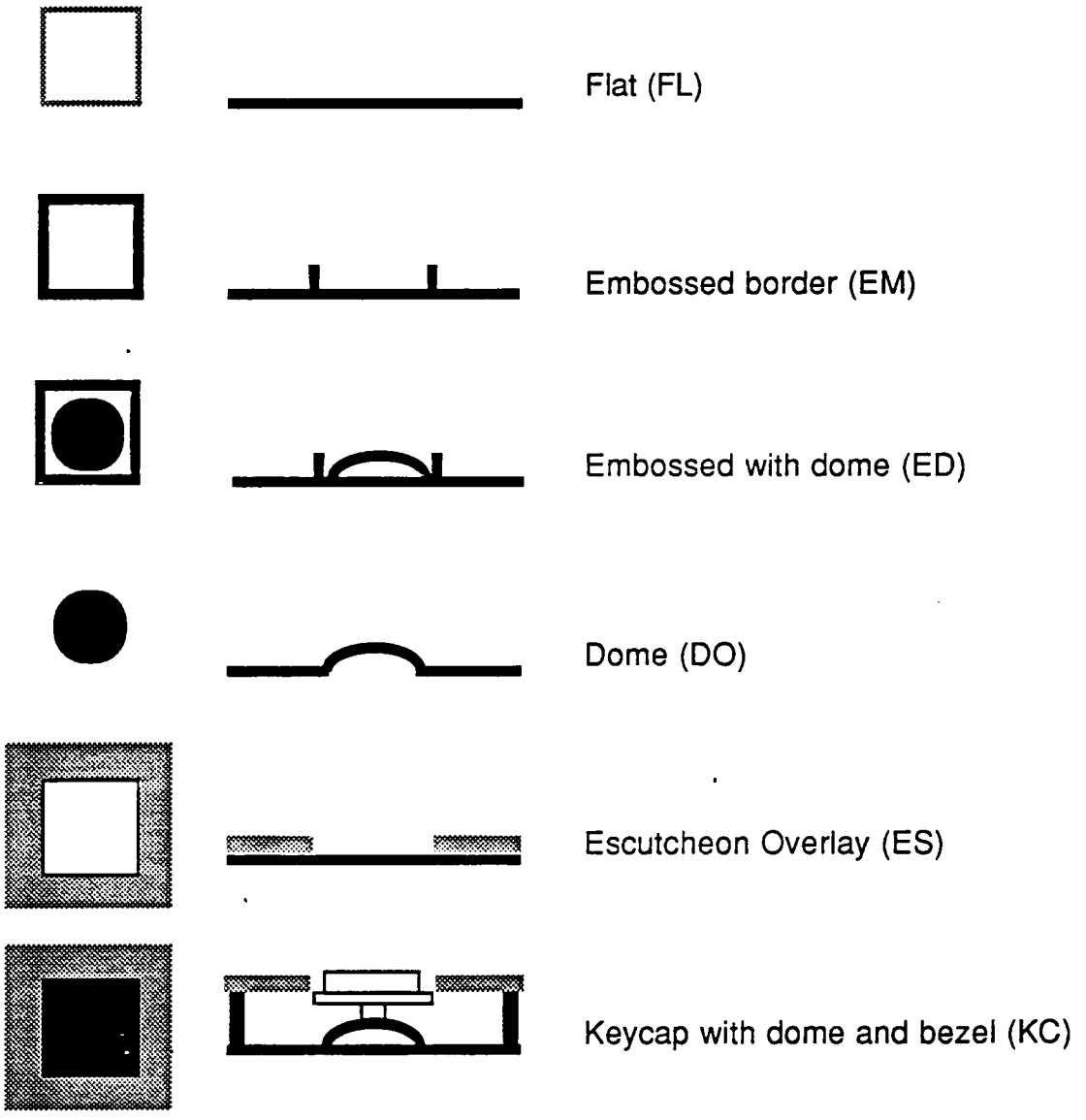



Figure 28. Six aesthetic overlays used in Experiment II.

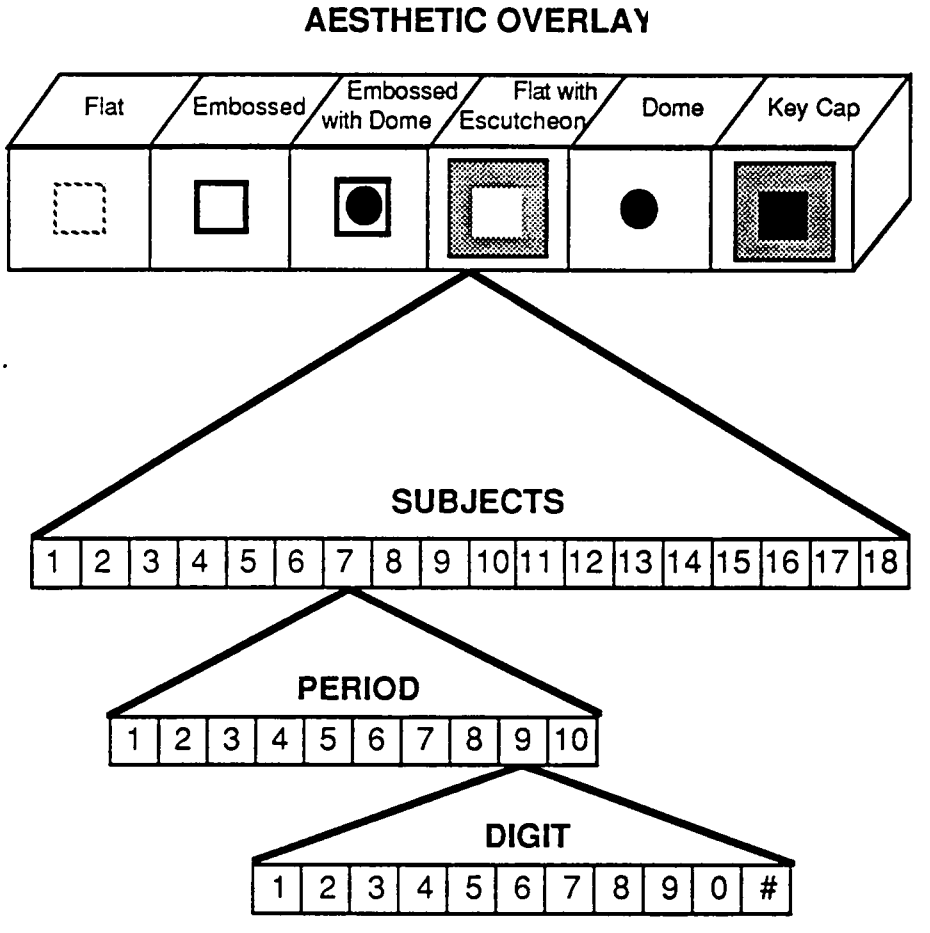



Figure 29. Experimental design for aesthetic overlay study.

*Procedure*

The calibration procedures, experimental protocol, and data collection and handling procedures for Experiment II were identical to those in Experiment I. The minimum RAFs for the six touchpads are shown in Table 20.

*Results and Discussion*

Parametric analyses were performed on the force, duration, and excessive force measures, as well as the subjective ratings. As with Experiment I, the four force measures (AAMF, DWMF, EAAMF, and EDWMF) exhibited very similar results.

The Analysis of Variance procedure was used to analyze the data. Summary tables for each of the six dependent measures may be found in Tables 46 to 51, Appendix H. A significance level of $p < 0.05$ was used for both the ANOVA and post-hoc Newman-Keuls multiple comparisons. Results are presented below by dependent measure.

*Duration-Weighted Mean Force.* The ANOVA summary table for the dependent measure DWMF is presented in Table 46, Appendix H. The main effect of Touchpad ($F_{(5,80)} = 51.48$, $p < 0.0001$) demonstrates an effect of the type of overlay on the forces exerted. The dome (kinesthetic), flat (no feedback), and escutcheon (tactile) overlays elicited significantly greater forces than did the embossed with dome (kinesthetic + tactile), embossed (tactile), and keycap with dome (kinesthetic + tactile) overlays. The ED overlay elicited greater

Table 20. Minimum Required Actuation Forces for Touchpads used in Experiment II

| Touchpad | Minimum RAF |
|---|---|
| Dome (DO) | 3.923 N |
| Embossed with Dome (ED) | 3.530 N |
| Embossed (EM) | 2.059 N |
| Escutcheon Plate (ES) | 3.138 N |
| Flat (FL) | 2.746 N |
| Key Caps (KC) | 3.530 N |

applied forces than the embossed overlay without a dome, although the ED overlay had a higher RAF than the EM overlay. Of the three configurations with domes, the KC overlay elicited significantly lesser forces than either the ED or DO overlays. The mean forces exerted along with the results of the multiple comparisons are presented in Table 21.

The main effect of Period ($F_{(9,144)} = 8.69$, $p < 0.0001$) demonstrates a slight increase in applied force over time. Subjects applied a mean force of 11.736 N during Period 10, compared with 10.153 N during Period 1. The increase in force between successive periods is greatest between Periods 9 and 10. The mean applied force and the results of the post-hoc comparisons are shown in Table 22.

A main effect of Digit was found ($F_{(10,160)} = 157.58$, $p < 0.0001$). Key locations in the far right corner (Digits 2, 3, and 6) were pressed significantly harder than those in the near left and near edge locations (Digits 4, 5, 7, 8, 0, and #). The *0* key location was pressed with the least force (10.285 N).

The interaction of Period by Digit ($F_{(90,1440)} = 3.48$, $p < 0.0001$) was also found. This effect, however, was considered to be of little practical interest. It is perhaps attributable in part to the higher power attained through the large number of observations and thus the many degrees of freedom in the test of the Period by Digit interaction.

*Absolute Amplitude Mean Force.* The ANOVA summary table for the dependent measure AAMF is shown in Table 47, Appendix H. The main effect

Table 21. Newman-Keuls Comparison of Means for DWMF: Main Effect of Touchpad

| Touchpad | Mean (N) | |
|---|---|---|
| Keycaps (KC) | 7.718 | |
| Embossed (EM) | 8.928 | |
| Embossed with Dome (ED) | 10.903 | |
| Escutcheon (ES) | 12.381 | ▒ |
| Flat (FL) | 12.650 | ▒ |
| Dome (DO) | 13.036 | ▒ |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 22. Newman-Keuls Comparison of Means for DWMF: Main Effect of Period

| Period | Mean Force (N) |
|---|---|
| 1 | 10.153 |
| 2 | 10.537 |
| 3 | 10.545 |
| 4 | 10.905 |
| 6 | 10.956 |
| 7 | 11.059 |
| 5 | 11.117 |
| 8 | 11.132 |
| 9 | 11.217 |
| 10 | 11.736 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

of touchpad ($F_{(5,80)} = 25.45$, $p < 0.0001$) clearly demonstrates an effect of touchpad overlay. As with the DWMF measure, highest forces were found to be exerted on the DO, FL, and ES touchpads. The KC and EM touchpads elicited the least force. Although the ED and KC touchpads had the same RAF, subjects applied significantly more force to the ED touchpad. The mean AAMFs and multiple comparisons are shown in Table 23.

A main effect of Period ($F_{(9,144)} = 3.17$, $p = 0.0016$) again shows a slight increase in the force applied over time, as significantly higher forces were applied in Period 10 than in previous periods. Table 24 gives the mean forces applied and multiple comparisons for the main effect of Period. The effect of Period is shown graphically in Figure 30, for both the AAMF and DWMF metrics. An effect of Period (i.e., a systematic change in applied force as a function of the number of keypresses completed) might be indicative of overall changes in keying behavior. Such changes, in turn, might be attributable to changes in keying strategy resulting from adaptation or the learning of effective keying techniques. Alternatively, such changes might identify fatigue-related phenomena. Because the Period effect demonstrated performance changes which resulted in less efficient keying in subsequent periods, as the applied forces continued to increase beyond what was necessary for actuation, the effect of Period identified here most likely is attributable to fatigue. This effect is discussed further in the conclusions.

Table 23. Newman-Keuls Comparison of Means for AAMF: Main Effect of Touchpad

| Touchpad | Mean (N) | |
|---|---|---|
| Keycaps (KC) | 9.181 | ▒ |
| Embossed (EM) | 10.616 | ▒ |
| Embossed with Domes (ED) | 12.550 | |
| Escutcheon (ES) | 15.039 | ▒ |
| Flat (FL) | 15.134 | ▒ |
| Domes (DO) | 15.721 | ▒ |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 24. Newman-Keuls Comparison of Means for AAMF: Main Effect of Period

| Period | Mean Force (N) |
|---|---|
| 1 | 11.762 |
| 3 | 12.678 |
| 2 | 12.692 |
| 6 | 12.930 |
| 4 | 12.940 |
| 9 | 13.013 |
| 7 | 13.085 |
| 5 | 13.161 |
| 8 | 13.208 |
| 10 | 14.933 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

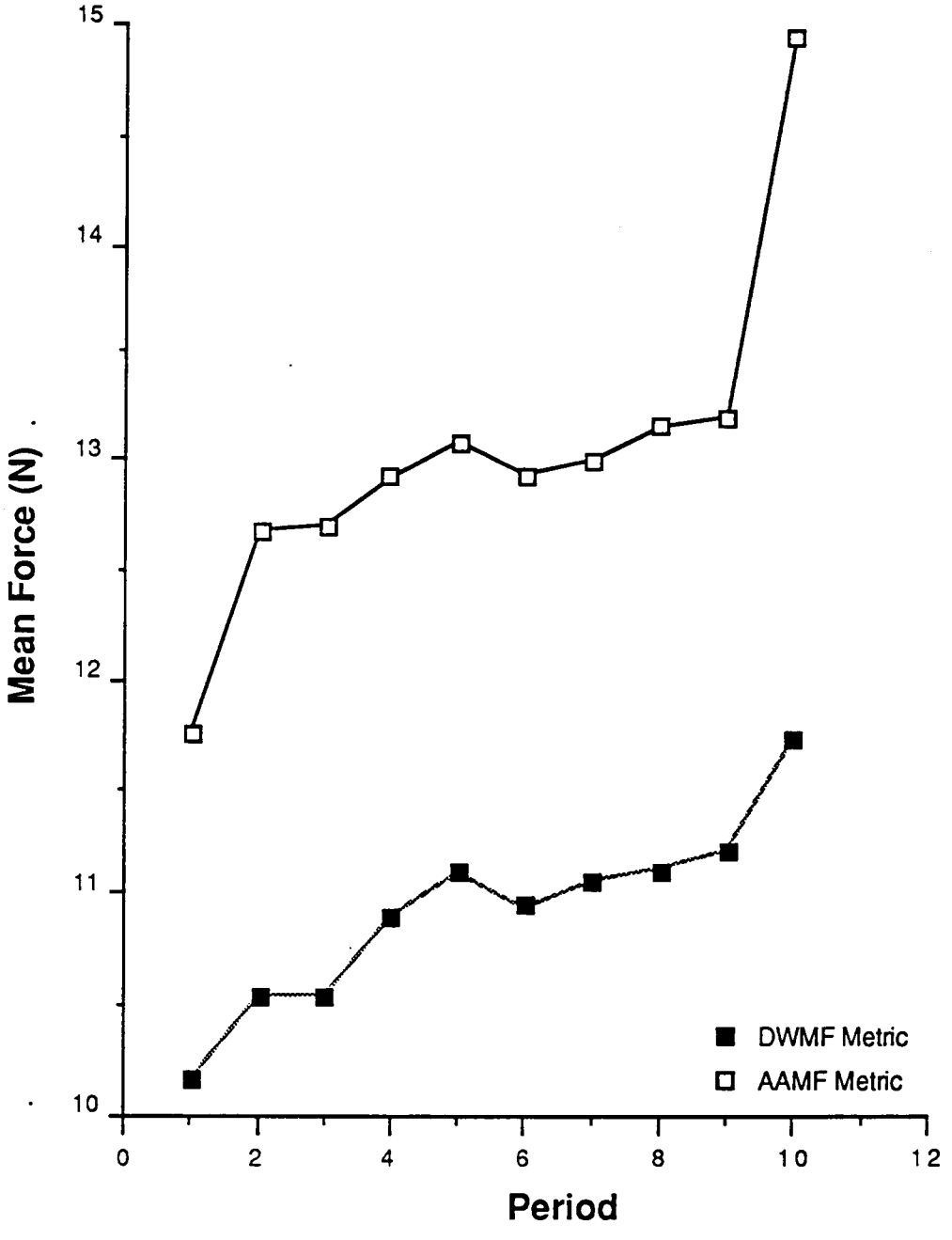



Figure 30. Main effect of Period for the dependent measures absolute amplitude mean force and duration-weighted mean force.

A significant interaction of Period by Digit ($F_{(90,1440)} = 2.02$, $p < 0.0001$) was also found for the dependent measure AAMF. This effect is of little practical interest for the reasons previously stated.

*Excessive Force: EDWMF Metric.* The ANOVA summary table for the dependent measure EDWMF may be found in Table 48, Appendix H. Recalling that the EDWMF is the DWMF measure corrected for the RAF of individual touchpads, the sums of squares and mean values for all effects except for the main effect of touchpad remain the same. Hence, only the main effect of touchpad ($F_{(5,80)} = 48.24$, $p < 0.0001$) is presented. The mean excessive force and post-hoc comparisons are presented in Table 25. As with the dependent measure DWMF, which does not account for different RAFs among touchpads, the DO, ES, and FL touchpads elicited significantly higher forces than the other touchpads. However, while the DWMF showed significant differences between the EM and ED touchpads, when corrected for the RAF differentials, the forces elicited by these two touchpads are not significantly different. Although subjects exerted greater forces on the touchpads with domes, these differences were most likely due to the higher RAF of dome touchpads. The touchpad with the keycap overlay elicited the lowest forces applied and the lowest excessive forces.

It is interesting that the embossed touchpad, one that provides tactile but not kinesthetic feedback, elicited lower forces than non-tactile touchpads.

Table 25. Newman-Keuls Comparison of Means for EDWMF: Main Effect of Touchpad

| Touchpad | Mean Force (N) | |
|---|---|---|
| Keycaps (KC) | 4.188 | |
| Embossed (EM) | 6.869 | ▒ |
| Embossed with Domes (ED) | 7.373 | ▒ |
| Domes (DO) | 9.113 | ▒ |
| Escutcheon (ES) | 9.242 | ▒ |
| Flat (FL) | 9.904 | ▒ |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Tactile feedback is generally provided as a means for aiding key localization, while kinesthetic feedback is generally thought to provide the user with information as to actuation. However, when the surface area of the finger is such that it contacts the embossed border during actuation, the tactile sensation may aid in reducing excessive forces. When the volar surface of the finger contacts the key, the surface area of the finger is most likely to exceed the dimensions of the key, thereby resulting in contact with the embossed border.

Although the emboss height and the escutcheon thickness were the same, it is still possible that the saliency of tactile differences between the two touchpads differed. Geldard (1972) noted that the physical phenomenon that gives rise to the sensation of pressure within the fingertip is the relative deformation of adjacent skin areas, with steeper deformation gradients facilitating stronger tactile sensations. The deformation gradient varies as a function of the surface area deformed. The embossed border may provide more salient tactile feedback than the escutcheon overlay, despite their equivalent thicknesses, in that the embossed border is a very narrow, dual-edge surface while the escutcheon provides a single-edge gradient and a plane surface. Because the contact area of the embossed border is less than that of the escutcheon overlay, a steeper deformation gradient, and thus a stronger tactile sensation, may result. Basic research into the sensory thresholds of plane and edge contact pressure might provide some guidance in explaining differences between the tactile sensations of the two overlays.

*Excessive Force: EAAMF Metric.* The ANOVA summary table for the dependent measure EAAMF may be found in Table 49, Appendix H. The main

effect of touchpad found for the dependent measure AAMF remains significant when the measure is corrected for RAF differentials ($F_{(5,80)} = 23.95$, $p < 0.0001$). Table 26 presents the means and multiple comparisons. For both the AAMF and EAAMF dependent measures, touchpads with DO, ES, and FL overlays elicited significantly greater force than others. However, EM and ED touchpads are not significantly different with regard to excessive applied forces, although significantly greater force was applied to the ED touchpads. Again, the greater applied forces were likely the result of a greater RAF for the DO touchpad. Finally, while essentially equivalent force levels were applied to the KC and EM touchpads, when corrected for RAF differentials, it can be seen that the KC touchpad elicited significantly less excess force.

*Duration.* The ANOVA summary table for the dependent measure Duration is given in Table 50, Appendix H. In addition to different mean force levels applied to the different touchpads, a main effect of Touchpad was found for the dependent measure Duration ($F_{(5,80)} = 3.03$, $p = 0.0148$). Keypress durations on the FL touchpad were significantly longer than those on the ED touchpad, although other differences in keypress duration were not significant (Table 27). As the FL touchpad was the only touchpad void of feedback (except for the supplemental auditory tone), this may suggest that tactile as well as kinesthetic feedback in the form of embossing, escutcheon overlays, domes, and keycaps provides salient and important information regarding actuation.

Keypress duration varied significantly over time, as evidenced by a main effect of Period ($F_{(9,144)} = 429.74$, $p < 0.0001$). Keypress duration increased monotonically over all periods, with significant increases occurring between all

Table 26. Newman-Keuls Comparison of Means for EAAMF: Main Effect of Touchpad

| Touchpad | Mean Force (N) |
|---|---|
| Keycaps (KC) | 5.651 |
| Embossed (EM) | 8.557 |
| Embossed with Domes (ED) | 9.020 |
| Domes (DO) | 11.798 |
| Escutcheon (ES) | 11..901 |
| Flat (FL) | 12.388 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

Table 27. Newman-Keuls Comparison of Means for Duration: Main Effect of Touchpad

| Touchpad | Mean (s) | | |
|---|---|---|---|
| Embossed with Dome (ED) | 0.2178 | ▒ | |
| Keycap (KC) | 0.2252 | ▒ | ▒ |
| Embossed (EM) | 0.2333 | ▒ | ▒ |
| Escutcheon (ES) | 0.2512 | ▒ | ▒ |
| Dome (DO) | 0.2519 | ▒ | ▒ |
| Flat (FL) | 0.2543 | | ▒ |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

periods except Periods 4 and 5, 8 and 9, and 9 and 10. This suggests that an asymptotic level for keypress duration does occur, and does so in the latter periods, after approximately 400 to 500 presses.

As with the force measures, a main effect of digit was found for the dependent measure duration ($F_{(10,160)} = 86.69$, $p < 0.0001$). The mean duration and multiple comparisons are shown in Table 28. The Digit 3 was pressed for a longer duration than all other numerical keys. As in Experiment I, of all keys, presses to the # key were significantly longer. The implications of this finding were described previously, in the results of Experiment I.

*Subjective Ratings.* The ANOVA summary table for the dependent measure subjective ratings is found in Table 51, Appendix H. A main effect of Touchpad ($F_{(5,85)} = 2.49$, $p = 0.0374$) demonstrates preferences among subjects for particular touchpads. The Newman-Keuls multiple comparison of means failed to isolate the effect, finding no means significantly different from one another. Fisher's Least Significant Difference (LSD) test was also used. Although the LSD controls the Type I comparison-wise error, it does not control for experiment-wise error. Hence, it is more prone to Type I errors than the Newman Keuls test. The LSD found the touchpad with a keycap overlay to be preferred over all others. Differences between other touchpad ratings were not significant.

Given the power of the LSD, its lack of discrimination between mean ratings for the various overlays is interesting. Despite strong differences in applied forces and keypress duration, subjects did not exhibit a strong

Table 28. Newman-Keuls comparison of means for Duration: Main effect of Digit

| Digit | Mean (s) |
|---|---|
| 7 | 0.2293 |
| 6 | 0.2294 |
| 8 | 0.2309 |
| 2 | 0.2315 |
| 0 | 0.2325 |
| 5 | 0.2351 |
| 9 | 0.2361 |
| 4 | 0.2366 |
| 1 | 0.2412 |
| 3 | 0.2432 |
| # | 0.2815 |

Note: Means adjacent to the same bar are not significantly different at $p \leq 0.05$.

preference for specific touchpad overlays. That the keycap overlay may be preferred over others is less important, in that this discrimination is accompanied by a higher probability that it is, in fact, a chance finding.

Additionally, these ratings were made after subjects had sufficient experience with all touchpads. The statement by Alden et al. (1972) that subjective preferences are related to experience is important here. Whether an individual has a preference for one touchpad over another may depend on his or her experience with those touchpads. For short-term use, it is quite possible that visual aesthetic influences or other factors may be more important and yield significant preferences. In a high-performance oriented task situation like that which subjects experienced in this study, the lack of significant preferences does not suggest the relative superiority of one overlay over others.

# CONCLUSIONS

An ideal keypress can be defined as one which maximizes efficiency while maintaining effectiveness, and which minimizes discomfort to the user and wear to the switch device. Both spurious and omitted inputs must be minimized and the potential for rapid keying (i.e., efficiency) must be maximized. A switch which leaves the user prone to excessive fatigue emanating from its use must also be avoided, as should a switch which exhibits a low life expectancy for its intended use. In terms of the force and duration measures used in this study, an *ideal keypress* would be one with the shortest duration that results in a valid press and an exerted force that only slightly exceeds the RAF.

## *Adaptation and Fatigue Effects*

Whether users can learn to adapt their behavior or to in some way become accustomed to the operating characteristics and adapt their behavior to approximate the ideal keypress described above was addressed as part of this study. Significance of the Period effects suggests that changes do occur over time; analysis of these changes is necessary to ascribe the changes to the effects of learning or adaptation versus fatigue.

An adaptation effect would be illustrated by the approach of force and duration levels to approximate the ideal keypress, previously defined. As found in both experiments, applied force levels remain substantially higher than necessary for actuation for all touchpads.

The significant interaction between Membrane Thickness and Period for applied force metrics in Experiment I, however, suggests that some degree of adaptation may be mediated by design. Touchpads with thinner membranes elicited less force than touchpads with thicker membranes. Because this adaptation is correlated with RAF differentials inherent in different membrane thicknesses, this result is not surprising. However, since the applied force trends showed opposing directions over subsequent periods, with thinner membrane touchpads demonstrating a slight adaptive trend, it appears that structure influenced the application of force.

Between-touchpad adaptation was observed. Subjects applied differential forces to touchpads with different RAFs, specifically higher forces to touchpads with higher RAFs. This relationship is not illustrated in the Period effect, most likely because it occurs very rapidly, perhaps within the first few keypresses. Two null keypresses preceded data collection, when the subject pressed the # key to advance through the task instructions. The learning of touchpad characteristics may have occurred during these two presses and actually concluded before data collection began. Although force and duration data were not collected for these two presses, the experimenter observed that subjects had a higher instance of omitted inputs for the task instruction advance keypresses, particularly for those touchpads with higher RAFs. Thus, it appears that adaptation to touchpad characteristics might occur within the first few keypresses. Overall, subjects did not continue to adapt (optimize) their behavior to yield the ideal keypress, except when the structure of the touchpad was taken into account, as previously stated.

A fatigue effect would not likely result in a sharp drop in performance or even a clear decline, as noted by Welford (1953). Instead, fluctuations in performance are a more likely indicator of fatigue. The nature of fatigue requires that these fluctuations have an overall deleterious effect (Bartlett, 1953).

In this study, subjects were given instructions to maintain accuracy and speed during the keying task studied. Subjects were, however, unaware of the fact that force and keypress duration were being measured. Goldmark (1912) and Wells (1912) demonstrated that performance decrements resulting from fatigue may be masked by augmented efforts of subjects. Particularly if subjects are aware of the criteria being monitored, they are likely to strive to maintain those criteria. As fatigue intervenes, subjects will continue to maintain those criteria by changing strategies or methods as asserted by Welford (1953). Fatigue effects would thus be demonstrated in aspects of the task which the subject compromises to maintain the criteria.

In striving to maintain speed and accuracy, fatigue may manifest itself in a change in keying technique. Thus, the monotonic increase in keypress duration might be attributable to fatigue. Ballistic tapping methods yield a short duration press, although slower, deliberate pressing yields a longer duration press. Subjects likely compensated for fatigue by altering their keying technique rather than sacrifice speed or accuracy.

*Differences among Touchpads*

In these experiments, it was found that subjects exert substantially greater forces than necessary for actuation of the membrane switch touchpads, regardless of RAF, structure, or overlay. Peak forces ranging from approximately 8 N to over 30 N were applied to touchpads with minimum RAFs between 0.6 N and 5.2 N. The RAF influenced the forces exerted on touchpads—subjects did differentiate among touchpads of differing RAFs by applying greater forces to those touchpads with higher RAFs. In addition, keypress durations were longer for touchpads with high RAFs and shorter for touchpads with low RAFs. However, when RAF differentials were accounted for, systematic variations in applied force indicate that other factors influenced the applied force. Membrane construction appears to be one such factor.

Thicker membranes elicited disproportionately greater applied forces over time than did thinner membranes. Touchpads with virtually the same RAFs exhibited significant differences in applied force as a function of structure. Smaller spacer aperture diameters yielded disproportionately greater applied forces. In general, thicker spacers elicited greater applied forces than did a thinner spacer; however, when RAF differentials were taken into account, this relationship reversed. For touchpads with equivalent RAFs; those with thin membranes, thick spacers, and large spacer aperture diameters elicited the least force.

Thus, structure clearly affects the forces applied to membrane switch touchpads and should be considered not a by-product of RAF attainment, but an important human factors design consideration in its own right.

As for feedback provisions, the present research found that when auditory feedback is provided, tactile feedback (in the form of embossed key borders) may be more effective than kinesthetic feedback (in the form of metal domes) for reducing the forces exerted by extended-use keyers. Touchpads which incorporated metal domes elicited significantly greater forces than similar configurations without domes. Touchpads with embossed key borders elicited significantly lower applied forces than similar configurations without embossing. Although domes increase the switch's RAF and embossing typically decreases the RAF, differences in the RAFs among touchpads were insubstantial relative to the differences in applied force.

When auditory feedback is provided, the addition of tactile and/or kinesthetic feedback to membrane switch devices does not have a significant effect on user preferences. Differences in subjective ratings for Experiment I (Structure) but not Experiment II (Overlays) suggests that RAF may be more important for preference than feedback provided by the aesthetic overlay.

*Experimental Task*

Studies comparing conventional, full-travel keyboards with membrane keyboards have demonstrated some performance advantage to the conventional key technologies and definite preferences for the full-travel devices. Guidelines emanating from these studies recommend the use of

conventional key technologies which provide salient feedback over membrane alternatives. For many applications, particularly those where extended use, high entry rates, and 10-finger keying are required, full-travel devices have a clear advantage. Where environmental concerns dictate the use of membrane switch devices, improving the human operating characteristics of these devices is necessary.

The purpose of this research was to study membrane switch touchpad use for those applications for which they may not be ideally suited, but for which no other viable alternative exists. Examples of such use would include touchpanels on process control equipment located in the harsh environs of a factory floor, touchpanels on fast-food cash registers, and touchpanels on photographic processing systems and medical equipment, which would likely be exposed to dust, liquid, or chemical contamination and hence require a switch with sealed construction. Accordingly, the task used in this experiment might not be considered typical of those ascribed to membrane touchpanels in general use. Subjects in the experiments described herein entered data via the membrane touchpads over a period of 10 to 25 minutes. In applications such as those stated above, an operator may use the touchpanel for extended periods of time, not unlike the subjects in these experiments. Therefore, for the purposes of this research, the task chosen was justified. Generalization of the findings reported herein should be approached with caution, as the task scenario and conditions are likely to affect performance. However, many of the fundamental concepts of structure and aesthetic overlays would be similar despite differing task scenarios.

*Switch Life Testing Implications*

This research demonstrates an effect of influences (in addition to RAF) which affect forces applied to membrane touchpanels. Life testing of membrane switches typically accounts for RAF differences by applying the minimum RAF. However, current life testing practices do not account for differences in the structure of the membrane switch or in the feedback conditions which would affect the manner in which they are used in application. Life testing of membrane switch devices is a closed-loop system, whereas human keying behavior makes use of sensory feedback to mediate behavior and its resulting effect on the device. The validity of life testing estimates is related to the extent to which they accurately represent end-use conditions. Thus, the present results suggest that current life-testing procedures require modification.

*Human Factors Design Recommendations*

As noted above, application of typical applied forces to touchpads is necessary for valid life-estimation for membrane touchpads. Switch durability is an important consideration for designing or specifying membrane switch touchpads. Data on switch life should be considered and incorporated with the following recommendations, based on the results of the present research. It should be noted that these recommendations apply to extended-use keying applications, although they might also be of benefit in casual-use scenarios as well.

- The lowest RAF appropriate to the application should be used, incorporating an effective bounce protection mechanism.

- Recalling that a thicker membrane, a thicker spacer, or a smaller spacer aperture yields a greater RAF than a thinner membrane, a thinner spacer, or a larger aperture, the results of this study suggest that a thin membrane and a large spacer aperture should be used to minimize applied forces. As necessary, increased resistance may be achieved by using a thicker spacer, which appears to have the additional benefit of eliciting less force than thinner spacers. Specific construction parameters should also take into account durability/switch-life data, and hence are not quantitatively specified here.

- When auditory feedback is provided, supplemental kinesthetic feedback is redundant. Because supplemental kinesthetic feedback (i.e., metal domes) increases the RAF of the switch, typically shortens the life expectancy of the switch, increases the cost of the configuration, and does not appear to reduce applied forces or influence preference, the addition of supplemental kinesthetic feedback is undesirable. This recommendation is in accordance with the findings of Roe (1984), and is limited to configurations where supplemental kinesthetic feedback is a *redundant* indicator of actuation.

- Even when auditory feedback is provided, supplemental tactile feedback is desirable. As auditory feedback provides information regarding actuation while tactile feedback provides information regarding key localization, these forms of feedback are not redundant. Furthermore, tactile feedback typically reduces the RAF of the membrane switch, does not appear to appreciably degrade switch life, adds minimally to the cost of the configuration, and appears to reduce applied forces.

• The addition of tactile+kinesthetic keycaps to membrane switch touchpads is recommended as a general strategy for improving preference and reducing applied forces. For some applications, particularly where ease of maintenance in a harsh environment is paramount, keycaps might not be pratical. Furthermore, it is recognized that such keycaps may increase the cost of the configuration by 100% to 500%. However, the tactile+kinesthetic keycaps used in this study significantly reduced applied forces compared to a switch with the same RAF which incorporated tactile and kinesthetic feedback in the form of an embossed key border and metal dome.

Additionally, it should be realized that the tactile+kinesthetic keycaps used in this study are quite crude, relative to the numerous varieties currently available on the market, such as the full-travel keycaps which give membrane switches the same feel and operating characteristics of non-membrane devices. While ease of maintainability is compromised with the addition of keycaps, these types of touchpads are often still appropriate for many harsh environments, as the sealed base construction nonetheless maintains switch integrity.

*Further Research Needs*

In addition to the effects previously discussed, these experiments have demonstrated the feasibility of obtaining objective measures of the forces exerted on touchpanel switch devices. Since the inception of this research, significant progress has been made by the membrane switch manufacturing

industry to develop innovative and appealing aesthetic overlays which were not available before. Evaluation of new overlay types would be beneficial.

The force platform system and the process control software developed for use in this experiment would be suitable for related research as to the forces applied to touchpanel switch devices. The experiments described herein provided supplemental auditory feedback for all experimental conditions. Research which evaluated the forces applied in the absence of any feedback could yield useful information concerning the basic perception, expectancies, and use of touchpanel switch devices. The platform/software system is capable of simulating a touchpad even in the absence of the membrane structure. Research to assess the forces people prefer or are capable of applying could be assessed independent of touchpad structure, and used as a guide for future switch designs. In addition, true aesthetic design parameters (i.e., color, contrast, and graphical representation aspects of the overlay) could be evaluated with respect to their effect on keying behavior. Such aesthetic design parameters may have particular relevance with respect to casual-use applications, such as ATMs, vending machines, etc.

Finally, research which relates the forces applied by users to the resulting effects on switch life and performance would be extremely valuable in optimizing the performance/reliability aspect of touchpanel switch design. By combining reliability/switch-life data with the human performance data obtained in the present study, it should be possible to model switch construction and feedback parameters to identify optimal switch configurations.

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# APPENDIX A

# STIMULUS PRESENTATION AND PROCESS CONTROL SOFTWARE

```
10 REM PROGRAM: PAULA113.BAS
20 REM DATA ACQUISITION SYSTEM FOR MEMBRANE SWITCH STUDY
30 REM BY ROBERT T. KINTZ, Ph.D.
40 :
50 :
60 REM VERSION 11.0: DECEMBER 27, 1988
70 REM : INCORPORATES SUBJECT QUESTIONNAIRE
75 REM VERSION 11.1: JANUARY 25, 1989
76 REM : CHANGES OUTPUT TO 80 COLUMN FORMAT
77 REM VERSION 11.2: JANUARY 27, 1989
78 REM : INPUTS SESSION NUMBER AND REVISED DEMOGRAPHICS
79 REM VERSION 11.3: FEBRUARY 3, 1989
80 REM : INCORPORATES DURATION LOGGING FOR 4-DIGIT STIMULUS
81 REM : AND CALIBRATION VARIANCE TOLERANCE CHECKING
82 :
90 REM WRITTEN IN MICROSOFT QUICKBASIC 4.5
100 REM : INCORPORATES BURR-BROWN PCI-20090S-1 SOFTWARE DRIVERS
110 :
120 :
270  ' *** Header File for PCI-20090S-1 BASIC Interface ***
280  '
290  DEFINT A-E, G-Z
300  '
310  ' Define the internal signature
320  '
330  DIM VCHK(6): VCHK.L = 6
340  DIM VERS(6): VERS.L = 6
350     VERS(1) = 512
360     VERS(2) = 32
370     VERS(3) = 32
380     VERS(4) = 8192
390     VERS(5) = 8192
400     VERS(6) = 32
410  '
420  ' Define the PCI-20090S-1 instruction offsets.
430  '
440     AUTOGRPH = 12
450     CNF.AI = 18
460     CNF.CNTR = 24
470     CNF.HS = 30
480     CNF.RG = 36
490     CNF.TCPL = 42
500     ERR.SYS = 54
510     HS.RUN = 60
520  '
```

```
530     INIT = 66
540     READ.CH = 72
550     READ.FRQ = 84
560     STAT.CNT = 96
570     SYSINIT = 102
580     WRITE.CH = 108
590  ' Define the PCI-20090S-1 I/O types.
600  '
610     AI = 1
620     CT = 3
630     RG = 8
640     TCPL = 9
650  '
660  ' Thermocouple types supported:
670  '
680     TYPE.J = 74
690     TYPE.K = 75
700     TYPE.T = 84
710  '
720  ' Check for installed software
730  '
740  DEF SEG = 0: INTVEC = &H180
750  SEGMT = PEEK(INTVEC + 2) + &H100 * PEEK(INTVEC + 3)
760  DEF SEG = SEGMT
770  IF (SEGMT <> 0) AND (PEEK(11) = 1) AND (PEEK(12) = &H9A) THEN 790
780  PRINT "PCI-20090S-1 not installed or invalid.", CHR$(7): END
790  CALL ABSOLUTE(VERS.L, VCHK(1), VCHK.L, AUTOGRPH)
800  IF (VCHK.L <> VERS.L) THEN 780
810  FOR I = 1 TO VCHK.L: IF (VERS(I) <> VCHK(I)) THEN 780
820  NEXT I
830 :
840 REM SET UP ARRAYS FOR LOAD CELL DATA, SUBJECTIVE EVALUATIONS, AND THRESHOLD
860 DIM LC(1, 5, 7, 100)
870 DIM TC(1, 5, 0, 100)
880 DIM A$(100, 4)
890 DIM TIM#(5, 5)
900 DIM QUEST$(7)
920 DIM CALDATA(65, 7)
925 :
930 :
940 :
950 REM BEGIN WITH KEYPAD COUNTER AT 0
960 KPAD = 0
970 :
980 KEY OFF: CLS
```

```
990 :
1000 REM CONFIGURE BURR-BROWN PCI-20089W-1 BOARD
1010 CALL ABSOLUTE(SYSINIT)
1020 REM INITIALIZE BOARD
1030 SEGMT = &HCD80
1040 CALL ABSOLUTE(SEGMT, INIT)
1050 :
1060 REM CHECK FOR ERRORS
1070 CALL ABSOLUTE(ERROR.CODE, ERR.SYS)
1080 IF ERROR.CODE <> 0 THEN PRINT "ERROR: "; ERROR.CODE: STOP
1090 :
1100 REM CONFIGURE ANALOG INPUT CHANNELS (0-6)
1110 REM TO GAIN OF 1 WITH NO AUTO ZERO CHANNEL
1120 CHN = I
1130 GAIN = 1
1140 RANGE = 1
1150 FOR I = 0 TO 6
1160 CALL ABSOLUTE(CHN, GAIN, Z.CHN, RANGE, CNF.AI)
1170 PRINT I
1180 :
1190 REM CHECK FOR ERRORS
1200 EROR$ = "ERROR FOUND DURING CONFIGURE"
1210 CALL ABSOLUTE(ERROR.CODE, ERR.SYS)
1220 IF ERROR.CODE <> 0 THEN PRINT EROR$: PRINT ERROR.CODE: STOP
1230 NEXT I
1240 :
1250 REM DRAW OPENING SCREEN
1260 CLS
1270 SCREEN 9
1280 GOSUB 1530
1290 CIRCLE (325, 100), 100
1300 LINE (225, 100)-(425, 100)
1310 PAINT (200, 50), 1, 15
1320 PAINT (226, 101), 14, 15
1330 FOR J = 1 TO 10
1340 PAINT (227, 99), 4, 15
1350 START! = TIMER
1360 FINISH! = TIMER
1370 IF FINISH! - START! < 1! THEN 1360
1380 PAINT (227, 99), 2, 15
1390 START! = TIMER
1400 FINISH! = TIMER
1410 IF FINISH! - START! < 1! THEN 1400
1420 :
1430 IF J < 10 THEN 1460
```

```
1450 :
1460 GOSUB 1590
1470 NEXT J
1480 PAINT (227, 99), 14, 15
1490 START! = TIMER
1500 FINISH! = TIMER
1510 IF FINISH! - START! < 2! THEN 1500
1520 GOTO 1620
1525 REM ***** SUBROUTINE *****
1530 FOR I = 1 TO 14: PRINT : NEXT I
1540 PRINT TAB(28); "KMSR DATA ACQUISITION SYSTEM"
1550 PRINT "                Copyright 1988 by Amadeus Associates, (Very) Ltd."
1560 PRINT : PRINT
1570 PRINT : PRINT : PRINT "   PRESS ANY KEY TO CONTINUE"
1580 RETURN
1585 REM ***** SUBROUTINE *****
1590 A$ = INKEY$
1600 IF LEN(A$) = 0 THEN RETURN
1620 CLS
1630 :
1650 OBSFL = 0: REM NO DATA GATHERED  AT THIS POINT
1660 SS$ = "Medium": SM$ = "Medium": NS = 100
1670 NM$ = "Wolfgang Amadeus Mozart"
1680 :
1685 :
1690 REM DRAW MAIN MENU SCREEN
1700 LINE (130, 35)-(530, 190), 14, B
1710 LOCATE 3, 32: PRINT "KMSR SYSTEM MAIN MENU"
1720 LOCATE 5, 19
1730 PRINT "1  -  Set System Parameters"
1740 LOCATE 6, 19
1750 PRINT "2  -  Run Demonstration"
1760 LOCATE 7, 19
1770 PRINT "3  -  Enter Observer Data"
1780 LOCATE 8, 19
1790 PRINT "4  -  Run Data Acquisition Session"
1800 LOCATE 9, 19
1810 PRINT "5  -  Store Observer Data to Disk"
1820 LOCATE 10, 19
1830 PRINT "6  -  Perform Calibration Check"
1840 LOCATE 11, 19
1850 PRINT "7  -  EXIT Program"
1860 GOSUB 1890
1870 GOTO 2090
```

```
1880 :
1885 REM ***** SUBROUTINE *****
1890 REM SET UP SYSTEM STATUS WINDOW
1900 LINE (20, 215)-(630, 345), 14, B
1910 LOCATE 16, 36: PRINT "SYSTEM STATUS"
1920 LOCATE 17, 6: PRINT "No. Trials = "; NS
1930 LOCATE 19, 6: PRINT "Trial Pace = "; SS$
1940 LOCATE 21, 6: PRINT "A/D Threshold= "; TH
1950 LOCATE 23, 6: PRINT "Observer:  "; NM$; "     Date:  "; DATE$;
1960 LOCATE 17, 44: PRINT "Session Keyboard Sequence"
2000 :
2010 LOCATE 20, 38: PRINT "Session No. in Progress = "; SESSION$
2070 RETURN
2080 :
2090 REM GET MENU SELECTION
2100 LOCATE 13, 20: PRINT "    SELECTION?"
2110 SCREEN 9: COLOR , 8
2120 A$ = INKEY$
2130 IF LEN(A$) = 0 THEN 2120
2140 A = VAL(A$)
2150 SCREEN 9
2160 CLS
2170 ON A GOTO 2190, 2740, 2820, 3960, 5840, 6410, 6380
2180 :
2190 REM SET SYSTEM PARAMETERS
2200 LINE (130, 35)-(530, 190), 2, B
2210 LOCATE 3, 30: PRINT "SET SYSTEM PARAMETERS MENU"
2220 LOCATE 5, 19: PRINT "1  -  Set Number of Trials"
2230 LOCATE 6, 19: PRINT "2  -  Set Trial Pacing"
2240 LOCATE 7, 19: PRINT "3  -  Set A/D Threshold"
2250 LOCATE 8, 19: PRINT "4  -  Return To Main Menu"
2260 LOCATE 9, 19: PRINT "5  -  EXIT To DOS"
2270 GOSUB 1890
2280 LOCATE 12, 18: PRINT "     SELECTION?"
2290 SCREEN 9: COLOR , 8
2300 A$ = INKEY$: IF LEN(A$) = 0 THEN 2300
2310 A = VAL(A$)
2320 CLS
2330 ON A GOTO 2350, 2470, 2610, 2680, 2710
2340 :
2350 REM SET NUMBER OF TRIALS
2360 LINE (130, 35)-(530, 190), 2, B
2370 LOCATE 3, 33: PRINT "SET NUMBER OF TRIALS"
2380 GOSUB 1890
2390 LOCATE 5, 19: PRINT "Default number of trials = 100."
```

```
2400 LOCATE 6, 19: PRINT "You may enter any  number between 10 and 1000,"
2410 LOCATE 7, 19: PRINT "BUT it must be a multiple of 10 (e.g., 170)"
2420 LOCATE 9, 19: INPUT "Your selection"; NS
2440 CLS .: GOTO 2190
2450 GOSUB 1890
2460 :
2470 REM SET TRIAL PACE
2480 LINE (130, 35)-(530, 190), 2, B
2490 LOCATE 3, 33: PRINT "Set Trial Pacing"
2500 LOCATE 5, 19: PRINT "There are three system trial paces."
2510 LOCATE 7, 19: PRINT "1  -  Low "
2520 LOCATE 8, 19: PRINT "2  -  Medium (Default)"
2530 LOCATE 9, 19: PRINT "3  -  High"
2540 LOCATE 12, 21: INPUT "Your Selection"; SSS$
2550 IF SSS$ = "1" THEN SS$ = "Low"
2560 IF SSS$ = "2" THEN SS$ = "Medium"
2570 IF SSS$ = "3" THEN SS$ = "High"
2580 :
2590 CLS : GOTO 2190
2600 :
2610 REM SET A/D THRESHOLD COUNT VALUE
2612 REM SAMPLE @ 1 HZ FOR 60 S
2614 FOR I = 1 TO 60
2616 FOR K = 0 TO 6
2618 CHN = K
2620 CALL ABSOLUTE(AI, CHN, ADATA, READ.CH)
2622 CALDATA(I, K) = ADATA
2624 NEXT K
2626 START! = TIMER
2628 FINISH! = TIMER
2629 IF FINISH! - START! < 1! THEN GOTO 2628
2630 LOCATE 6, 21: PRINT "COUNTDOWN ="; 60 - I
2631 NEXT I
2632 REM COMPUTE MEAN, VARIANCE, MAX AND THRESHOLD VALUES
2633 TOT! = 0: TOT2! = 0: MAX! = 0: MIN! = 0: NCT = 0
2634 FOR I = 1 TO 60
2635 FOR K = 0 TO 6
2636 TOT! = TOT! + CALDATA(I, K)
2637 TOT2! = TOT2! + (CALDATA(I, K)) ^ 2
2638 NCT = NCT + 1
2639 IF CALDATA(I, K) > MAX! THEN MAX! = CALDATA(I, K)
2640 IF CALDATA(I, K) < MIN! THEN MIN! = CALDATA(I, K)
2641 NEXT K
2642 NEXT I
2643 MEAN! = TOT! / NCT
```

```
2644 VAR! = TOT2! / NCT - MEAN! ^ 2
2645 REM SET TO THRESHOLD
2646 TH = MAX! + 4
2654 SD! = VAR ^ .5
2655 RANGEHI! = MEAN! + (2 * (SD! / (NCT ^ .5)))
2656 RANGELO! = MEAN! - (2 * (SD! / (NCT ^ .5)))
2659 CLS
2660 :
2665 LINE (110, 35)-(560, 190), 2, B
2666 LOCATE 3, 36: PRINT "Set A/D Threshold"
2667 LOCATE 6, 21: PRINT "A/D Value Mean = "; MEAN!
2668 LOCATE 8, 21: PRINT "Variance = "; VAR!
2669 LOCATE 10, 21: PRINT "A/D COMPUTED THRESHOLD = "; TH
2670 IF MIN! < RANGELO! OR MAX! > RANGEHI! THEN LOCATE 22, 25: PRINT "WARNING:  EXCESSIVE VARIANCE"
2671 LOCATE 16, 20: PRINT "Enter threshold value to confirm, or a new value"
2672 LOCATE 17, 20: INPUT "to change"; TH
2673 LOCATE 9, 20: PRINT "95% RANGE ="; RANGELO!, " -"; RANGEHI!
2678 CLS : GOTO 2190
2679 :
2680 REM RETURN TO MAIN MENU
2690 CLS : GOTO 1700
2700 :
2710 REM RETURN TO DOS
2720 SYSTEM
2730 :
2740 REM RUN DEMONSTRATION PROGRAM
2750 CLS : SCREEN 9: COLOR , 8
2760 LINE (20, 76)-(630, 225), 14, B
2770 LOCATE 10, 16: PRINT "DEMONSTRATION NOT AVAILABLE - RUN DATA ACQUISITION."
2780 LOCATE 13, 16: PRINT "Press Any Key To Return To System MAIN MENU."
2790 A$ = INKEY$
2800 IF LEN(A$) = 0 THEN 2790 ELSE CLS : GOTO 1690
2810 :
2820 REM ENTER OBSERVER DATA
2830 IF NM$ = "" OR FILE$ = "" THEN OBSFL = 0
2840 IF OBSFL = 1 THEN 3190
2850 SCREEN 9: COLOR , 8
2860 LINE (20, 76)-(630, 250), 14, B
2870 LOCATE 10, 6: INPUT "Is this a new subject (Y/N)"; A$
2880 IF A$ = "Y" OR A$ = "y" THEN CLS : GOTO 3190
2890 LOCATE 15, 22: PRINT "Hit RETURN to go back to MAIN MENU"
2900 LOCATE 17, 22: PRINT "Hit 'F1' for Directory of Data Files"
2910 KEY 1, "1" + CHR$(13)
2920 LOCATE 12, 6: INPUT "Enter File Name for previous data  ", FILE$
2930 KEY 1, "LIST "
```

```
2940 IF LEN(FILE$) > 1 THEN 2985
2950 IF LEN(FILE$) = 0 THEN CLS : GOTO 1690
2960 IF FILE$ = "1" THEN 7250
2970 GOTO 2890
2980 :
2984 REM ENTER SESSION NUMBER
2985 GOSUB 10400
2990 REM GET OBSERVER DATA FILE
3000 OPEN FILE$ + ".DAT" FOR INPUT AS 1
3010 :
3020 :
3030 INPUT #1, NM$
3040 INPUT #1, LOC$
3050 INPUT #1, SEX$
3060 REM XX$=DUMMY VARIABLES FOR TIME & DATE
3070 INPUT #1, XX$
3080 INPUT #1, XX$
3090 INPUT #1, MCODE$
3100 INPUT #1, PH$
3110 INPUT #1, HD$
3120 INPUT #1, FILE$
3121 INPUT #1, KPAD11$
3122 INPUT #1, KPAD12$
3123 INPUT #1, KPAD21$
3124 INPUT #1, KPAD22$
3125 INPUT #1, KPAD31$
3126 INPUT #1, KPAD32$
3130 CLOSE #1
3140 REM SET OBSERVER DATA FLAG TRUE
3150 OBSFL = 1
3160 :
3170 :
3180 CLS
3190 SCREEN 9: COLOR , 8
3200 LINE (130, 35)-(530, 280), 2, B
3210 LOCATE 3, 30: PRINT "Observer Data Entry Menu"
3220 LOCATE 6, 19: PRINT "1  Name_____________________________"
3230 LOCATE 7, 19: PRINT "2  Location_________________________"
3240 LOCATE 8, 19: PRINT "3  Sex (M/F)_________________________"
3250 LOCATE 9, 19: PRINT "4  KODAK Mailcode____________________"
3260 LOCATE 10, 19: PRINT "5  Phone____________________________"
3270 LOCATE 11, 19: PRINT "6  Handedness(R/L)__________________"
3280 LOCATE 12, 19: PRINT "7  Data File Name___________________"
3290 LOCATE 13, 19: PRINT "8  Session 1 Keypad 1._____________"
3300 LOCATE 14, 19: PRINT "9  Session 1 Keypad 2._____________"
```

```
3301 LOCATE 15, 19: PRINT "10 Session 2 Keypad 1._________________"
3302 LOCATE 16, 19: PRINT "11 Session 2 Keypad 2._________________"
3303 LOCATE 17, 19: PRINT "12 Session 3 Keypad 1._________________"
3304 LOCATE 18, 19: PRINT "13 Session 3 Keypad 2._________________"
3305 :
3306 :
3307 :
3308 :
3310 LOCATE 19, 19: PRINT "Session No._____________________________"
3320 REM LOCATE 16, 20: PRINT "_____________________________________"
3330 LOCATE 23, 5: PRINT "TIME:  "; TIME$;
3340 LOCATE 23, 50: PRINT "DATE:  "; DATE$;
3350 :
3360 IF OBSFL = 1 THEN 3670
3370 LOCATE 6, 27: INPUT "", NM$
3380 IF DTAFLG = 1 THEN 3570
3390 LOCATE 7, 31: INPUT "", LOC$
3400 IF DTAFLG = 1 THEN 3570
3410 LOCATE 8, 32: INPUT "", SEX$
3420 IF DTAFLG = 1 THEN 3570
3430 LOCATE 9, 37: INPUT "", MCODE$
3440 IF DTAFLG = 1 THEN 3570
3450 LOCATE 10, 29: INPUT "", PH$
3460 IF DTAFLG = 1 THEN 3570
3470 LOCATE 11, 38: INPUT "", HD$
3480 IF DTAFLG = 1 THEN 3570
3490 LOCATE 12, 37: INPUT "", FILE$
3500 IF DTAFLG = 1 THEN 3570
3510 LOCATE 13, 41: INPUT "", KPAD11$
3530 IF DTAFLG = 1 THEN 3570
3540 LOCATE 14, 41: INPUT "", KPAD12$
3550 IF DTAFLG = 1 THEN 3440
3551 LOCATE 15, 41: INPUT "", KPAD21$
3552 IF DTAFLG = 1 THEN 3570
3553 LOCATE 16, 41: INPUT "", KPAD22$
3554 IF DTAFLG = 1 THEN 3570
3555 LOCATE 17, 41: INPUT "", KPAD31$
3556 IF DTAFLG = 1 THEN 3570
3557 LOCATE 18, 41: INPUT "", KPAD32$
3558 IF DTAFLG = 1 THEN 3570
3560 :
3570 REM CHECK ENTRIES
3580 LOCATE 22, 34: PRINT "                                        "
3590 LOCATE 22, 34: PRINT "ALL ENTRIES OK? (Y/N)"
3600 LOCATE 22, 55: INPUT OK$
```

```
3610 IF OK$ <> "Y" AND OK$ <> "y" AND OK$ <> "N" AND OK$ <> "n" THEN 3570
3620 IF OK$ = "Y" OR OK$ = "y" THEN DTAFLG = 0: GOTO 3940
3630 IF OK$ = "N" OR OK$ = "n" THEN DTAFLG = 1: LOCATE 17, 34
3640 LOCATE 22, 28: INPUT "Which item number to change"; ITEM$
3650 ITEM = VAL(ITEM$): ON ITEM GOTO 3370, 3390, 3410, 3430, 3450, 3470, 3490, 3510
3660 :
3670 REM OBSERVER DATA - 2ND LOOK
3680 LOCATE 6, 27: PRINT NM$
3690 LOCATE 7, 31: PRINT LOC$
3700 LOCATE 8, 32: PRINT SEX$
3710 LOCATE 9, 37: PRINT MCODE$
3720 LOCATE 10, 29: PRINT PH$
3730 LOCATE 11, 38: PRINT HD$
3740 LOCATE 12, 37: PRINT FILE$
3750 LOCATE 13, 41: PRINT KPAD11$
3760 LOCATE 14, 41: PRINT KPAD12$
3761 LOCATE 15, 41: PRINT KPAD21$
3762 LOCATE 16, 41: PRINT KPAD22$
3763 LOCATE 17, 41: PRINT KPAD31$
3764 LOCATE 18, 41: PRINT KPAD32$
3765 :
3766 :
3770 LOCATE 19, 35: PRINT SESSION$
3780 GOTO 3590
3790 :
3800 OBSFL = 1: CLS
3810 :
3820 :
3825 REM ***** SUBROUTINE *****
3830 DATFIL$ = "DATFIL"
3840 REM GET APPROPRIATE DATA FILE
3850 REM FIND SOME WAY TO IDENTIFY RIGHT KEYPAD
3860 OPEN DATFIL$ + SESSION$ + ".DAT" FOR INPUT AS #1
3870 FOR I = 0 TO 99
3880 FOR J = 0 TO 3
3890 INPUT #1, A$(I, J)
3900 NEXT J: NEXT I
3910 CLOSE #1
3920 RETURN
3930 :
3940 OBSFL = 1: CLS : GOTO 1700
3950 :
3960 REM RUN SIX REAL SESSIONS
3970 CLS
3980 :
```

```
3990 REM DATA ACQ PROHIBITED W.O. OBSERVER DATA FILE
4000 IF OBSFL = 0 THEN 7130
4010 IF NM$ = "" OR FILE$ = "" THEN 7130
4020 :
4030 REM GET APPROPRIATE KEYPAD DATA FILE
4040 GOSUB 3830
4050 :
4060 REM TECMAR BOARD USED FOR SUBJECTS'S KEYBOARD INPUT IS
4070 REM I/O MAPPED AT BAS LOCATION 0170H (1808)
4080 REM *** 8255 ***
4090 REM PORT A R/W=BAS+12
4100 REM PORT B R/W=BAS+13
4110 REM PORT C R/W=BAS+14
4120 REM CONTROL REGISTER=BASE+15
4130 BAS = 1808
4140 REM SET 8255 CONFIGURATION - ALL PORTS AS INPUTS, MODE 0
4150 OUT BAS + 15, 155
4160 :
4170 REM DATA ACQUISITION INSTRUCTION SCREENS
4180 SCREEN 9: COLOR , 8
4190 LINE (5, 20)-(635, 330), 14, B
4200 LOCATE 10, 24: PRINT "  D A T A  A C Q U I S I T I O N "
4210 FOR K = 1 TO 4000!: NEXT K: BEEP: CLS
4220 LINE (5, 48)-(635, 330), 14, B
4230 LOCATE 4, 26: PRINT " I N S T R U C T I O N S"
4240 LOCATE 7, 4: PRINT "   This experiment involves the evaluation of six membrane touchpads.";
4250 LOCATE 8, 4: PRINT "You will be using two touchpads each day for three days over the next";
4260 LOCATE 9, 4: PRINT "two weeks.  I would like to emphasize that we are not testing you nor";
4270 LOCATE 10, 4: PRINT "your ability to use these touchpads, but rather how well the touchpads"
4280 LOCATE 11, 4: PRINT "perform and which you prefer."
4290 LOCATE 22, 45: PRINT "PRESS THE '#' KEY TO CONTINUE"
4293 :
4294 REM GET RESPONSE FROM KEYPAD
4295 OFSET = 14: X = 235
4300 A = INP(BAS + OFSET)
4310 IF A = 255 OR (A = 251 AND OFSET = 14) THEN 4300
4312 IF A <> X THEN 4300
4314 SOUND 1000, 2
4320 CLS
4330 :
4340 REM NEXT SCREEN
4350 LINE (5, 20)-(635, 330), 14, B
4360 LOCATE 2, 26: PRINT " I N S T R U C T I O N S "
4370 LOCATE 4, 4: PRINT "  When we begin, a 4-digit number will appear in the box below.  When"
4380 LOCATE 5, 4: PRINT "you are ready, please enter the number using the touchpad.  After you have"
```

```
4390 LOCATE 6, 4: PRINT "entered the number, press the '#' key and the next number to be entered"
4400 LOCATE 7, 4: PRINT "will appear.  Continue entering numbers, always followed by '#', until"
4410 LOCATE 8, 4: PRINT "a SESSION FINISHED message appears instead of a number."
4420 LOCATE 10, 4: PRINT "  A 'BEEP' signal will be heard with every correct entry."
4430 LOCATE 12, 4: PRINT "  Work as quickly and accurately as you can.  If you make a mistake,"
4440 LOCATE 13, 4: PRINT "simply press the correct key and continue."
4450 :
4460 LINE (230, 220)-(360, 280), 4, B
4470 LINE (226, 216)-(364, 284), 4, B
4480 LINE (228, 218)-(362, 282), 14, B
4490 :
4500 LOCATE 23, 25: PRINT "    PRESS '#' TO BEGIN."
4520 LOCATE 18, 36: PRINT "XXXX"
4530 A = INP(1822)
4540 IF A <> 235 THEN 4530
4550 LOCATE 23, 25: PRINT "                              "
4560 :
4570 REM SET DISK DATA COUNTER
4580 DCTR = 0
4590 :
4600 REM BEGIN DATA COLLECTION
4610 I = DCTR
4620 FOR J = 0 TO 3
4630 :
4640 LOCATE 18, 36 + J: PRINT A$(I, J);
4650 NEXT J
4660 SOUND 1000, 1: START! = TIMER
4662 FINISH! = TIMER
4663 IF FINISH! - START! < .25 THEN 4662
4664 SOUND 1000, 1
4670 :
4680 REM GET RESPONSE
4690 FOR J = 0 TO 4
4710 :
4720 REM SET LOOP FLAG TO 0
4730 LOOPFLG = 0
4740 REM SET CHANNEL COUNTER TO 0
4750 CTR = 0: DFLAG = 0: CTRTOT = 0
4760 :
4770 REM SET FLAG TO INDICATE IF CORRECT KEY WAS PRESSED
4780 TRUFLG = 0
4790 :
4800 REM GET KEYPAD CODE CONVERSIONS
4810 GOSUB 6950
4820 IF J = 4 THEN A$(I, J) = "#": X = 235: OFSET = 14
```

```
4830 :
4870 REM FIRST START RATE GENERATOR
4880 REM CONFIGURE FOR 100 HZ PULSE TRAIN ON CHANNEL 0, MODE 2
4890 CALL ABSOLUTE(0, 224, 224, 2, CNF.RG)
4900 :
4910 REM ENABLE THE RATE GENERATOR
4920 ENABLE = 1: DISABLE = 0
4930 CALL ABSOLUTE(RG, 0, ENABLE, WRITE.CH)
4940 :
4950 REM CONFIGURE COUNTER
4960 COUNT = 100: TEMP = COUNT - 4
4970 REM COUNT IS, THEREFORE, IN 0.04 SEC INTERVALS
4980 CALL ABSOLUTE(3, COUNT, 0, 2, CNF.CNTR)
4990 :
5000 REM ENABLE COUNTER CHANNEL 3, MODE 2
5010 CALL ABSOLUTE(CT, 3, ENABLE, WRITE.CH)
5020 :
5030 REM READ COUNTER
5040 CALL ABSOLUTE(CT, 3, ADATA0, READ.CH)
5050 IF ADATA0 <> 100 THEN 5040
5070 :
5080 REM READ A/D CONVERTERS FOR LOAD CELL VOLTAGES
5090 :
5100 FOR K = 0 TO 6
5110 CHN = K
5120 CALL ABSOLUTE(AI, CHN, ADATA, READ.CH)
5130 LC(I, J, K, LOOPFLG) = ADATA
5140 IF K = 0 THEN CALL ABSOLUTE(CT, 3, TDATA, READ.CH)
5150 IF K = 0 THEN TC(I, J, K, LOOPFLG) = TDATA
5155 IF K = 0 AND LOOPFLG > 0 AND TC(I, J, K, LOOPFLG) = TC(I, J, K, LOOPFLG - 1) THEN GOTO 5110
5170 NEXT K
5180 :
5190 REM CHECK FOR MINIMAL CHANGE IN ANY CHANNEL
5200 FOR K = 0 TO 6
5210 IF LC(I, J, K, LOOPFLG) < TH THEN CTR = 0 ELSE CTR = 1
5220 CTRTOT = CTRTOT + CTR
5225 IF CTRTOT >= 1 THEN STARTIME! = TIMER
5230 :
5240 NEXT K
5250 :
5260 REM IF NO DATA, GO BACK & DO IT AGAIN
5270 IF CTRTOT = 0 AND DFLAG = 0 THEN 4870
5280 REM IF DATA AT AN END, LOG IT
5290 IF CTRTOT = 0 AND DFLAG = 1 AND TRUFLG = 1 THEN 5490
5294 REM IF WE HAVE LONG, BAD KEYPRESS - INCR MISS CTR & GO BACK
```

```
5295 IF LOOPFLG = 99 AND TRUFLG <> 1 THEN MCTR = MCTR + 1: GOTO 4720
5297 REM IF WE HAVE LONG GOOD KEYPRESS THEN INCR MISS CTR & GO BACK
5298 IF LOOPFLG = 99 AND TRUFLG = 1 THEN MCTR = MCTR + 1: GOTO 4720
5300 REM IF THERE IS DATA, INCREMENT INDEX AND GO ON
5310 LOOPFLG = LOOPFLG + 1
5320 :
5330 REM LOOK AT 8255 KEYBOARD INPUT PORT
5340 A = INP(BAS + OFSET)
5360 :
5370 REM EVALUATE KEYBOARD RESPONSES
5384 REM TO LIMIT TONE DURATION TO APPROX. 50 ms
5385 IF TRUFLG = 1 THEN GOTO 5410
5390 IF A = X THEN TRUFLG = 1: SOUND 1000, 1
5400 :
5410 REM SET DATA FLAG TO INDICATE A KEYPRESS IS IN PROGRESS
5420 DFLAG = 1
5430 CTRTOT = 0
5440 :
5450 REM CONTINUE DATA ACQUISITION UNTIL LOAD CELL DATA CEASES
5460 REM BUT DO NOT RESTART TIMER
5470 GOTO 5080
5480 :
5490 REM PRINT RESPONSE - CORRECT CHARCTERS ONLY
5510 :
5520 REM  LOG DURATION FOR THIS KEYPRESS
5530 CALL ABSOLUTE(CT, 3, ADATA1, READ.CH)
5540 TIM#(I, J) = (ADATA0 - ADATA1) * .05
5580 :
5590 REM WAIT UNTIL KEY IS RELEASED BEFORE ALLOWING NEW INPUT
5600 A = INP(BAS + OFSET):
5610 :
5620 IF (A <> 255 AND OFSET = 12) OR (A <> 251 AND OFSET = 14) THEN 5600
5630 NEXT J
5635 ENDTIME! = TIMER
5640 :
5650 REM HOLD FOR TRIAL PACING VARIABLE
5660 REM IF SS$ = "Low" THEN DUR = 1!
5670 REM IF SS$ = "Medium" THEN DUR = .5
5680 REM IF SS$ = "High" THEN DUR = .25
5690 REM START! = TIMER
5700 REM FINISH! = TIMER
5710 REM IF FINISH! - START! < DUR THEN 5700
5720 LOCATE 20, 63: PRINT "              ";
5791 :
5792 REM DISPLAY WAIT FOR DISK WRITE MESSAGE
```

```
5793 LOCATE 22, 20: PRINT "CORRECT!  PLEASE WAIT FOR NEXT NUMBER.";
5794 :
5800 GOTO 5870
5830 :
5840 REM SAVE OBSERVER DATA TO DISK FILE
5841 REM FIRST, GIVE WARNING MESSAGE
5842 GOTO 7690
5848 REM CONTINUE
5849 :
5850 IF FILE$ = "" OR NM$ = "" THEN GOTO 7380
5860 OPEN FILE$ + ".DAT" FOR OUTPUT AS 1: GOTO 5880
5870 OPEN FILE$ + ".DAT" FOR APPEND AS 1: GOTO 6030
5880 :
5890 :
5900 PRINT #1, NM$
5910 PRINT #1, LOC$
5920 PRINT #1, SEX$
5930 PRINT #1, DATE$
5940 PRINT #1, TIME$
5950 PRINT #1, MCODE$
5960 PRINT #1, PH$
5970 PRINT #1, HD$
5980 PRINT #1, FILE$
5981 PRINT #1, KPAD11$
5982 PRINT #1, KPAD12$
5983 PRINT #1, KPAD21$
5984 PRINT #1, KPAD22$
5985 PRINT #1, KPAD31$
5986 PRINT #1, KPAD32$
5990 :
6000 CLOSE #1
6010 CLS : GOTO 1700
6020 :
6030 REM WRITE SAMPLE TO DISK
6040 IF DCTR >= 1 THEN GOTO 6090
6050 PRINT #1, DATE$
6060 PRINT #1, TIME$
6070 PRINT #1, NM$
6080 PRINT #1, OPKPD$
6082 PRINT #1, TH
6084 PRINT #1, MEAN!
6086 PRINT #1, VAR!
6088 :
6090 REM FOR II = DCTR TO DCTR + 5
6100 FOR J = 0 TO 4
```

```
6110 FOR K = 0 TO 6
6120 IF K = 0 THEN GOSUB 7600
6130 PRINT #1, DCTR; A$(II, J); K
6135 JJ = 0
6140 FOR LOOPFLG = JJ TO JJ + 10
6150 PRINT #1, LC(DCTR, J, K, LOOPFLG);
6160 NEXT LOOPFLG: PRINT #1, " "
6165 JJ = JJ + 10: IF JJ < 50 THEN 6140
6170 NEXT K: NEXT J: REM NEXT II
6180 CLOSE #1
6190 REM INCREMENT KPAD COUNTER
6200 :
6210 :
6211 REM ERASE DISK WRITING MESSAGE
6212 LOCATE 22, 20: PRINT "                                        ";
6213 :
6220 :
6230 REM RETURN TO MAIN MENU IF ALL DONE
6240 IF DCTR = NS THEN KPAD = KPAD + 1: GOSUB 6280: GOTO 1700
6255 DCTR = DCTR + 1: MCTR = 0
6260 GOTO 4600
6270 :
6275 REM ***** SUBROUTINE *****
6280 REM DRAW FINISHED SESSION SCREEN
6290 CLS : SCREEN 9: COLOR , 8
6300 LINE (20, 76)-(630, 225), 14, B
6310 LOCATE 6, 25: PRINT " * C O N G R A T U L A T I O N S * "
6320 LOCATE 12, 27: PRINT " This Session Is FINISHED !!"
6330 START! = TIMER
6331 FINISH! = TIMER
6332 IF FINISH! - START! < 3 THEN 6331
6335 :
6340 REM OBTAIN SUBJECTIVE PREFERENCE DATA
6345 CLS
6346 GOSUB 8000
6350 :
6351 REM FOR DD = 440 TO 1000 STEP 10
6352 REM SOUND DD, DD / 1000
6353 REM NEXT DD
6354 REM FOR DD = 1000 TO 440 STEP -10
6355 REM SOUND DD, DD / 1000
6356 REM NEXT DD
6357 BEEP: BEEP: BEEP
6358 LOCATE 13, 16: PRINT "THIS SESSION IS FINISHED.  THANK YOU FOR PARTICIPATING!"; ""
6359 A$ = INKEY$
```

```
6360 IF LEN(A$) = 0 THEN 6359
6369 CLS : RETURN
6370 :
6380 REM EXIT PROGRAM
6390 END: SYSTEM
6400 :
6410 REM PERFORM CALIBRATION CHECK
6420 CLS : SCREEN 9: COLOR , 8
6430 LINE (20, 20)-(630, 190), 14, B
6440 LINE (20, 215)-(630, 345), 14, B
6450 LOCATE 2, 35: PRINT "CALIBRATION CHECK"
6460 LOCATE 4, 45: PRINT "Current Threshold Count="; TH
6470 LOCATE 16, 38: PRINT "INSTRUCTIONS"
6480 LOCATE 19, 15: PRINT "Adjust amplifier gains until all channels "
6490 LOCATE 20, 15: PRINT "output are equal, within +/-0.01 volts."
6500 LOCATE 22, 15: PRINT "Hit any key to return to MAIN MENU."
6510 LOCATE 6, 10: PRINT "AMPLIFIER NO.     VOLTS OUT           A/D COUNT"
6520 FOR K = 0 TO 6
6530 CHN = K
6540 CALL ABSOLUTE(AI, CHN, ADATA, READ.CH)
6550 REM CONVERT TO VOLTS
6560 FDATA = (ADATA * 20! / 4096! - 10!) / GAIN
6570 LOCATE 7 + K, 15: PRINT K + 1; "           "; : PRINT USING "##.###"; FDATA
6580 LOCATE 7 + K, 50: PRINT ADATA
6590 GOSUB 6720
6600 NEXT K
6610 :
6620 REM PAUSE & CHECK KEYBOARD
6630 FOR L = 1 TO 400: GOSUB 6720: NEXT L
6640 :
6650 REM ERASE
6660 FOR K = 0 TO 6
6670 LOCATE 7 + K, 18: PRINT "                                        ";
6680 NEXT K
6690 GOTO 6520
6700 :
6710 :
6715 REM ***** SUBROUTINE *****
6720 REM CHECK KEYBOARD
6730 A$ = INKEY$
6740 IF LEN(A$) = 0 THEN RETURN
6750 CLS : GOTO 1690
6760 LOCATE 7 + K, 15: PRINT K + 1; "    FDATA"
6770 :
6780 END: SYSTEM
```

```
6790 :
6800 REM ***** SUBROUTINE *****
6950 REM DECODE 8255 PORTS A AND C
6960 REM OFSET=12=PORTA: OFSET=14=PORTC
6970 IF A$(I, J) = "1" THEN X = 127: OFSET = 12
6980 IF A$(I, J) = "2" THEN X = 191: OFSET = 12
6990 IF A$(I, J) = "3" THEN X = 223: OFSET = 12
7000 IF A$(I, J) = "4" THEN X = 239: OFSET = 12
7010 IF A$(I, J) = "5" THEN X = 247: OFSET = 12
7020 IF A$(I, J) = "6" THEN X = 251: OFSET = 12
7030 IF A$(I, J) = "7" THEN X = 253: OFSET = 12
7040 IF A$(I, J) = "8" THEN X = 254: OFSET = 12
7050 IF A$(I, J) = "9" THEN X = 123: OFSET = 14
7060 IF A$(I, J) = "0" THEN X = 219: OFSET = 14
7070 IF A$(I, J) = "*" THEN X = 187: OFSET = 14
7080 IF A$(I, J) = "#" THEN X = 235: OFSET = 14
7090 REM CATCH A 'RETURN' AFTER EACH 4-CHARACTER STRING
7100 IF J = 4 THEN X = 235: OFSET = 14
7110 RETURN
7120 :
7130 REM DATA ACQ PROHIBITED W.O. VALID OBSERVER DATA FILE
7140 CLS
7150 SCREEN 9: COLOR , 8
7160 LINE (20, 76)-(630, 225), 14, B
7170 LOCATE 6, 32: PRINT " * W A R N I N G * "
7180 LOCATE 10, 16: PRINT "NOTICE:  DATA ACQUISITION PROHIBITED UNTIL VALID"
7190 LOCATE 11, 16: PRINT "         OBSERVER DATA FILE HAS BEEN CREATED."
7200 LOCATE 13, 16: PRINT "  PRESS ANY KEY TO RETURN TO SYSTEM MAIN MENU."
7210 A$ = INKEY$
7220 IF LEN(A$) = 0 THEN 7210
7230 CLS : GOTO 1690
7240 :
7250 REM GET DIRECTORY OF DATA FILES
7260 CLS : SCREEN 9: COLOR , 8
7270 LINE (175, 50)-(450, 75), 14, B
7280 LINE (100, 300)-(525, 325), 14, B
7290 LOCATE 5, 27: PRINT "D A T A   D I R E C T O R Y"
7300 LOCATE 23, 16: PRINT "  PRESS ANY KEY TO RETURN TO SYSTEM MAIN MENU."
7310 LOCATE 8, 5: FILES "*.DAT"
7320 A$ = INKEY$
7330 IF LEN(A$) = 0 THEN 7320
7340 REM RESTORE F1 KEY
7350 KEY 1, "LIST "
7360 CLS : GOTO 1690
7370 :
```

```
7380 REM INVALID DATA - DO NOT WRITE TO DISK
7390 CLS : SCREEN 9: COLOR , 8
7400 LINE (20, 76)-(630, 225), 14, B
7410 LOCATE 6, 32: PRINT " * W A R N I N G * "
7420 LOCATE 10, 16: PRINT "NOTICE: DATA FILE WRITE PROHIBITED UNTIL VALID"
7430 LOCATE 11, 16: PRINT "        OBSERVER AND/OR FILE NAME ARE SPECIFIED."
7440 LOCATE 13, 16: PRINT "  PRESS ANY KEY TO RETURN TO SYSTEM MAIN MENU."
7450 A$ = INKEY$
7460 IF LEN(A$) = 0 THEN 7450
7470 CLS : GOTO 1690
7480 REM ERROR HANDLING ROUTINE
7490 CLS : SCREEN , 9: COLOR , 8
7500 LINE (20, 76)-(630, 225), 14, B
7510 LOCATE 6, 32: PRINT " * W A R N I N G * "
7520 LOCATE 10, 16: PRINT "NOTICE:  A DISK I/O ERROR HAS OCCURRED!!  HAVE"
7530 LOCATE 11, 16: PRINT "         YOU SPECIFIED A PROPER DATA FILE?"
7540 LOCATE 13, 16: PRINT "  PRESS ANY KEY TO RETURN TO SYSTEM MAIN MENU."
7550 A$ = INKEY$
7560 IF LEN(A$) = 0 THEN 7550
7570 CLS : GOTO 1690
7580 :
7590 :
7595 REM ***** SUBROUTINE *****
7600 REM DISK WRITE FOR TIME DATA
7610 PRINT #1, TIM#(II, J); MCTR; STARTIME!; ENDTIME!
7615 KK = 0
7620 FOR LOOPFLG = KK TO KK + 10
7630 PRINT #1, TC(DCTR, J, K, LOOPFLG);
7640 NEXT LOOPFLG: PRINT #1, " "
7645 KK = KK + 10: IF KK < 50 THEN 7620
7650 RETURN
7680 :
7690 REM WARNING: DISK WRITE WILL ERASE EARLIER DATA
7700 CLS : SCREEN 9: COLOR , 8
7710 LINE (20, 76)-(630, 225), 14, B
7720 LOCATE 6, 32: PRINT " * W A R N I N G * "
7730 LOCATE 10, 14: PRINT " A DISK WRITE at this time will destroy data from any"
7735 LOCATE 11, 14: PRINT " previous sessions.  To CANCEL the disk write, press"
7740 LOCATE 12, 14: PRINT " RETURN."
7750 LOCATE 13, 14: PRINT " To PROCEED with the disk write, press the 'F1' key."
7760 KEY 1, "1"
7770 A$ = INKEY$
7780 IF LEN(A$) = 0 THEN 7770
7790 IF A$ = "1" THEN KEY 1, "LIST ": GOTO 5848
7800 IF A$ = "" THEN KEY 1, "LIST ": CLS : GOTO 1690
```

```
7995 REM ***** SUBROUTINE *****
8000 REM THIS SUBROUTINE COLLECTS SUBJECTIVE EVALUATIONS OF PREFERENCE AND
8001 REM PERFORMANCE FROM THE SUBJECT AFTER USING EACH TOUCHPAD.
8002 REM IT REQUIRES THE SUBJECT TO RESPOND VERBALLY AND THE EXPERIMENTER TO
8003 REM KEY IN THE RESPONSE USING THE ASCII KEYBOARD.
8004 :
8005 BEEP: BEEP: BEEP
8006 GOSUB 10000
8010 LOCATE 23, 6: PRINT "When you are ready to continue, say 'READY'"
8020 A$ = INKEY$
8030 IF LEN(A$) = 0 THEN 8020 ELSE 8040
8040 ISEQ = ISEQ + 1
8050 INUM = INUM + 1
8060 LOCATE 23, 6: PRINT "                                                    "
8070 :
8080 REM INUM=1
8090 LOCATE 17, 12: PRINT "HAS A"
8100 LOCATE 17, 66: PRINT "HAS A"
8110 LOCATE 18, 8: PRINT "VERY POOR"
8120 LOCATE 18, 66: PRINT "VERY GOOD"
8130 LOCATE 19, 11: PRINT "'FEEL'"
8140 LOCATE 19, 66: PRINT "'FEEL'"
8150 GOSUB 10000
8160 :
8170 REM INUM=2
8180 LOCATE 17, 3: PRINT "VERY DIFFICULT"
8190 LOCATE 17, 66: PRINT "VERY EASY"
8200 LOCATE 18, 9: PRINT "TO PRESS"
8210 LOCATE 18, 66: PRINT "TO PRESS"
8220 GOSUB 10000
8230 :
8240 REM INUM=3
8250 LOCATE 17, 4: PRINT "DISLIKE USING"
8260 LOCATE 17, 66: PRINT "LIKE USING"
8270 LOCATE 18, 8: PRINT "VERY MUCH"
8280 LOCATE 18, 66: PRINT "VERY MUCH"
8290 GOSUB 10000
8300 :
8310 REM INUM=4
8320 LOCATE 17, 13: PRINT "VERY"
8330 LOCATE 17, 66: PRINT "VERY"
8340 LOCATE 18, 4: PRINT "UNCOMFORTABLE"
8350 LOCATE 18, 66: PRINT "COMFORTABLE"
8360 LOCATE 19, 11: PRINT "TO USE"
8370 LOCATE 19, 66: PRINT "TO USE"
```

```
8380 GOSUB 10000
8390 :
8400 REM INUM=5
8410 LOCATE 17, 13: PRINT "VERY"
8420 LOCATE 17, 66: PRINT "NOT TIRING"
8430 LOCATE 18, 11: PRINT "TIRING"
8440 LOCATE 18, 66: PRINT "AT ALL"
8450 LOCATE 19, 11: PRINT "TO USE"
8460 LOCATE 19, 66: PRINT "TO USE"
8470 GOSUB 10000
8480 :
8490 REM INUM=6
8500 LOCATE 17, 13: PRINT "VERY"
8510 LOCATE 17, 66: PRINT "VERY"
8520 LOCATE 18, 6: PRINT "INEXPENSIVE"
8530 LOCATE 18, 66: PRINT "EXPENSIVE"
8540 LOCATE 19, 11: PRINT "'FEEL'"
8550 LOCATE 19, 66: PRINT "'FEEL'"
8560 GOSUB 10000
8570 :
8580 REM INUM=7
8590 LOCATE 17, 10: PRINT "DISLIKE"
8600 LOCATE 17, 66: PRINT "LIKE"
8610 LOCATE 18, 8: PRINT "VERY MUCH"
8620 LOCATE 18, 66: PRINT "VERY MUCH"
8630 LOCATE 19, 9: PRINT "OVER ALL"
8640 LOCATE 19, 66: PRINT "OVER ALL"
8650 GOSUB 10000
8660 :
8670 REM WRITE SUBJECTIVE PREFERENCE DATA TO DISK
8680 :
8690 OPEN FILE$ + ".DAT" FOR APPEND AS #1
8700 FOR INUM = 1 TO 7
8710 PRINT #1, QUEST$(INUM)
8720 NEXT INUM
8730 CLOSE #1
8740 RETURN
8750 :
8800 :
9999 REM ***** SUBROUTINE *****
10000 REM THIS SUBROUTINE PRINTS THE SCALE ON THE DISPLAY
10010 :
10020 SCREEN 9: COLOR , 8
10030 LINE (5, 20)-(635, 330), 14, B
10040 LOCATE 4, 15: PRINT "K E Y P A D  U S E  R A T I N G  S C A L E"
```

```
10050 LOCATE 7, 4: PRINT "   Using the following scale, rate the touchpad you have just used."
10060 LOCATE 8, 4: PRINT "Say your response aloud and it will be entered in the computer."
10070 LOCATE 9, 4: PRINT "Use '4' only if you can make no distinction between the descriptions"
10080 LOCATE 10, 4: PRINT "at the ends of the scale."
10090 LOCATE 18, 20: PRINT "1"
10100 LOCATE 18, 27: PRINT "2"
10110 LOCATE 18, 34: PRINT "3"
10120 LOCATE 18, 41: PRINT "4"
10130 LOCATE 18, 48: PRINT "5"
10140 LOCATE 18, 55: PRINT "6"
10150 LOCATE 18, 62: PRINT "7"
10160 IF ISEQ < 1 THEN RETURN
10170 LOCATE 23, 6: PRINT "PLEASE SAY YOUR RESPONSE ALOUD."
10180 A$ = INKEY$
10190 IF LEN(A$) = 0 THEN 10180 ELSE QUEST$(INUM) = A$
10200 INUM = INUM + 1
10210 IF A$ = "1" THEN LINE (149, 235)-(163, 255), 4, B: GOTO 10300
10220 IF A$ = "2" THEN LINE (205, 235)-(219, 255), 4, B: GOTO 10300
10230 IF A$ = "3" THEN LINE (261, 235)-(275, 255), 4, B: GOTO 10300
10240 IF A$ = "4" THEN LINE (317, 235)-(331, 255), 4, B: GOTO 10300
10250 IF A$ = "5" THEN LINE (373, 235)-(387, 255), 4, B: GOTO 10300
10260 IF A$ = "6" THEN LINE (429, 235)-(443, 255), 4, B: GOTO 10300
10270 IF A$ = "7" THEN LINE (485, 235)-(499, 255), 4, B: GOTO 10300
10280 LOCATE 20, 34: PRINT A$; " IS NOT A VALID CHOICE": GOTO 10180
10290 :
10300 START! = TIMER
10310 FINISH! = TIMER
10320 IF FINISH! - START! < 2 THEN 10310
10330 CLS
10340 RETURN
10400 REM ***** SUBROUTINE *****
10410 REM ENTER CURRENT SESSION NUMBER
10420 CLS : SCREEN , 9: COLOR , 8
10430 LINE (20, 76)-(630, 225), 14, B
10440 LOCATE 6, 28: PRINT " ENTER CURRENT SESSION NUMBER"
10450 LOCATE 10, 16: INPUT "SESSION NUMBER: ", SESSION$
10460 LOCATE 13, 16: INPUT "ARE YOU SURE (Y/N)"; ANSW$
10470 IF ANSW$ = "N" OR ANSW$ = "n" THEN 10450
10480 IF LEN(ANSW$) <> 1 THEN 10460
10490 RETURN
```

# APPENDIX B

# VERBAL INSTRUCTIONS TO SUBJECTS

## INSTRUCTIONS TO SUBJECTS

I would like to thank you for participating in this research project. This is a study of membrane touchpads, the type of touchpads you might find on microwave ovens, ATMs, or some Kodak products such as photocopiers, minilab systems, etc.

When we begin, I will ask you to use a touchpad to enter 100 numbers into the computer and answer a questionnaire about the "feel" of the touchpad, after which you will have a ten minute break. When you return, I will ask you to complete the same task using a different touchpad. This is what you can expect to do for each of the three days you particpate in this experiment. If you complete all three sessions, you will receive a small gift in appreciation for your help with this study.

Please have a seat in this chair. Is the height alright? You should be able to rest your feet flat on the floor, without pressure on the back of your thighs. (Assist subject in adjusting the height, if necessary; the primary criterion is to ensure that the subject is comfortable in the chair.)

Now, I would like you to move up here to the touchpad. Is the height of the table alright? It should be high enough so that you can fit your legs beneath it comfortably, with the top just a little higher than your elbow (approximately 15° above elbow height). Is that comfortable?

Is the height of the display alright? (Adjust the height so that the center of the screen is in the direct line of sight when a comfortable posture is assumed. Adjust the tilt to minimize glare from overhead lights.) Using this button (designate the contrast control), I would like you to adjust the contrast so that you can see the display well. The characters should be bright enough to see, but not fuzzy or blurred.

Finally, before we begin, I'd like to ask you to wipe your hands off with this towelette (hand them a moist towelette). This is to protect the touchpads from becoming soiled with ink or hand lotions.

The instructions will come up on the screen and tell you what to do. If you have any questions, please feel free to ask. I want to emphasize that you should work as quickly and as accurately as you can. You may begin anytime you are ready.

# APPENDIX C

## SPECIFIC TASK INSTRUCTIONS PRESENTED TO SUBJECTS ON THE CRT

## INSTRUCTIONS

This experiment involves the evaluation of six membrane touchpads. You will be using two touchpads each day for three days over the next two weeks. I would like to emphasize that we are not testing you nor your ability to use these touchpads, but rather how well the touchpads perform and which you prefer.

PRESS THE '#' KEY TO CONTINUE

## INSTRUCTIONS

When we begin, a 4-digit number will appear in the box below. When you are ready, please enter the number using the touchpad. After you have entered the number, press the '#' key and the next number to be entered will appear. Continue entering numbers, always followed by "#', until a SESSION FINISHED message appears instead of a number. A 'BEEP' signal will be heard with every correct entry. Work as quickly and as accurately as you can. If you make a mistake, simply press the correct key and continue.

PRESS THE '#' KEY TO BEGIN

# APPENDIX D

## MAGNITUDE ESTIMATION SCALING TECHNIQUE: INSTRUCTIONS TO SUBJECTS

## INSTRUCTIONS

You have now used six touchpads over the three days you have participated in this study. I'd like to get a better idea of how you feel about these touchpads with respect to one another. I will ask you to use each touchpad briefly, and then give me a number which represents how well you liked the "feel" of the touchpad. To the first one, assign any number that seems appropriate. To the second one, assign a number which is proportional to your rating of the "feel" of the first. You may use whole numbers and fractions, just make sure that the number you give is proportional to your rating of the previous touchpad. For example, if you like the second one fifteen times as much as the first, assign it a number fifteen times as large. If you like the second one only half as much as the first, assign it a number half as large, and so on. Your number assignments should always be relative to the touchpad you had used immediately prior to the current one. Do you have any questions about how to assign numbers? Let's practice assigning numbers to these squares, on the basis of size, with higher numbers representing bigger squares.

**FOR THE FIRST TOUCHPAD:** Using this touchpad, I would like you to enter a few numbers, so that you are familiar with its "feel". (After they have input several numbers): Now, please give me a number which expresses the extent to which you like the "feel" of this touchpad.

**FOR SUBSEQUENT TOUCHPADS:** Using this touchpad, I would like you to enter a few numbers, so that you are familiar with its "feel". (After they have input several numbers): Now, please give me a number which expresses the extent to which you like the "feel" of this touchpad, remembering that you gave the last touchpad a rating of _____.

# APPENDIX E

# DATA TRANSFORMATION SOFTWARE

```
10 REM XFORM.BAS
20 REM BY PAULA M. SIND
30 REM :  FIRST TRANSFORM OF FORCE PLATFORM DATA TO NET FORCE
40 :
50 REM SET UP ARRAYS FOR LOAD CELL, TIME, AND EVALUATION DATA
55 DIM LC%(7, 55, 11)
65 DIM TC(55), SIGMA%(55, 11), STDV(11)
70 DIM DIG(400), STIM(11)
75 DIM SIGAV(55, 11)
90 :
100 REM INPUT HEADER INFORMATION FOR FILE TO BE TRANSFORMED
120 INPUT "Name of File to be Transformed (DRIVE:filename)"; FILE$
130 INPUT "Subject Number"; SUBJ
160 INPUT "Session Number"; SESS
161 :
163 REM  DETERMINE WHICH WAVETEK (AND HENCE, SAMPLING RATE) WAS USED
170 IF SUBJ = 2 OR SUBJ = 4 OR SUBJ = 5 OR SUBJ = 6 OR SUBJ = 7 THEN WT = 0: GOTO 230
180 IF SUBJ > 9 THEN WT = 1: GOTO 230
181 IF SUBJ = 1 AND SESS < 5 THEN WT = 0: GOTO 230
182 IF SUBJ = 1 AND SESS > 4 THEN WT = 1: GOTO 230
183 IF SUBJ = 3 AND SESS < 5 THEN WT = 0: GOTO 230
184 IF SUBJ = 3 AND SESS > 4 THEN WT = 1: GOTO 230
185 IF SUBJ = 8 AND SESS < 3 THEN WT = 0: GOTO 230
186 IF SUBJ = 8 AND SESS > 2 THEN WT = 1: GOTO 230
187 IF SUBJ = 9 AND SESS < 3 THEN WT = 0: GOTO 230
188 IF SUBJ = 9 AND SESS > 2 THEN WT = 1
230 INPUT "Touchpad Used"; KPAD$
270 FOR K = 1 TO 7
280    INPUT "Subjective Ratings"; RAT(K)
290 NEXT K
300 :
310 REM  CHECK TO MAKE SURE ENTRIES ARE CORRECT
320 CLS : LOCATE 5, 8: PRINT "1) File Name = "; FILE$
330 LOCATE 6, 8: PRINT "2) Subject Number = "; SUBJ
360 LOCATE 7, 8: PRINT "3) Session Number = "; SESS
370 LOCATE 8, 8: PRINT "4) Touchpad Used = "; KPAD$
410 LOCATE 10, 8: PRINT "5) Subjective Ratings:"
420 LOCATE 12, 10: PRINT RAT(1)
430 LOCATE 12, 13: PRINT RAT(2)
440 LOCATE 12, 16: PRINT RAT(3)
450 LOCATE 12, 19: PRINT RAT(4)
460 LOCATE 12, 22: PRINT RAT(5)
470 LOCATE 12, 25: PRINT RAT(6)
480 LOCATE 12, 28: PRINT RAT(7)
490 LOCATE 16, 10: PRINT "PREPARING TO WRITE INFORMATION TO FILE."
```

```
500 LOCATE 17, 12: INPUT "IS ALL INFORMATION CORRECT (Y/N)"; ANS$
510 IF ANS$ = "n" OR ANS$ = "N" THEN 540
520 IF ANS$ = "y" OR ANS$ = "Y" THEN 565
530 GOTO 500
540 LOCATE 19, 12: INPUT "Which item needs to be changed"; X
550 CLS : ON X GOTO 120, 130, 160, 230, 270
560 :
565 GOSUB 4000: REM INPUT STIMULI
566 :
570 REM  WRITE SUBJECTIVE EVALUATION DATA TO FILE
580 OPEN "RATINGS.DAT" FOR APPEND AS 2
590 FOR J = 1 TO 7
600    PRINT #2, SUBJ; KPAD$; RAT(J); J
610 NEXT J
620 CLOSE #2
630 :
640 REM  WRITE DEMOGRAPHIC/ARCHIVE INFORMATION TO FILE
650 OPEN "ARCHIVE.DAT" FOR APPEND AS 4
660 PRINT #4, SUBJ; KPAD$; SESS; GENDER$; " "; HAND$; " "; TH; XADVAL; ADVAR; WT
670 CLOSE #4
680 :
700 REM  INPUT INFORMATION FROM DATA FILE
710 :
720 CLS : LOCATE 15, 10: PRINT "PROCESSING FILE.  THIS MAY TAKE A WHILE."
730 LOCATE 16, 5: PRINT "YOU MAY WANT TO GRAB A CUP OF COFFEE OR SOMETHING."
731 :
732 OPEN FILE$ + ".DAT" FOR INPUT AS #1
733 GOSUB 3000: REM READ HEADER INFORMATION
740 :
758 REM  WRITE QUANTITATIVE INFORMATION TO FILE
760 SUBJ$ = LTRIM$(STR$(SUBJ))
762 OPEN "Q" + SUBJ$ + "_" + KPAD$ + ".DAT" FOR OUTPUT AS #3
764 :
770 REM  READ TIME DATA
774 :
775 FOR BLOCK = 1 TO 10
777 FOR KP = 1 TO 50
 INPUT #1, TIM#, ERRORCNT, STARTIME, ENDTIME
 FOR I = 1 TO 55
    INPUT #1, TC(I)
 NEXT I
GOSUB 2300: REM LOG DURATION AND PACING INFORMATION TO DATA FILE
 :
 REM DISPLAY STATUS COUNTER TO SCREEN
 STAT = STAT + 1
```

```
LOCATE 2, 5: PRINT STAT
:
REM  READ LOAD CELL DATA
FOR K = 0 TO 6
INPUT #1, TRIAL
DIGIT$ = INPUT$(1, #1)
   IF DIGIT$ = "#" THEN DIGIT$ = "10"
IF K = 0 THEN KKK = KKK + 1
IF K = 0 AND DIGIT$ = "10" THEN KKK = KKK - 1
DIGG = DIG(KKK)
IF DIGIT$ = "10" THEN DIGG = VAL(DIGIT$)
  STDV(DIGG) = STDV(DIGG) + 1: REM INCREMENT N FOR SIGAVG DIVISOR
INPUT #1, CHNL
FOR I = 1 TO 55
      IF TC(I) = TC(I - 1) THEN INPUT #1, JUNK: GOTO JUMP2: REM SKIP TIME REPRINTS
      INPUT #1, LC%(K, I, DIGG)
JUMP2: NEXT I
NEXT K
  :
GOSUB 5000: REM CHANNEL SUMMATION PROCEDURE
GOSUB 2100: REM WAVETEK CORRECTION
  :
REM  WRITE INFORMATION TO OUTPUT FILE
FOR I = 1 TO 55
IF TC(I) = 0 THEN GOTO SKIP
IF TC(I) = TC(I - 1) THEN GOTO SKIP
PRINT #3, SUBJ; KPAD$; SESS; BLOCK; TRIAL; STARTIME;
IF DIGIT$ = "10" THEN PRINT #3, 10;
IF DIGIT$ <> "10" THEN PRINT #3, DIG(KKK);
FOR STIM = 0 TO 10
IF SIGMA%(TC(I), STIM) = 0 THEN GOTO SKIP
IF SIGMA%(TC(I), STIM) > 20000 THEN SIGMA%(TC(I), STIM) = SIGMA%(TC(I), STIM) / 2
PRINT #3, TC(I); SIGMA%(TC(I), STIM)
SKIP: NEXT STIM: NEXT I
ERASE LC%: ERASE TC: ERASE STIM: ERASE SIGAV: ERASE SIGMA%
NEXT KP:  REM FOR SUMMATION OVER A SINGLE KEYPRESS
NEXT BLOCK
1000 CLOSE #3: CLOSE #1
1005 BEEP: BEEP
1010 END
1020 :
1030 :
1040 :
1050 :
1060 :
```

```
2100 REM ***** SUBROUTINE: CORRECT FOR SAMPLING RATE ERRORS *****
2110 REM IF WT = 0, SESSION WAS RUN USING RTK'S WAVETEK.
2120 REM IF WT = 1, SESSION WAS RUN USING THE KAD WAVETEK.
2130 FOR L = 1 TO 55
2132 IF TC(L) = 0 THEN 2150
2135 REM IF WT = 0, THEN TC(L) = TC(L)
2140 IF WT = 1 THEN TC(L) = 100 - ((100 - TC(L)) * (100 / 167))
2150 NEXT L
2180 RETURN
2190 :
2195 :
2300 REM ***** SUBROUTINE: COMPUTE & LOG PACING DATA *****
2305 PACELOOP = PACELOOP + 1
2310 DUR = 0: LAST = 0
2320 FOR I = 1 TO 55
2330 IF TC(I) > 0 THEN LAST = TC(I)
2340 NEXT I
2350 DUR = 100 - LAST
2360 IF TRIAL = 0 THEN PACE = 0
2370 IF TRIAL > 0 THEN PACE! = STARTIME - OLDSTART
2380 OPEN "PACING.DAT" FOR APPEND AS 6
2390 IF PACELOOP = 1 THEN PRINT #6, SUBJ; KPAD$; SESS; BLOCK; TRIAL; PACE!;
2392 IF PACELOOP < 5 THEN PRINT #6, ERRORCNT; DUR;
2394 IF PACELOOP = 5 THEN PRINT #6, ERRORCNT; DUR
2400 CLOSE #6
2410 OLDSTART = STARTIME
2415 IF PACELOOP = 5 THEN PACELOOP = 0
2420 RETURN
2430 :
2440 :
3000 REM ***** SUBROUTINE:  READS HEADER INFORMATION *****
3010 INPUT #1, NM$
3020 INPUT #1, LOC$
3030 INPUT #1, GENDER$
3040 INPUT #1, XX$
3050 INPUT #1, YY$
3060 INPUT #1, MCODE$
3070 INPUT #1, PH$
3080 INPUT #1, HAND$
3090 INPUT #1, FIL$
3100 INPUT #1, KPAD11$
3110 INPUT #1, KPAD12$
3120 INPUT #1, KPAD21$
3130 INPUT #1, KPAD22$
3140 INPUT #1, KPAD31$
```

```
3150 INPUT #1, KPAD32$
3160 INPUT #1, XX$
3170 INPUT #1, YY$
3180 INPUT #1, NM$
3190 INPUT #1, OPKPD$
3200 INPUT #1, TH
3210 INPUT #1, XADVAL
3220 INPUT #1, ADVAR
3230 RETURN
3998 :
3999 :
4000 REM ***** SUBROUTINE:  INPUT THE STIMULUS VALUES *****
4010 SESS$ = LTRIM$(STR$(SESS))
4020 OPEN "DATFIL" + SESS$ + ".DAT" FOR INPUT AS #5
4030 FOR I = 1 TO 400
4040    INPUT #5, DIG(I)
4050 NEXT I
4060 CLOSE #5
4070 RETURN
4080 :
4090 :
5000 REM ***** SUBROUTINE:  SIGNAL SUMMATION PROCEDURE *****
5020 FOR I = 1 TO 55
5025 FOR II = 0 TO 6
5027 IF LC%(II, I, DIGG) = 0 THEN LC%(II, I, DIGG) = XADVAL
5030 SIGMA%(TC(I), DIGG) = SIGMA%(TC(I), DIGG) + LC%(II, I, DIGG)
5040 NEXT II
5050 NEXT I
5060 RETURN
```

# APPENDIX F

## ANOVA SUMMARY TABLES: EXPERIMENT I

Table 29. ANOVA summary table for Duration-Weighted Mean Force: Required Actuation Force Analysis

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 45092.52 | 45092.52 | 6.16 | 0.0221 |
| Gender (G) | 1 | 13387.42 | 13387.42 | 1.83 | 0.1912 |
| M x G | 1 | 3085.35 | 3085.35 | 0.42 | 0.5243 |
| Subject\|G,M | 20 | 146292.70 | 7314.64 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 9 | 676283.02 | 75142.56 | 60.61 | 0.0001 |
| G x T\|M | 9 | 10024.94 | 1113.88 | 0.90 | 0.5289 |
| T\|M x S\|G,M | 90 | 111578.68 | 1239.76 | | |
| Period (P) | 9 | 1197.88 | 133.10 | 2.75 | 0.0049 |
| P x M | 9 | 4664.26 | 518.25 | 10.69 | 0.0001 |
| P x G | 9 | 376.10 | 41.79 | 0.86 | 0.5622 |
| P x M x G | 9 | 250.56 | 27.84 | 0.57 | 0.8205 |
| P x S\|G,M | 180 | 8725.20 | 48.47 | | |
| Digit (D) | 10 | 5791.73 | 579.17 | 20.78 | 0.0001 |
| D x M | 10 | 227.66 | 22.77 | 0.82 | 0.6097 |
| D x G | 10 | 270.07 | 27.01 | 0.97 | 0.4708 |
| D x M x G | 10 | 221.31 | 22.13 | 0.79 | 0.6384 |
| D x S\|G,M | 200 | 5573.93 | 27.87 | | |
| Residual | 13342 | 228809.67 | 17.15 | | |
| Total: | 13929 | 1261852.99 | | | |

Table 30. ANOVA summary table for Absolute Amplitude Mean Force: Required Actuation Force Analysis

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 53471.38 | 53471.38 | 4.99 | 0.0371 |
| Gender (G) | 1 | 19310.87 | 19310.87 | 1.80 | 0.1947 |
| M x G | 1 | 6937.89 | 6937.89 | 0.65 | 0.4296 |
| Subject\|G,M | 20 | 214499.06 | 10724.95 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 9 | 867303.03 | 96367.00 | 49.75 | 0.0001 |
| G x T\|M | 9 | 12311.89 | 1367.99 | 0.71 | 0.6983 |
| T\|M x S\|G,M | 90 | 174328.612 | 1936.98 | | |
| Period (P) | 9 | 1732.54 | 192.50 | 1.61 | 0.1152 |
| P x M | 9 | 4912.341 | 545.82 | 4.57 | 0.0001 |
| P x G | 9 | 1624.77 | 180.53 | 1.51 | 0.1473 |
| P x M x G | 9 | 1233.42 | 137.05 | 1.15 | 0.3301 |
| P x S\|G,M | 180 | 21483.98 | 119.36 | | |
| Digit (D) | 10 | 2643.43 | 264.34 | 6.00 | 0.0001 |
| D x M | 10 | 505.83 | 50.58 | 1.15 | 0.3270 |
| D x G | 10 | 951.59 | 95.16 | 2.16 | 0.0217 |
| D x M x G | 10 | 433.85 | 43.38 | 0.99 | 0.4534 |
| D x S\|G,M | 200 | 8807.24 | 44.04 | | |
| Residual | 13342 | 661802.48 | 49.60 | | |
| Total: | 13929 | 2054294.18 | | | |

Table 31. ANOVA summary table for Excessive Applied Force: Required Actuation Force Analysis (DWMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 24691.72 | 24691.72 | 3.38 | 0.0809 |
| Gender (G) | 1 | 13387.42 | 13387.42 | 1.83 | 0.1912 |
| M x G | 1 | 3085.35 | 3085.35 | 0.42 | 0.5243 |
| Subject\|G,M | 20 | 146292.70 | 7314.64 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 9 | 476435.40 | 52937.27 | 42.70 | 0.0001 |
| G x T\|M | 9 | 10024.94 | 1113.88 | 0.90 | 0.5289 |
| T\|M x S\|G,M | 90 | 111578.68 | 1239.76 | | |
| Period (P) | 9 | 1197.88 | 133.10 | 2.75 | 0.0049 |
| P x M | 9 | 4664.26 | 518.25 | 10.69 | 0.0001 |
| P x G | 9 | 376.10 | 41.79 | 0.86 | 0.5622 |
| P x M x G | 9 | 250.56 | 27.84 | 0.57 | 0.8205 |
| P x S\|G,M | 180 | 8725.20 | 48.47 | | |
| Digit (D) | 10 | 5791.73 | 579.17 | 20.78 | 0.0001 |
| D x M | 10 | 227.66 | 22.77 | 0.82 | 0.6097 |
| D x G | 10 | 270.07 | 27.01 | 0.97 | 0.4708 |
| D x M x G | 10 | 221.31 | 22.13 | 0.79 | 0.6384 |
| D x S\|G,M | 200 | 5573.93 | 27.87 | | |
| Residual | 13342 | 228809.68 | 17.15 | | |
| Total: | 13929 | 1041604.57 | | | |

Table 32. ANOVA summary table for Excessive Applied Force: Required Actuation Force Analysis (AAMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 30984.72 | 30984.72 | 2.89 | 0.1046 |
| Gender (G) | 1 | 19310.87 | 19310.87 | 1.80 | 0.1947 |
| M x G | 1 | 6937.89 | 6937.89 | 0.65 | 0.4296 |
| Subject\|G,M | 20 | 214499.06 | 10724.95 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 9 | 636966.22 | 70774.02 | 36.54 | 0.0001 |
| G x T\|M | 9 | 12311.89 | 1367.99 | 0.71 | 0.6983 |
| T\|M x S\|G,M | 90 | 174328.61 | 1936.98 | | |
| Period (P) | 9 | 1732.54 | 192.50 | 1.61 | 0.1152 |
| P x M | 9 | 4912.34 | 545.82 | 4.57 | 0.0001 |
| P x G | 9 | 1624.77 | 180.53 | 1.51 | 0.1473 |
| P x M x G | 9 | 1233.42 | 137.05 | 1.15 | 0.3301 |
| P x S\|G,M | 180 | 21483.98 | 119.36 | | |
| Digit (D) | 10 | 2643.43 | 264.34 | 6.00 | 0.0001 |
| D x M | 10 | 505.83 | 50.58 | 1.15 | 0.3270 |
| D x G | 10 | 951.59 | 95.16 | 2.16 | 0.0217 |
| D x M x G | 10 | 433.85 | 43.38 | 0.99 | 0.4534 |
| D x S\|G,M | 200 | 8807.24 | 44.04 | | |
| Residual | 13342 | 661802.48 | 49.60 | | |
| Total: | 13929 | 1801470.72 | | | |

Table 33. ANOVA summary table for Duration: Required Force Analysis

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 0.5902 | 0.5902 | 0.22 | 0.6441 |
| Gender (G) | 1 | 0.0874 | 0.0874 | 0.03 | 0.8642 |
| M x G | 1 | 4.6725 | 4.6725 | 1.72 | 0.2046 |
| Subject\|G,M | 20 | 54.3466 | 2.7173 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 9 | 27.5707 | 3.0634 | 8.78 | 0.0001 |
| G x T\|M | 9 | 2.9240 | 0.3249 | 0.93 | 0.5033 |
| K\|M x S\|G,M | 90 | 31.3932 | 0.3488 | | |
| Period (P) | 9 | 11.2265 | 1.2474 | 72.55 | 0.0001 |
| P x M | 9 | 0.0129 | 0.0014 | 0.08 | 0.9998 |
| P x G | 9 | 0.0099 | 0.0011 | 0.06 | 1.0000 |
| P x M x G | 9 | 0.0926 | 0.0103 | 0.60 | 0.7960 |
| P x S\|G,M | 180 | 3.0950 | 0.0172 | | |
| Digit (D) | 10 | 2.0484 | 0.2048 | 39.18 | 0.0001 |
| D x M | 10 | 0.0632 | 0.0063 | 1.21 | 0.2863 |
| D x G | 10 | 0.0205 | 0.0021 | 0.39 | 0.9500 |
| D x M x G | 10 | 0.0405 | 0.0041 | 0.77 | 0.6576 |
| D x S\|G,M | 200 | 1.0457 | 0.0052 | | |
| Residual | 13342 | 43.403 | 0.0033 | | |
| Total: | 13929 | 182.64 | | | |

Table 34. ANOVA Summary Table for Subjective Ratings: Required Actuation Force Analysis

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 5286.16 | 5286.16 | 1.17 | 0.2920 |
| Subject\|M (S\|M) | 22 | 99751.86 | 4534.18 | | |
| **Within Subjects** | | | | | |
| Touchpad\|M (T\|M) | 10 | 50872.64 | 5087.26 | 3.78 | 0.0002 |
| T\|M x S | 110 | 147946.46 | 1344.97 | | |
| Total: | 143 | 303857.12 | | | |

Table 35. Summary Table for Duration-Weighted Mean Force: Structural Analysis (0.127 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 68350.58 | 6213.69 | | |
| **Within Subjects** | | | | | |
| Aperture (A) | 2 | 210355.50 | 105177.75 | 58.90 | 0.0001 |
| A x Sub | 22 | 39283.67 | 1785.62 | | |
| Spacer (S) | 1 | 112112.59 | 112112.59 | 106.97 | 0.0001 |
| S x Sub | 11 | 11528.30 | 1048.03 | | |
| A x S | 2 | 15896.92 | 7948.46 | 8.26 | 0.0001 |
| A x S x Sub | 22 | 21181.76 | 962.81 | | |
| Total: | 71 | 478709.32 | | | |

Table 36. Summary Table for Duration-Weighted Mean Force: Structural Analysis (0.254 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 94414.90 | 8583.17 | | |
| **Within Subjects** | | | | | |
| Aperture,Spacer (A,S) | 4 | 337918.02 | 84479.51 | 74.93 | 0.0001 |
| A,S x Sub | 44 | 49609.89 | 1127.50 | | |
| Total: | 59 | 481942.81 | | | |

Table 37. ANOVA summary table for Absolute Amplitude Mean Force: Structural Analysis (0.127 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 92842.37 | 8440.22 | | |
| **Within Subjects** | | | | | |
| Aperture (A) | 2 | 276818.51 | 138409.25 | 44.64 | 0.0001 |
| A x Sub | 22 | 68210.15 | 3100.46 | | |
| Spacer (S) | 1 | 157531.42 | 157531.42 | 111.84 | 0.0001 |
| S x Sub | 11 | 15493.95 | 1408.54 | | |
| A x S | 2 | 30193.66 | 15096.83 | 8.88 | 0.0001 |
| A x S x Sub | 22 | 37402.70 | 1700.12 | | |
| Total: | 71 | 678492.76 | | | |

Table 38. ANOVA summary table for Absolute Amplitude Mean Force: Structural Analysis (0.254 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 147905.45 | 13445.95 | | |
| **Within Subjects** | | | | | |
| Aperture,Spacer (A,S) | 4 | 402795.45 | 100698.86 | 67.61 | 0.0001 |
| A,S x Sub | 44 | 65533.71 | 1489.40 | | |
| Total: | 59 | 616234.61 | | | |

Table 39. ANOVA summary table for Excessive Applied Force: Structural Analysis (0.127 mm Membrane Thickness, DWMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 68350.58 | 6213.69 | | |
| **Within Subjects** | | | | | |
| Aperture (A) | 2 | 157237.10 | 78618.55 | 44.03 | 0.0001 |
| A x Sub | 22 | 39283.67 | 1785.62 | | |
| Spacer (S) | 1 | 67555.15 | 67555.15 | 64.46 | 0.0001 |
| S x Sub | 11 | 11528.30 | 1048.03 | | |
| A x S | 2 | 12023.46 | 6011.73 | 6.24 | |
| A x S x Sub | 22 | 21181.76 | 962.81 | | |
| Total: | 71 | 377160.02 | | | |

Table 40. ANOVA summary table for Excessive Applied Force: Structural Analysis (0.254 mm Membrane Thickness, DWMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 94414.90 | 8583.17 | | |
| **Within Subjects** | | | | | |
| Aperture,Spacer (A,S) | 4 | 239619.68 | 59904.92 | 53.13 | 0.0001 |
| A,S x Sub | 44 | 49609.89 | 1127.50 | | |
| Total: | 59 | 383644.47 | | | |

Table 41. ANOVA summary table for Excessive Applied Force: Structural Analysis (0.127 mm Membrane Thickness, AAMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 92842.37 | 8440.22 | | |
| **Within Subjects** | | | | | |
| Aperture (A) | 2 | 215670.81 | 107835.41 | 34.78 | 0.0001 |
| A x Sub | 22 | 68210.15 | 3100.46 | | |
| Spacer (S) | 1 | 103673.59 | 103673.59 | 73.60 | 0.0001 |
| S x Sub | 11 | 15493.95 | 1408.54 | | |
| A x S | 2 | 24760.16 | 12380.08 | 7.28 | 0.0001 |
| A x S x Sub | 22 | 37402.70 | 1700.12 | | |
| Total: | 71 | 558053.73 | | | |

Table 42. ANOVA summary table for Excessive Applied Force: Structural Analysis (0.254 mm Membrane Thickness, AAMF Metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 147905.45 | 13445.95 | | |
| **Within Subjects** | | | | | |
| Aperture,Spacer (A,S) | 4 | 292861.65 | 73215.41 | 49.16 | 0.0001 |
| A,S x Sub | 44 | 65533.71 | 1489.40 | | |
| Total: | 59 | 506300.81 | | | |

Table 43. ANOVA summary table for Duration:
Structural Analysis (0.127 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 32.4172 | 2.9470 | | |
| **Within Subjects** | | | | | |
| Aperture (A) | 2 | 12.9278 | 6.4639 | 22.17 | 0.0001 |
| A x Sub | 22 | 6.4140 | 0.2915 | | |
| Spacer (S) | 1 | 5.1451 | 5.1451 | 28.28 | 0.0001 |
| S x Sub | 11 | 2.0015 | 0.1820 | | |
| A x S | 2 | 1.9751 | 0.9876 | 3.20 | |
| A x S x Sub | 22 | 6.7960 | 0.3089 | | |
| Total: | 71 | 67.6767 | | | |

Table 44. ANOVA summary table for Duration:
Structural Analysis (0.254 mm Membrane Thickness)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 11 | 26.6893 | 2.4263 | | |
| **Within Subjects** | | | | | |
| Aperture,Spacer (A,S) | 4 | 7.5227 | 1.8807 | 4.33 | 0.0001 |
| A,S x Sub | 44 | 19.1050 | 0.4342 | | |
| Total: | 59 | 53.3170 | | | |

Table 45. ANOVA Summary Table for Subjective Ratings: Structural Analysis

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Membrane (M) | 1 | 5286.16 | 5286.16 | 1.17 | 0.2920 |
| Subject\|M (Sub\|M) | 22 | 99751.86 | 4534.18 | | |
| **Within Subjects** | | | | | |
| Spacer (S) | 1 | 12211.18 | 12211.18 | 6.86 | 0.0657 |
| S x M | 1 | 3410.18 | 3410.18 | 1.92 | 0.1801 |
| S x Sub\|M | 22 | 39149.03 | 1779.50 | | |
| Aperture (A) | 2 | 28256.79 | 14128.40 | 8.41 | 0.0008 |
| A x M | 2 | 3044.67 | 1522.34 | 0.91 | 0.4113 |
| A x Sub\|M | 44 | 73881.06 | 1679.11 | | |
| S x A | 2 | 1244.64 | 622.32 | 0.78 | 0.4628 |
| S x A x M | 2 | 2705.17 | 1352.58 | 1.70 | 0.1937 |

# APPENDIX G

# MAGNITUDE ESTIMATION DATA RESCALING ALGORITHM

```
*THIS SAS PROGRAM WAS WRITTEN BY RICHARD G. PIGION 12/88;
*HE IS TOTALLY UNRESPONSIBLE FOR ITS USE AND MISUSE;
*IF YOU HAVE ANY QUESTIONS CONTACT S. S. STEVENS;

*THE PURPOSE OF THIS PROGRAM IS TO TRANSFORM MAGNITUDE;
*ESTIMATION DATA SO THAT IT CAN BE ANALYZED USING ANOVA;
CMS FILEDEF KMSR DISK MAGEST DATA A1;
*READ "RAW" MAGNITUDE DATA;
DATA RAW;
  INFILE KMSR;
  INPUT SUB KEYPAD MAG;
*TAKE BASE 10 LOG OF RAW DATA;
DATA RAWLOG;  SET RAW;
LMAG=LOG10(MAG);
*DETERMINE THE GEOMETRIC MEAN OF ALL DATA;
*THIS IS THE SAME AS THE ARITHMETIC MEAN OF THE LOG DATA;
PROC MEANS DATA=RAWLOG NOPRINT;
  VAR LMAG;  OUTPUT OUT=GRAND MEAN=GRANDM STD=GRDST;
*PROC PRINT DATA=GRAND;
*DETERMINE EACH SUBJECT'S MEAN ACROSS ALL CONDITIONS;
PROC SORT DATA=RAWLOG;  BY SUB;
PROC MEANS DATA=RAWLOG NOPRINT;
  VAR LMAG;  OUTPUT OUT=SUBJM MEAN=SUBJM STD=SUBJSTD;
  BY SUB;
*PROC PRINT DATA=SUBJM;
*DETERMINE DIFFERENCE BETWEEN THE GRAND MEAN AND EACH SUBJECT'S MEAN;
DATA CORRECT;
  IF _N_=1 THEN SET GRAND;
  SET SUBJM;
    DIFFM=GRANDM-SUBJM;
*PROC PRINT DATA=CORRECT;
PROC SORT DATA=CORRECT; BY SUB;
PROD SORT DATA=RAWLOG; BY SUB;
*ADD EACH SUBJECT'S DIFFERENCE TO EACH OF HIS/HER RESPONSES;
DATA RAWSCALE;  MERGE RAWLOG CORRECT;
  BY SUB;
  RAWCOR=LMAG+DIFFM;
*PROC PRINT DATA=RAWSCALE;
*TAKE ANTILOG OF ALL DATA;
DATA FINAL;  SET RAWSCALE;
  DROP GRDST SUBJSTD;
RATE=10**RAWCOR;
PROC PRINT DATA=FINAL;
TITLE 'MEMBRANE SWITCH RESEARCH';
*WRITE NEW DATA FILE TO DISK FN=RESCALED DATA;
CMS FI OUT DISK EXP1RES DATA A1 (LRECL 80 BLKSIZE 80);
DATA FINAL;  SET FINAL;
  FILE OUT;
  PUT SUB KEYPAD$ MAG LMAG GRANDM SUBJM DIFFM RAWCOR RATE;
RUN;
```

# APPENDIX H

## ANOVA SUMMARY TABLES: EXPERIMENT II

Table 46. ANOVA summary table for Duration-Weighted Mean Force

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender (G) | 1 | 304.88 | 304.88 | 0.17 | 0.6856 |
| Subject\|G (S\|G) | 16 | 28878.22 | 1804.89 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 47170.99 | 9434.20 | 51.48 | 0.0001 |
| T x G | 5 | 1747.87 | 349.57 | 1.91 | 0.1018 |
| T x S\|G | 80 | 14661.06 | 183.26 | | |
| Period (P) | 9 | 2057.10 | 228.57 | 8.69 | 0.0001 |
| P x G | 9 | 54.41 | 6.05 | 0.23 | 0.9897 |
| P x S\|G | 144 | 3789.01 | 26.31 | | |
| T x P | 45 | 1355.71 | 30.13 | 1.16 | 0.2233 |
| T x P x G | 45 | 1243.45 | 27.63 | 1.06 | 0.3692 |
| T x P x S\|G | 720 | 18719.45 | 26.00 | | |
| Digit (D) | 10 | 1575.76 | 157.58 | 11.52 | 0.0001 |
| D x G | 10 | 136.34 | 13.63 | 1.00 | 0.4458 |
| D x S\|G | 160 | 2188.11 | 13.68 | | |
| T x D | 50 | 466.07 | 9.32 | 0.87 | 0.7253 |
| T x D x G | 50 | 510.82 | 10.22 | 0.95 | 0.5737 |
| T x D x S\|G | 712 | 7666.26 | 10.77 | | |
| P x D | 90 | 2548.72 | 28.32 | 3.48 | 0.0001 |
| P x D x G | 90 | 197.33 | 2.19 | 0.27 | 1.0000 |
| P x D x S\|G | 1440 | 11727.72 | 8.14 | | |
| T x P x D | 450 | 3346.79 | 7.44 | 0.83 | 0.9956 |
| T x P x D x G | 450 | 4021.16 | 8.94 | 1.00 | 0.4920 |
| T x P x D x S\|G | 6991 | 62752.06 | 8.98 | | |
| Total: | 11582 | 217119.28 | | | |

Table 47. ANOVA summary table for Absolute Amplitude Mean Force

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender (G) | 1 | 198.60 | 198.60 | 0.06 | 0.8096 |
| Subject\|G (S\|G) | 16 | 57729.42 | 3608.09 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 72428.96 | 14485.79 | 25.45 | 0.0001 |
| T x G | 5 | 5231.61 | 1046.32 | 1.84 | 0.1144 |
| T x S\|G | 80 | 45543.74 | 569.30 | | |
| Period (P) | 9 | 6576.32 | 730.70 | 3.17 | 0.0016 |
| P x G | 9 | 259.69 | 28.85 | 0.12 | 0.9992 |
| P x S\|G | 144 | 33950.69 | 235.77 | | |
| T x P | 45 | 7869.38 | 174.88 | 0.76 | 0.8744 |
| T x P x G | 45 | 11778.13 | 261.74 | 1.13 | 0.2625 |
| T x P x S\|G | 720 | 166219.61 | 230.86 | | |
| Digit (D) | 10 | 1097.66 | 109.77 | 1.57 | 0.1200 |
| D x G | 10 | 103.92 | 10.39 | 0.15 | 0.9988 |
| D x S\|G | 160 | 11216.01 | 70.10 | | |
| T x D | 50 | 2355.53 | 47.11 | 0.64 | 0.9751 |
| T x D x G | 50 | 4140.94 | 82.82 | 1.12 | ..26896 |
| T x D x S\|G | 712 | 52510.99 | 73.75 | | |
| P x D | 90 | 11807.33 | 131.19 | 2.02 | 0.0001 |
| P x D x G | 90 | 1066.52 | 11.85 | 0.18 | 1.0000 |
| P x D x S\|G | 1440 | 93696.41 | 65.07 | | |
| T x P x D | 450 | 24667.98 | 54.82 | 0.81 | 0.9984 |
| T x P x D x G | 450 | 33689.50 | 74.87 | 1.10 | 0.0771 |
| T x P x D x S\|G | 6991 | 474323.53 | 67.85 | | |
| Total: | 11582 | 1118462.44 | | | |

Table 48. ANOVA summary table for excessive applied force (DWMF metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender (G) | 1 | 304.88 | 304.88 | 0.17 | 0.6856 |
| Subject\|G (S\|G) | 16 | 28878.22 | 1804.89 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 44205.84 | 8841.17 | 48.24 | 0.0001 |
| T x G | 5 | 1747.87 | 349.57 | 1.91 | 0.1018 |
| T x S\|G | 80 | 14661.06 | 183.26 | | |
| Period (P) | 9 | 2057.10 | 228.57 | 8.69 | 0.0001 |
| P x G | 9 | 54.41 | 6.05 | 0.23 | 0.9897 |
| P x S\|G | 144 | 3789.01 | 26.31 | | |
| T x P | 45 | 1355.71 | 30.13 | 1.16 | 0.2233 |
| T x P x G | 45 | 1243.45 | 27.63 | 1.06 | 0.3692 |
| T x P x S\|G | 720 | 18719.45 | 26.00 | | |
| Digit (D) | 10 | 1575.76 | 157.58 | 11.52 | 0.0001 |
| D x G | 10 | 136.34 | 13.63 | 1.00 | 0.4458 |
| D x S\|G | 160 | 2188.11 | 13.68 | | |
| T x D | 50 | 466.07 | 9.32 | 0.87 | 0.7253 |
| T x D x G | 50 | 510.82 | 10.22 | 0.95 | 0.5737 |
| T x D x S\|G | 712 | 7666.26 | 10.77 | | |
| P x D | 90 | 2548.72 | 28.32 | 3.48 | 0.0001 |
| P x D x G | 90 | 197.33 | 2.19 | 0.27 | 1.0000 |
| P x D x S\|G | 1440 | 11727.72 | 8.14 | | |
| T x P x D | 450 | 3346.79 | 7.44 | 0.83 | 0.9956 |
| T x P x D x G | 450 | 4021.16 | 8.94 | 1.00 | 0.4920 |
| T x P x D x S\|G | 6991 | 62752.06 | 8.98 | | |
| Total: | 11582 | 214154.13 | | | |

Table 49. ANOVA summary table for excessive applied force (AAMF metric)

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender (G) | 1 | 198.60 | 198.60 | 0.06 | 0.8096 |
| Subject\|G (S\|G) | 16 | 57729.42 | 3608.09 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 68174.69 | 13634.94 | 23.95 | 0.0001 |
| T x G | 5 | 5231.61 | 1046.32 | 1.84 | 0.1144 |
| T x S\|G | 80 | 45543.74 | 569.30 | | |
| Period (P) | 9 | 6576.32 | 730.70 | 3.17 | 0.0016 |
| P x G | 9 | 259.69 | 28.85 | 0.12 | 0.9992 |
| P x S\|G | 144 | 33950.69 | 235.77 | | |
| T x P | 45 | 7869.38 | 174.88 | 0.76 | 0.8744 |
| T x P x G | 45 | 11778.13 | 261.74 | 1.13 | 0.2625 |
| T x P x S\|G | 720 | 166219.61 | 230.86 | | |
| Digit (D) | 10 | 1097.66 | 109.77 | 1.57 | 0.1200 |
| D x G | 10 | 103.92 | 10.39 | 0.15 | 0.9955 |
| D x S\|G | 160 | 11216.01 | 70.10 | | |
| T x D | 50 | 2355.53 | 47.11 | 0.64 | 0.9751 |
| T x D x G | 50 | 4140.94 | 82.82 | 1.12 | 0.2690 |
| T x D x S\|G | 712 | 52510.99 | 73.75 | | |
| P x D | 90 | 11807.33 | 131.19 | 2.02 | 0.0001 |
| P x D x G | 90 | 1066.52 | 11.85 | 0.18 | 1.0000 |
| P x D x S\|G | 1440 | 93696.41 | 65.07 | | |
| T x P x D | 450 | 24667.98 | 54.82 | 0.81 | 0.9984 |
| T x P x D x G | 450 | 33689.50 | 74.87 | 1.10 | 0.0771 |
| T x P x D x S\|G | 6991 | 474323.53 | 67.85 | | |
| Total: | 11582 | 1114208.18 | | | |

Table 50. Summary Table for Duration

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender (G) | 1 | 0.0253 | 0.0253 | 0.08 | 0.7809 |
| Subject\|G (S\|G | 16 | 4.7812 | 0.2988 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 2.4170 | 0.4834 | 3.03 | 0.0148 |
| T x G | 5 | 0.1625 | 0.0325 | 0.20 | 0.9616 |
| T x S\|G | 80 | 12.7553 | 0.1594 | | |
| Period (P) | 9 | 17.3851 | 1.9317 | 429.74 | 0.0001 |
| P x G | 9 | 0.0515 | 0.0057 | 1.27 | 0.2581 |
| P x S\|G | 144 | 0.6473 | 0.0045 | | |
| T x P | 45 | 0.2229 | 0.0050 | 1.25 | 0.1306 |
| T x P x G | 45 | 0.1501 | 0.0033 | 0.84 | 0.7633 |
| T x P x S\|G | 720 | 2.8620 | 0.0040 | | |
| Digit (D) | 10 | 2.3695 | 0.2369 | 86.69 | 0.0001 |
| D x G | 10 | 0.0123 | 0.0012 | 0.45 | 0.9193 |
| D x S\|G | 160 | 0.4373 | 0.0027 | | |
| T x D | 50 | 0.1543 | 0.0031 | 0.84 | 0.7765 |
| T x D x G | 50 | 0.1449 | 0.0029 | 0.79 | 0.8508 |
| T x D x S\|G | 712 | 2.6064 | 0.0037 | | |
| P x D | 90 | 1.0185 | 0.0113 | 4.49 | 0.0001 |
| P x D x G | 90 | 0.2206 | 0.0025 | 0.97 | 0.5604 |
| P x D x S\|G | 1440 | 3.6316 | 0.0025 | | |
| T x P x D | 450 | 1.1944 | 0.0027 | 0.82 | 0.9973 |
| T x P x D x G | 450 | 1.2545 | 0.0028 | 0.86 | 0.9832 |
| T x P x D x S\|G | 6991 | 22.5933 | 0.0032 | | |
| Total: | 11582 | 77.0977 | | | |

Table 51. ANOVA summary table for Subjective Ratings

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Subject (Sub) | 17 | 103347.80 | 6079.28 | | |
| **Within Subjects** | | | | | |
| Touchpad (T) | 5 | 19656.28 | 3931.26 | 2.49 | 0.0374 |
| T x Sub | 85 | 134224.47 | 1579.11 | | |
| Total: | 107 | 257228.55 | | | |

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