Determination and Evaluation of Acceptable Force Limits in Single-Digit Tasks

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Acceptable limits derived from psychophysical methodologies have been proposed, measured, and employed in a range of applications. There is little existing work, however, on such limits for single-digit exertions and relatively limited evidence on several fundamental issues related to data collection and processing of a sequence of self-regulated exertion levels. An experimental study was conducted using 14 male and 10 female participants (age range 18–31 years) from whom maximal voluntary exertions and maximal acceptable limits (MALs) were obtained using the index finger and thumb. Moderate to high levels of consistency were found for both measures between sessions separated by one day. Single MAL values, determined from a time series of exertions, were equivalent across three divergent processing methods and between values obtained from 5- and 25-min samples. A critical interpretation of these and earlier results supports continued use of acceptable limits but also suggests that they should be used with some caution and not equated with safe limits. This research can be applied toward future development of exertion limits based on perceived acceptability.

INTRODUCTION

An important goal of ergonomics design is ensuring that workers have sufficient physical strength to perform the required tasks. It is usually of additional interest that tasks be performed without excessive discomfort and to levels of desired performance and quality. These separate aspects also interact, in that when job demands require high levels of a worker's capacity (strength), comfort, performance, and quality typically decrease.

The present work addresses a current need for quantitative guidelines regarding recommended levels of forces during finger-intensive tasks. Whether used proactively as a source of data for part/process designers or reactively to evaluate and guide redesign of current tasks, such guidelines require appropriate data that can be applied to a variety of occupational tasks. Reviews of the existing literature indicated that such data do not exist in sufficient depth or breadth. As an initial step toward obtaining such data, a study was conducted to develop and evaluate a methodology for determining acceptability limits in tasks requiring single-digit exertions.

Psychophysics, the study of relationships between physical stimuli and sensory responses, has been used in diverse ergonomics applications. Early work by Snook and colleagues (e.g., Snook & Irvine, 1967) used a method of self-adjustment to obtain maximum acceptable weights of lift (MAWLs). MAWL procedures, which have been extensively modified and applied, usually require participants to imagine performing a task for a set period and then to perform the task for some fraction of this time. As such, the traditional psychophysical concept of sensation and response (e.g., Weber's law, Stevens's power law) is expanded by requiring perceptual judgments of force and extrapolation in time. Participants are typically given control over one task variable and allowed to adjust

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that variable to an acceptable level based on comfort or another instructed criteria.

Several reports of psychophysical research on the upper extremity have appeared in the past decade, perhaps in part because of reports of high numbers of work-related musculoskeletal disorders of the hand, wrist, shoulder, and so forth. For example, Putz-Anderson and Galinsky (1993) allowed participants to determine acceptable work durations in tasks requiring repetitive arm elevations. Decreases in duration were associated with increases in repetition rate, required force, tool weight, and reach height. Fernandez, Fredericks, and Marley (1995) reviewed several studies in which maximum acceptable frequencies were obtained during gripping and pinching tasks. They noted consistent inverse relationships between force and duration and resulting acceptable frequencies. Snook and coworkers presented a series of studies on maximal force limits during repetitive wrist motions (e.g., Snook, Vaillancourt, Ciriello, & Webster, 1995). Acceptable limits for hand impacts were recently reported by Potvin, Chiang, Mckean, and Stephens (2000), who found decreases in force and impulse at higher impact frequencies.

Many psychophysical protocols use an external load, resulting in consistent exertion levels (e.g., a weighted box). In the present work exertion (force) levels were self-regulated. Questions thus arise as to whether stable acceptable force limits can be achieved and whether these limits are repeatable. A review of the psychophysical literature suggests that common adjustment periods are in the range of 10 to 20 min. There have been few studies, however, of the requisite time needed to obtain stable limits, and it is not clear whether acceptable limits can be obtained more rapidly.

To address these issues, both maximum voluntary exertions (MVEs) and maximum acceptable limits (MALs) were obtained for simple, single-digit exertions. MVEs were obtained using a slight modification of standard strength-testing procedures, whereas a self-regulation protocol was used to obtain MALs. Several algorithms were developed so that a single MAL value could be extracted from a time series of exertions, and an empirical comparison is presented. In addition, repeatability of both MVEs and MALs was assessed, and the influence of task and individual factors on these values was investigated.

METHODS

Experimental Design

Both MVEs and MALs were obtained in two experimental sessions lasting approximately 2 h each. The second session was intended to occur 24 h after the first, but for ease of scheduling the delay was kept between 18 and 30 h. MVEs were assessed using a two-factor design (digit used and session). Each participant performed MVEs with his or her index finger and thumb in both sessions, with the order of presentation balanced across participants.

A three-factor design was used to examine MALs with respect to frequency of exertion, digit used, and session. Each participant used *either* the index finger or thumb, with the specific digit randomly assigned but balanced within genders. Three exertion frequencies (three, six, and nine/min) were performed by each participant in each session. These frequencies were selected based on analysis of several assembly jobs requiring repetitive finger efforts, and the range was considered representative of typical industrial tasks. Frequency presentation order was balanced across participants using a Latin square and was identical in both experimental sessions.

Participants

A sample size of 24 participants was selected to allow for two replications of the balanced design. All participants (14 men, 10 women) were university students, completed an informed consent procedure approved by the Virginia Tech Institutional Review Board, and were compensated for their participation. None reported any current musculoskeletal pain or injuries within the past 6 months. Participants were relatively young (range: 18–31 years), had average statures of 171.4 cm (*SD* = 8.8), and had average body masses of 73.6 kg (*SD* = 18.7).

Testing Procedures

Force data were obtained using a three-axis load cell (AMTI™ Model MSA-6-500, Watertown, MA), oriented with the loading surface horizontal, to which was attached a thin piece of stiff cardboard (to increase friction between the finger and load cell) with the center marked. Specific load cell heights were selected by the participants during initial submaximum practice exertions based on the height at which they felt most comfortable and best able to exert peak efforts. Whole-body postures were not controlled, but variability within participants was minimized by maintaining the load cell height at the initial selection. All participants selected heights near waist level, with an average value of 99.6 cm (SD = 6.3) that corresponded to 58.2% (SD = 3.5%) of stature. The dominant hand was used in all trials. Thumb and index finger exertions were performed with the hand pronated (palm facing down) and with contact limited to the distal pad of each digit.

During all exertion trials, three orthogonal forces were sampled and stored at 60 Hz and viewed after each exertion to ensure data quality. Participants were instructed to push in the center of the load cell and also to press vertically or normal to the device. If forces in the plane of the load cell were above minimal values (~5% of maximum normal force), indicating deviations from vertical, verbal feedback was provided and the trial repeated.

All MVE trials were completed prior to any MAL trials. Three MVEs were performed for each digit, with a minimum of 2 min of rest provided in the intervals. MVEs were completed for one digit before any exertions were performed with the remaining digit. Each MVE trial lasted 3 s and consisted of a brief ramp-up to maximum, hold, and ramp-down. Peak forces, exerted normal to the load cell, were recorded. If an increasing trend was seen in the three peak values, or if the variability among the values was high, a fourth trial was performed. The maximum value observed for a given participant and digit was recorded as the MVE.

After completing the MVE trials, participants were shown a brief video of several assembly tasks involving forceful hand/digit exertions, including inserting wire couplings, grommets, and fasteners. The video was intended to familiarize participants with the context of the latter portion of the experiment (MALs), given that many had no prior industrial experience.

MALs were obtained over 25-min periods, during which exertions were made at one of the three frequencies. Pacing was maintained using computer-generated tones. An initial tone served as a warning and was followed 1 s later by another tone indicating that the exertion should begin. Peak forces from each exertion were recorded, yielding 75, 150, or 225 values depending on the frequency. At least 5 min of rest were provided in the intervals between the three MAL periods. Participants were instructed to determine their own maximum limits as that which they believed they could generate at the given frequency for 2 h (a common upper limit when using job rotation). They were further instructed to exert forces at the highest level that they believed would not lead to development of more than minimal discomfort, pain, numbness, or a perceived increased risk of injury in the upper extremity. A consistent set of written instructions was used, adapted from Karwowski (1996).

Data Analysis

An example time series of MAL data obtained in the experiment is shown in Figure 1. This example is fairly representative, in that forces are initially high and variable and then reach a lower and more stable level. Three phases of analysis were conducted. In the first phase, general trends in the variability and means of the MAL time series were evaluated. In the second phase, several detection algorithms were developed, used to extract single MAL values from the time series of exertions, and the output compared. Although such extraction could be "eyeballed," a more rigorous procedure was desired. In the third phase, factor effects (i.e., digit used, session, and frequency) on the MVEs and extracted MAL values were determined, as were relationships between MALs and MVEs.

Effects of window size (W, number of consecutive samples) and start time (T, location of window) were first qualitatively determined (see Figure 1). Specifically, W was varied from a minimum of three samples (⅓–1 min in length, depending on exertion frequency) to a maximum of 25 min (the length of each MAL session). A minimum of three samples was assumed to be the least amount of time desired for a reliable sample. Starting points for each window were then varied from the first data

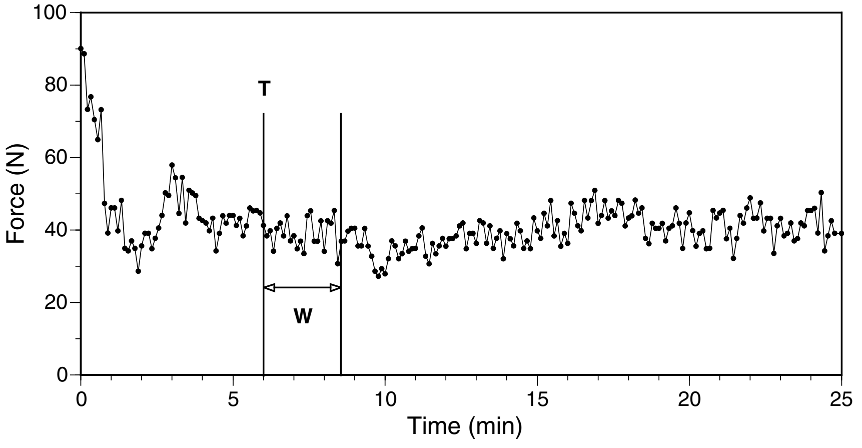

Figure 1. Sample MAL data obtained at nine exertions/min using the index finger. Effects of window size (*W*) and start time (*T*) on variability of derived MAL values were investigated (see Methods). In this illustration *W* = 2.5 min and *T* = 6 min.

point to the last possible location. Within each combination of *W* and *T,* the coefficient of variation (*CoV* = standard deviation/mean) was determined. (*CoV* was used rather than standard deviation in order to normalize across digits and participants.) More specific effects of the digit used, frequency of exertion, *T,* and session on *CoV* were then evaluated using a window size of 1 min and analysis of variance (ANOVA). The 1-min window size was selected as the smallest value that allowed for at least three MAL samples. The actual MAL data were then analyzed using a 2 (digit) × 3 (frequency of exertion) × 25 (start time) × 2 (session) mixed-factors ANOVA, with each MAL value normalized to the mean within each 25-min session to allow for comparisons across conditions and to emphasize time-dependent changes occurring within sessions.

Time series of MAL data within each session were subsequently reanalyzed to yield single MAL values for each participant and experimental condition using three detection algorithms: minimum variability window (MVW), low-pass filter (LPF), and last minute average (LMA). The MVW approach is based on several assumptions, the primary being that variability in discrete MAL values should be minimized once a participant has become familiarized with the task. In addition, it was assumed that if this low variability is maintained over a relatively long period, consisting of multiple samples, then reliability of the MAL is correspondingly high.

An MVW was determined by iteratively varying *W* and *T* and recording the mean value from the combination that yielded the smallest standard deviation. Using results from the previous analysis phase, we constrained *W* and *T* to 1.5 and 1 min, respectively. The LPF method was based on the observed similarity between the time series of MAL values and a noisy damped step response (high initial magnitude and volatility followed by subsequent stabilization). A MAL was determined by smoothing the time series (low-pass digital filter: fourth-order, 1 sample/min cutoff frequency) and recording the final value of the filtered series. The third approach (LMA) simply averaged the values in the last minute.

Each of these three detection algorithms was applied both to the full 25 min of data within each session and to a subset consisting of the first 5 min in order to determine the effect of sample duration on resulting MALs. Analysis of the effects of the three detection algorithms, using a 2 (digit) × 3 (frequency of exertion) × 2 (sample duration) × 3 (algorithms) mixed-factors ANOVA, showed minimal differences (see Results). MALs were thus determined using the MVW approach, as it appeared to offer the strongest arguments regarding consistency and reliability of derived MALs.

Mixed-factor ANOVAs were used to investigate factor effects on MVEs (2 genders × 2 digits × 2 sessions) and both the MALs and MAL/MVE ratios (2 genders × 2 digits × 3 frequencies of exertion × 2 sessions). Linear regression was used to evaluate repeatability of MVEs and MALs between sessions. Inspection of the dependent measures did not indicate any substantial deviations from normality, and thus parametric tests appeared justified. All statistical tests were considered significant when $p < 0.1$ (selected to increase power, given the relatively small sample size). For selected nonsignificant effects, minimal effect sizes were determined for which power = .9, with Type I error probability (α) set conservatively to .05.

RESULTS

Factor Effects on Time Series of MALs

Both window size (*W*) and start time (*T*) had substantial effects on MAL coefficients of variation (*CoV*). Results were similar for the three exertion frequencies (Figure 2) and indicated that *CoV* generally decreased with *W* and increased with *T*. Also notable was that *CoV* was relatively less affected by *T*, as long as *T* was greater than about 1.0 to 1.5 min.

*CoV*s within 1-min windows were significantly different between the sessions, digits, exertion frequencies, and start times. *CoV*s were slightly higher during the first session, with a mean of 0.103 (*SD* = 0.054) compared with 0.096 (*SD* = 0.058) in the second session. Exertions with the thumb yielded mean CoVs of 0.103 (*SD* = 0.058) versus slightly lower values for the index finger at 0.096 (*SD* = 0.055). *CoV*s increased with exertion frequency, at 0.088 (*SD* = 0.060), 0.103 (*SD* = 0.056), and 0.107 (*SD* = 0.051 N) for three/min, six/min, and nine/min, respectively. In contrast, the effect of *T* was substantial, with initially high levels (~0.152) followed by lower and more stable levels (~0.090) after 2 to 3 min. There was a significant Session × Frequency interaction, in which the effect of session was largest at the highest frequency (Figure 3). A significant Digit × *T* interaction was also found, wherein index finger *CoV*s reached stable values several minutes earlier than did those for the thumb (Figure 4).

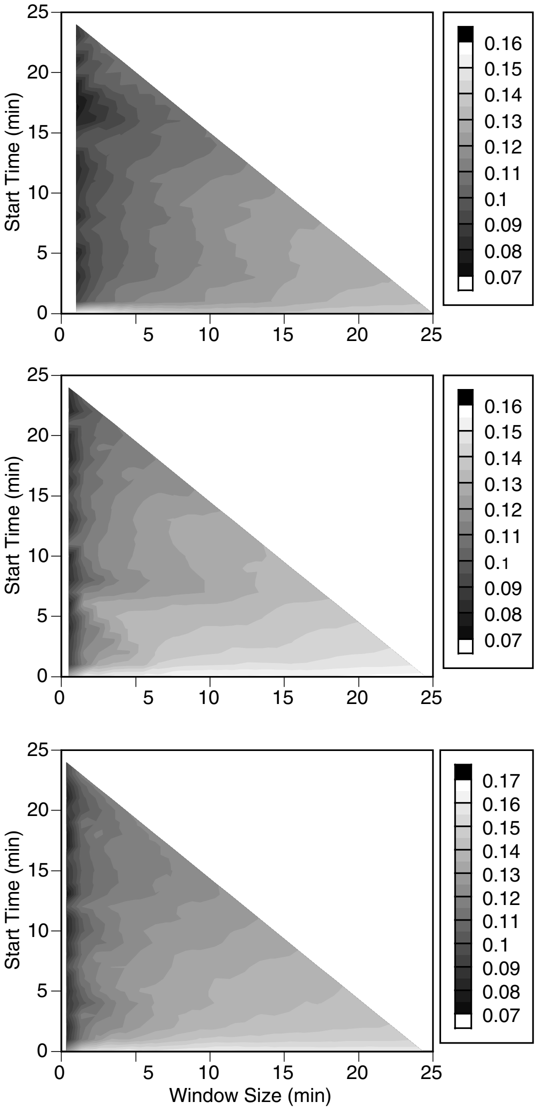

Figure 2. MAL coefficients of variation (*CoV*) as a function of window size and start time for exertions performed at three/min (top), six/min (middle), and nine/min (bottom). Darker shades indicate lower *CoV* magnitudes.

Normalized values within the 1-min windows showed significant changes with *T*. Values tended to be higher initially, at about 108% of the within-session mean, and then stabilized near the mean value within 3 to 4 min. A significant Frequency × *T* interaction was also found, in which values at the highest frequency were larger initially and did not stabilize as rapidly (Figure 5). All third-order interactions

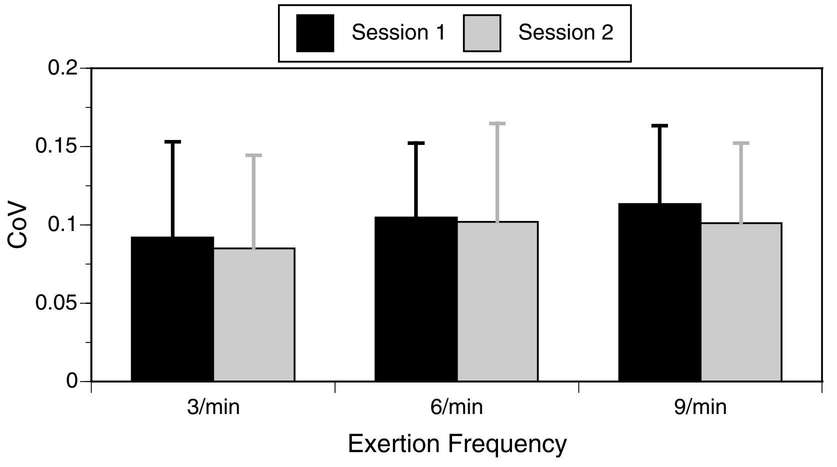

Figure 3. Effects of session and exertion frequency on MAL coefficients of variation (*CoV*). Both main effects and their interaction were significant.

were significant, but none was associated with any consistent or substantial impact in terms of magnitudes. No other main or second-order interaction effects were significant ($p > .8$).

Effects of Detection Method and Sample Duration

Differences in resulting MAL values for the three detection methods (MVW, LPF, LMA) were not significant ($p > .99$), and average differences were less than 1%. A range between the three detection methods of 2.2 N (~5% of overall mean) would have been detected with power = .9. The effect of sample duration (5 or 25 min) was also not significant ($p = 0.33$), and mean values for the 5- and 25-min samples were 49.0 N ($SD = 22.4$ N) and 47.2 N ($SD = 22.3$ N), respectively. These differences were somewhat higher for the index finger (6.2%) than for the thumb (1.7%), although the Duration × Digit interaction was not significant ($p = .14$).

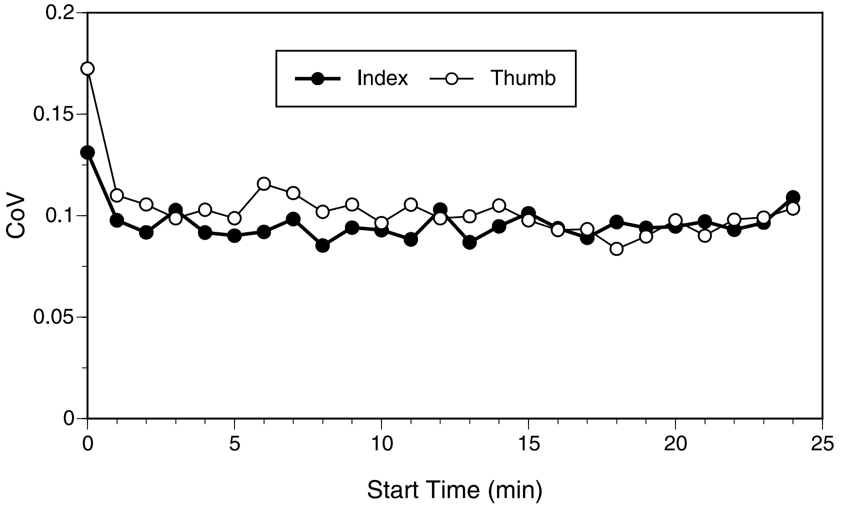

Figure 4. Effects of digit and start time on MAL coefficients of variation (*CoV*). Both main effects and their interaction were significant.

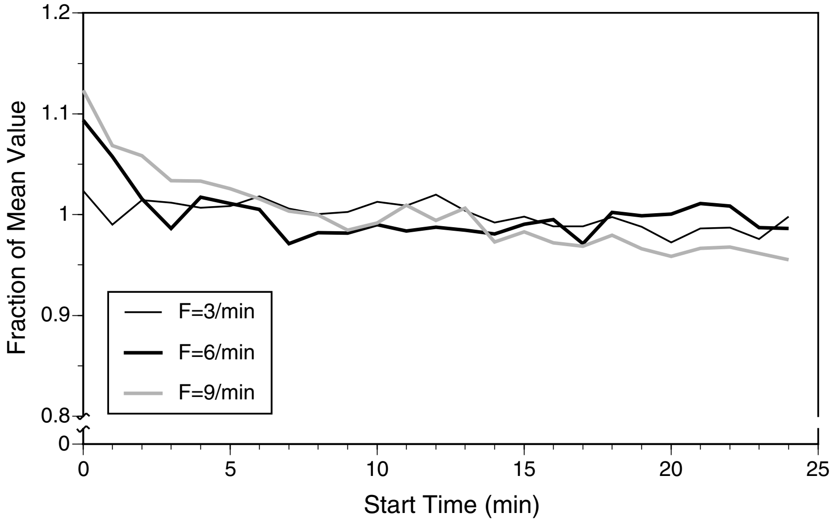

Figure 5. Effects of exertion frequency and start time on normalized MAL values. Both main effects and their interaction were significant. (Note: A broken ordinate is used to emphasize differences.)

Factor Effects on MVEs

MVEs were significantly different between genders and digits. MVEs for men averaged 28% higher than those for women, with respective means of 136.2 N (*SD* = 46.4) and 106.3 N (*SD* = 39.4 N). MVEs were higher for the thumb than the index finger, with means of 154.0 N (*SD* = 41.0 N) and 93.4 N (*SD* = 25.0 N), respectively. Although session was not significant ($p = .32$), MVEs during Session 2 were slightly lower than those in Session 1, with respective means of 120.7 N (*SD* = 43.8 N) and 126.8 N (*SD* = 48.1 N). A difference between the sessions of 14.5 N (~11% of overall mean) would have been detected with power = .9. The Gender × Digit interaction was significant; men had proportionally higher MVEs using the thumb versus index finger (170.6 vs. 101.9 N) compared with women (130.9 vs. 81.6 N).

Correspondence between MVE samples in the two sessions was moderate, with $R^2 = .51$ for the index finger and $R^2 = .34$ for the thumb. Also, MVEs appeared to be more variable for the thumb than for the index finger (Figure 6). When regression lines were forced to have

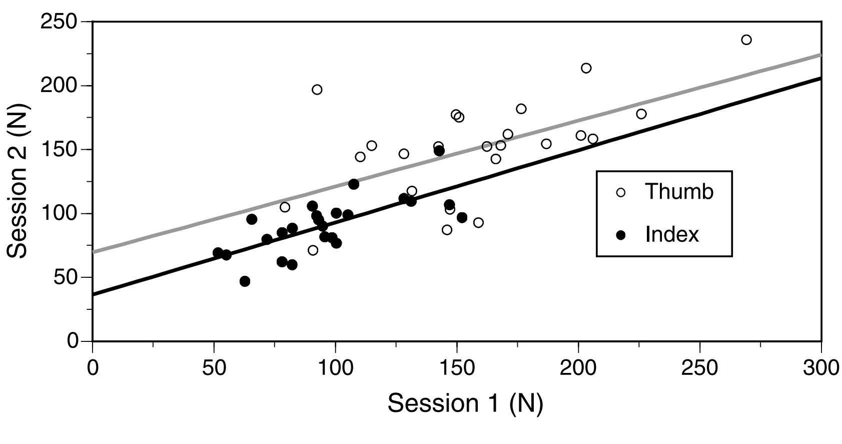

Figure 6. Correspondence between MVEs obtained during two experimental sessions. Separate regression lines are shown for the thumb (gray, top) and index finger (black, bottom).

zero intercept, the resulting regression slopes were .92 for the index finger and .93 for the thumb, indicating a relatively close correspondence between sessions, but with tendencies (noted earlier) for lower values in the second session.

Factor Effects on MALs

MALs, determined using the MVW detection algorithm, were significantly different between genders, frequencies, and digits, but no interaction effects were found ($p > .24$). Men's MALs averaged 37% higher than women's, with respective means of 53.5 N (SD = 22.4 N) and 39.1 N (SD = 16.7 N). MALs were higher for the thumb than for the index finger, with means of 50.2 N (SD = 26.2 N) and 44.9 N (SD = 14.9 N), respectively. MALs were lower at higher exertion frequencies, with means of 54.3 N (SD = 23.7 N), 46.4 N (SD = 20.6 N), and 41.8 N (SD = 18.0 N) for three/min, six/min, and nine/min, respectively.

Session was not significant as a main effect ($p = .80$), nor were any of its interactions ($p > .4$). MALs were marginally higher during Session 2 than during Session 1, with respective means of 48.2 N (SD = 21.0) and 46.9 N (SD = 21.9 N). A difference between the sessions of 4.6 N (~10% of overall mean) would have been detected with power = .9.

Correspondence between MALs in the two sessions was moderate, with $R^2 = .59$ for the index finger and $R^2 = .75$ for the thumb. Similar to MVEs, the MAL values appeared to be more variable for the thumb than for the index finger (Figure 7). When regression lines were forced to have zero intercept, the resulting regression slopes were 1.00 for the index finger and .98 for the thumb, indicating a close correspondence between sessions.

MALs versus MVEs

Within each participant, MALs were compared with MVEs by determining ratios for each session. Because session effects were found to be either small or nonsignificant, these ratios were averaged across sessions. MAL/MVE ratios differed between digits and exertion frequencies. MALs were a larger fraction of MVE for the index finger versus the thumb, with respective means of 45.6% (SD = 11.3%) and 35.4% (SD = 15.1%). MAL/MVE ratios declined nonlinearly with increasing exertion frequency, with mean values at three/min, six/min, and nine/min of 46.3% (SD = 15.0%), 39.4% (SD = 12.9%), and 35.7% (SD = 13.1%), respectively. The Digit × Frequency interaction was not significant ($p = .77$), and both digits showed the same trend with respect to frequency (Figure 8).

DISCUSSION

As a tool for determining subjective responses to physical stimuli (or demands), psychophysics has also been applied toward the development

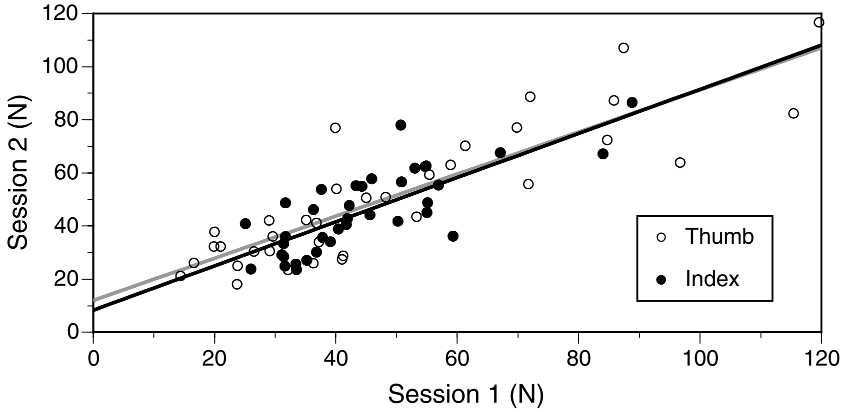

Figure 7. Correspondence between MALs obtained during two experimental sessions. Separate regression lines are shown for the thumb (gray, top) and index finger (black, bottom).

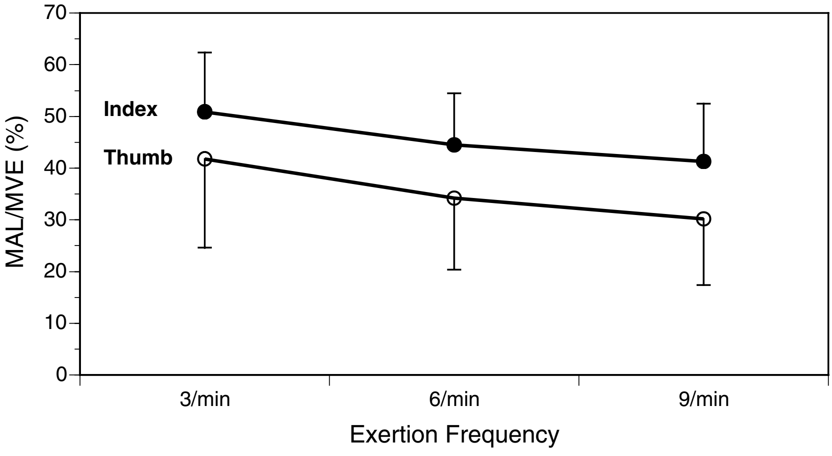

Figure 8. Ratios of MALs/MVEs for exertions performed with the thumb and index fingers at three exertion frequencies. Both main effects were significant, although the interaction was not.

of recommended ergonomics guidelines. Some authors have argued, conservatively, that psychophysical methods yield relevant data in the absence of more objective information (e.g., Fernandez et al., 1995). Others have been more explicit that these methods provide safe levels of physical activity (e.g., Ciriello, Snook, Hashemi, & Cotnam, 1999; Lu & Aghazadeh, 1994; Putz-Anderson & Grant, 1994). Based on the existing evidence, it appears warranted to conclude that acceptable limits should not be confused with safe limits (see Buckle, Stubbs, Randle, & Nicholson, 1992; Karwowski et al., 1999; Nicholson, 1989). However, until more robust and/or objective measures are developed, such limits provide useful alternatives for design and evaluation. This conclusion pertains in particular to the type of hand/finger activities studied here, given that little is known regarding specific exposure-response relationships and interactions among several risk factors.

This cautious approach stems in part from difficulty in validating psychophysically derived data. Although providing relatively weak support, numerous authors have reported on the repeatability of subjective load limits (e.g., Gamberale, Ljungberg, Annwall, & Kilbom, 1987; Legg & Myles, 1981; Snook & Irvine, 1968) and acceptable frequencies (e.g., Snook, Ciriello, & Webster, 1999). In the present study MVEs and MALs performed with individual digits were also repeatable and at a level comparable to that found in earlier evidence. This is notable because the simple exertions studied here differ from the common studies on MAWL. Protocols for obtaining MAWLs involve an external source of sensory stimuli (e.g., a box) and the use of relatively large muscles or muscle groups. In contrast, the tasks here required self-generation and self-regulation of exertions and small muscle groups.

Although there is prior evidence that low levels of hand/finger exertions can be maintained within narrow tolerances (Jones, 1998) and that predetermined force levels can be reproduced without bias (Wiktorin, Selin, Ekenvall, Kilbom, & Alfredsson, 1996), it was not known a priori whether single-digit MALs would show similar results. Repeatability has also been reported in terms of the consistency between studies (e.g., Ayoub, Mital, Asfour, & Bethea, 1980; Mital, 1984). Some, in contrast, have noted inconsistencies (Garg & Ayoub, 1980) and have highlighted potential sensitivity to instruction (Gamberale et al., 1987; Karwowski, 1996; Karwowski et al., 1999) and demand characteristics (Putz-Anderson & Galinsky, 1993).

Aspects of consistency also appear in the relationship between acceptable limits and maximum capacity. Several studies have found that roughly 50% to 80% of the variability in MAWLs can be accounted for using combinations of static and/or dynamic strength (e.g., Garg & Badger, 1989; Jiang, Smith, & Ayoub, 1986; Wu & Hsu, 1993). Some evidence also suggests that MAWLs are approximately 50% of maximum capacity (Baxter, Stålhammar, & Troup, 1986; Garg & Beller, 1994). Foreman, Baxter, and Troup (1984) found that maximum acceptable isometric forces were somewhat lower, at 24% to 40% of MVE, which is also lower than the 35% to 45% range found here. In contrast, evidence also exists for either no or low correlations between acceptable and maximal values (Gamberale et al., 1987; Griffin, Troup, & Lloyd, 1984; Ljungberg, Gamberale, & Kilbom, 1982) as well as for considerable variation in the ratio of these values (Garg, Chaffin, & Freivalds, 1982).

A third measure of consistency concerns the ability of participants to predict acceptable levels of exertion. Legg and Myles (1981) found that MAWL estimates for 8 h, obtained in a 20-min session, could be lifted for 8 h, although ratings of perceived fatigue and work intensity increased during the latter period. Other research has indicated that shorter-term estimates of acceptability or capacity for a longer period are equivalent to estimates actually obtained in the longer period (e.g., Fernandez et al., 1995; Karwowski & Yates, 1986; Morrissey & Liou, 1988). Acceptable limits, however, may also be overestimated based on short-term performance (Mital, 1983; Mital & Manivasagan, 1983; Snook & Irvine, 1968). A general consensus for MAWLs appears to be that 10 to 20 min is a sufficient duration for estimates of 2- to 4-h capacity.

The strongest argument for the use of psychophysically based guidelines has come from a small number of studies on subsequent injury risk. Results from Snook, Campanelli, and Hart (1978) are often cited in which more injuries occurred in manual handling jobs estimated to be acceptable to less than 75% of males based on MAWL. It should be noted that a substantial number of injuries occurred in jobs that had *higher* than 75% acceptability and that several other criteria (other than percentile MAWL) may have given similar results on relative injury numbers.

More direct evidence was provided by Ayoub, Selan, & Liles (1983), who showed that injuries increased with the ratio of task demands to psychophysical limits (the Job Severity Index), and by Herrin, Jaraiedi, and Anderson (1986), who showed that injuries reported were inversely related to minimum percentiles of MAWLs. In contrast, Troup, Foreman, Baxter, and Brown (1987) found that psychophysical lifting capacity was an inadequate predictor of future problems (low back pain).

Existing evidence thus provides some support that acceptable limits may be safe, but continued work is needed for confirmation, particularly in view of the fact that this evidence is limited to whole-body activities such as lifting.

As noted earlier, short-term estimates of longer-term capability or acceptability appear to be reasonable. Based on the present results, a much shorter time may be adequate for exertions involving the fingers or thumb. Although conducted for a maximum of 25 min, the MAL values stabilized rapidly in terms of both means and variability (see Figures 4 and 5). Differences between 5- and 25-min values were small and probably less than 5%, based on power calculations. There were indications, however, that such stabilization was achieved more rapidly for the index finger than for the thumb. This difference may reflect the more common use of the former in situations requiring forceful exertions or, perhaps, the differences in tactile sensitivity between the two digits.

Derived MALs were also equivalent for the three MAL detection methods, although each was based on distinct assumptions. A common approach has been to record the last value or an average of the last several values, and no advantage would thus seem to be gained by more sophisticated processing.

Significant and practically relevant effects of exertion frequency were found on MALs. Increasing the frequency from three to nine times/min led to reductions in MALs of approximately 20% that were nonlinear but similar in magnitude for both digits and genders. Similar effects of frequency have been found for MAWLs and exertion forces (e.g., Ayoub, Dryden, McDaniel, Knipfer, & Dixon 1979; Ciriello & Snook, 1983), although evidence for both linear and nonlinear effects has been reported. No comparable MAL data could be found for comparison with the single-digit exertions studied here (although the MVE averages by gender and digit are very close to the results of Kanis, 1993).

Within-digit averages of the MAL-frequency data could be modeled by the following relationship,

$$K = F^{0.5} \times MAL(\%)^2,$$

in which F is the frequency (exertions/min), $MAL(\%)$ is the MAL normalized as a percentage of MVE, and K is a constant (index finger = 5100; thumb = 3300). This model suggests that acceptable limits may be based more on force than on frequency, at least in the context of the tasks investigated. For example, if the force is doubled, the frequency must be reduced to 1/16 of its original value, whereas if frequency is doubled, the force need be reduced by only 1/6. Sensory and perceptual systems more adept at transducing static rather than cumulative stresses and strains might explain such behaviors, although additional evidence is needed to support this hypothesis.

In summary, maximal (MVE) and acceptable (MAL) limits for thumb and index finger exertions were obtained using slight modifications to existing methodologies. Both MVEs and MALs appeared to be repeatable across sessions separated by about 1 day. Single MAL values, obtained from a time series of exertions, appeared to be independent of the specific method used. Values from 5- and 25-min samples showed only minor differences, suggesting that acceptable limits for digit exertions can be obtained using relatively short experimental trials.

Although the results provide support for the specific methods described and employed, several additional issues related to validity of the psychophysical methodology require further investigation before full confidence can be placed on acceptable limits as ergonomics guidelines. Despite this caution, the methods described are applicable to obtaining force guidelines for evaluation and design for tasks involving hand- and finger-intensive exertions.

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