The Influence of Task Frequency and Force Direction on Psychophysically Acceptable Forces in the Context of the Biomechanically Weakest Links

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This study examined the influence of frequency and direction of force application on psychophysically acceptable forces for simulated work tasks. Fifteen male participants exerted psychophysically acceptable forces on a force transducer at 1, 3, or 5 repetitions per minute by performing both a downward press and a pull toward the body. These exertions were shown previously to be strength and balance limited, respectively. Workers chose acceptable forces at a lower percentage of their maximum voluntary force capacity during downward (strength-limited) exertions than during pulling (balance-limited) exertions at all frequencies (4% to 11%, \( P = .035 \)). Frequency modulated acceptable hand force only during downward exertions, where forces at five repetitions per minute were 13% less \( (P = .005) \) than those at one exertion per minute. This study provides insight into the relationship between biomechanically limiting factors and the selection of acceptable forces for unilateral manual tasks.

**Keywords:** psychophysics, ergonomics, psychophysically acceptable force, work design, biomechanical limitations

Psychophysics is frequently used as an approach to determine maximal acceptable exertion capacities to help establish guidelines for working practices in an attempt to limit overexertion. The psychophysical method has been found to provide realistic simulations of workplace tasks and integrates all job exposures, including biomechanical and physiological factors. The psychophysical method remains a consistently applied approach to produce threshold exertion limits for manual materials-handling tasks at low and moderate frequencies. Currently, the challenge surrounding psychophysically based limits is that they are costly and time intensive to develop. With this in mind, predictive approaches surrounding threshold exertion limits would be beneficial.

Psychophysical limits have been established empirically for many tasks; however, predictive models are sparse. The paucity of predictive approaches may stem from an incomplete understanding of the biomechanical and physiological rationale behind individual selection of psychophysical limits. Nussbaum and Johnson modeled psychophysically acceptable forces for single-digit finger and thumb exertions as a function of the task frequency and the maximum voluntary force for the finger or thumb, using the following equation:

\[
K = F^{0.5} \times \text{MAL}(\%)^2
\]

where maximal acceptable limits (%MAL), expressed relative to the participant’s maximum voluntary exertion (MVE), were derived from exertion frequency \( (F) \) and a specific finger constant \( (K) \). This equation highlights the hypothesis that psychophysically acceptable forces are related to individual maximal voluntary exertion capacity and the exertion frequency. Additional work by Potvin has provided additional quantitative support, indicating that psychophysically acceptable forces are proportionately related to maximal voluntary force in a frequency-dependent pattern. These findings support the hypothesis that psychophysically acceptable force is related to maximum voluntary force and the frequency of exertion.

Posture and force direction influence underlying balance, friction, and joint strength capabilities, which systematically affect maximum voluntary force capacity. Maximal voluntary force can be estimated by predicting which biomechanical factor will limit capacity. In a study examining maximal unilateral hand force strength, Fischer et al systematically demonstrated that downward exertions were most likely limited by upper limb strength, whereas pulling exertions were more likely limited by whole-body balance. If maximal voluntary force capacity is limited by different types of biomechanical constraints and psychophysically acceptable forces are related to maximum voluntary force, it remains...
plausible that the specific relationship or proportionality relating psychophysically acceptable forces to maximal voluntary force may also depend on the underlying biomechanical constraint. Downward exertions appear to be limited by elbow or shoulder joint strength, whereas pulling exertions appear to be limited by anterior-posterior balance. This interdependence has been preliminarily demonstrated whereby psychophysically acceptable forces (at one exertion per minute) were selected at approximately 86% of maximal voluntary force capacity during balance-limited exertions and at 67% during strength-limited exertions. This proportional decrease between psychophysically acceptable force and maximal voluntary force is greater during strength limited exertions, and should be affected by frequency more than balance-limited exertions. Frequency has also been shown to be a modulator of psychophysically acceptable force, as workers decreased psychophysically acceptable force levels with increasing frequency during manual hose insertions. Determination of the biomechanical limiters for workplace tasks is essential, especially in the context of how they might affect submaximal exertions of the same type.

The purpose of this study was to determine how the frequency of exertion influences psychophysically acceptable forces relative to maximum voluntary force capacity in the context of underlying biomechanical constraints limiting that capacity. It is hypothesized that the proportional relationship between psychophysically acceptable force and maximal voluntary force will decrease with the frequency of exertions, and both the direction and frequency of the exertion will independently affect the proportional relationships between psychophysically acceptable force and maximal voluntary force, with a greater influence on strength-limited exertions than balance-limited exertions.

**Methods**

**Participants**

Fifteen right-handed males were recruited from a temporary work agency to participate in this study (mean age 40.9 ± 13.9 years; height 1.74 ± 0.08 m; weight 80.7 ± 13.6 kg). All participants had a minimum of 6 months of work experience in a manufacturing industry, and had been free from injuries to the right forearm, upper arm, or shoulder for at least 6 months. This study was approved by the institutional Office of Research Ethics, and all participants provided informed consent. Each participant had been involved in a previous psychophysical study on the preceding day and was familiar with the psychophysical approach.

**Apparatus**

Kinematics and hand force were collected for all experimental trials. Three-dimensional motion was tracked using an 8-camera Vicon MX20 System (Vicon, Oxford, UK). Thirty-eight individual markers were placed over anatomical landmarks including the C7 and L5 vertebrae, over the suprasternal notch, xiphoid process, and bilaterally over the second and fifth metacarpals, radial and ulnar styloids, medial and lateral epicondyles, the acromion, ear, anterior superior iliac spine, greater trochanter, medial and lateral condyles of the knee, medial and lateral malleolus, the tip of the first and fifth metatarsals, and at the posterior border of the calcaneus. Additional marker clusters secured on rigid plates, were positioned over the sternum, and bilaterally over the forearm, upper arm, leg, shank, and over the top of the foot (shown in Figure 1). The marker clusters were used to track segment movement during experimental testing. A static calibration frame established the relationship between the clusters and the calibration markers over the anatomical landmarks, and subsequently joint centers and segment coordinate systems were described. Force data were collected using an AMTI six degrees of freedom transducer (MC3A-500, AMTI MA, USA) that was placed between a D-shaped cylindrical handle and a clamp apparatus. This allowed height adjustment of the apparatus between conditions and participants throughout the study. Both motion and force data were sampled at 50 Hz using Vicon Nexus 1.2 software (Oxford, UK).

**Figure 1** — Participants completed horizontal pulls (“A”) and downward presses (“B”), at one, three, and five exertions per minute for blocks of thirty minutes each, applying hand force at their psychophysically acceptable level. Participants also completed maximum voluntary force exertions in these positions, both before and following the psychophysical exertions. The obstruction was used to oblige participants to reach for the handle simulating a work environment.

**Experimental Protocol**

Participants completed exertions in two directions (a downward press and a pull toward the body) at three different frequencies (one, three, and five times per minute), resulting in six test scenarios. In each scenario, the cylindrical handle was placed so that the desired force exerted perpendicular to the handle, allowing maximal
force exertion without a friction limitation at the grip. The handle was positioned along the midline of the body at the height of the xiphoid process. A barrier was placed between the participant and the handle at a horizontal distance of 75% of the participant’s arm length and a vertical distance equivalent to the level of their anterior superior iliac spine to simulate a workplace barrier, allowing increased applicability of the resulting data to compare with workplace settings. Participants were allowed to adopt any foot placement, provided that they could comfortably reach the handle, were not contacting the barrier, and their shoulders were facing the handle. Experimental scenarios were completed in a randomized order in a single workday. Each scenario began with the participant completing two 5-second maximal voluntary force exertions in one of the force directions with two minutes of rest between them. Following these exertions, a 30 minute psychophysical estimation trial began whereby participants completed one-second exertions in the required direction at either one, three, or five times per minute. Two audible cues spaced one second apart were presented for each force exertion to the participant using a custom metronome (LabVIEW, National Instruments, Austin Texas, USA). Participants were instructed to exert a force magnitude that they found acceptable and that would not create any signs of pain, discomfort, or numbness at the selected cadence with the knowledge that the workday would be seven hours long. To ensure protocol adherence, discomfort ratings were taken at 10 and 20 minutes of each trial using the Borg CR-10 scale. If participants scored themselves at level 2 or higher, the researcher would remind them of the test protocol and repeat the instructions. Immediately following each trial, the participant completed two more maximal voluntary force exertions in one of the force directions with two minutes of rest between them. These provided an indication of fatigue if the final MVF magnitudes were significantly lower than the initial values.

The total collection time for this study was approximately four hours. Participants received a 15 minute rest period after two hours.

### Data Analysis

Psychophysically acceptable forces were calculated from the force data. Peak hand forces were extracted from each exertion as the peak value from a 500 ms moving window average over the raw force trace (a single peak value was retained from each maximal voluntary force trial, while 30, 90, or 150 minute-by-minute peak values were retained from the psychophysically acceptable force trials, depending on exertion frequency). A sliding window average was used to reduce the effects of force variability during the exertions. The psychophysically acceptable force was determined using the average of the peaks from the final five minutes of each trial (5, 15, and 25 peaks for each frequency respectively). This average was expressed relative to the highest peak from the four maximal voluntary forces, indicating the psychophysically acceptable force as a percentage of the maximal voluntary force and was termed the percentage of psychophysically acceptable force. The biomechanical factor most likely limiting force capacity during each maximal voluntary force exertion was determined. Specific evaluation criteria are detailed below and summarized in Table 1.

Potential elbow and shoulder strength limitations were determined by calculating net joint moments at the elbow and shoulder and expressing those moments as a percentage of the maximum predicted threshold strength values obtained using equations provided in the literature. If the normalized moment reached or exceeded 100% of the predicted maximum threshold, it was deemed limiting. Shoulder and elbow moments were calculated using a 3-dimensional static linked segment model based on the acquired force and posture information.

The location of the balance point, or fulcrum balancing the forces at the hand with the force due to gravity on the body, was calculated as the point along the shoe-floor interface that satisfied equations of static moment equilibrium about the anterior/posterior and medial/lateral axes. This is consistent with an approached used previously by Kerk et al and Fischer et al. To determine whether

### Table 1  The seven biomechanical criteria that were used to evaluate potential biomechanical limiting factors during the maximum hand force exertions for each condition tested

<table>
<thead>
<tr>
<th>Limiter to Evaluate</th>
<th>Measured/Calculated Variable</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow Strength</td>
<td>Elbow flex/ext. moment</td>
<td>Chaffin et al (2006) population</td>
</tr>
<tr>
<td>Shoulder Strength</td>
<td>Shoulder rotation moment</td>
<td>Chaffin et al (2006) population</td>
</tr>
<tr>
<td>Shoulder Strength</td>
<td>Shoulder ab/adduction moment</td>
<td>Chaffin et al (2006) population strength</td>
</tr>
<tr>
<td>Shoulder Strength</td>
<td>Shoulder flex/ext. moment</td>
<td>Chaffin et al (2006) population</td>
</tr>
<tr>
<td>Friction</td>
<td>$F_{\text{horizontal}}$</td>
<td>$\mu_{\text{Normal}}$</td>
</tr>
<tr>
<td>Balance (AP)</td>
<td>Y position of the balance point</td>
<td>AP boundaries of the shoe/floor</td>
</tr>
<tr>
<td>Balance (ML)</td>
<td>X position of the balance point</td>
<td>ML boundaries of the shoe/floor</td>
</tr>
</tbody>
</table>
balance was potentially limiting, the balance point was expressed relative to the distance between the geometric center of the shoe-floor interface and the boundaries of the shoe-floor interface (established using the markers placed on the tip of the 1st and 5th metatarsals and at the posterior border of the calcaneus). A trial was determined to be balance limited if the value was equal to or greater than 100% of this boundary.

This approach is underscored by the assumption that ground reaction forces can be modeled to act through a single center of pressure (or balance point) between the two feet, a common assumption used in similar work.20–23 However, this assumption does not take into account the force coupling between the feet as they act independently to counter the axial moments about the body. This is a recognized limitation in the current work and affects the interpretation of biomechanical limitations when the applied hand force imposes axial moments about the balance point. However, given that the exertions investigated did not impose considerable axial moments (as would a medially or laterally directed exertion), we accept this limitation.

To determine any possible friction limitations, the maximum available shoe-floor friction force was also calculated as the product of the normal force and a coefficient of friction ($\mu$) of 0.525 (average coefficient of friction during pushing and pulling on standard floors from Boocock et al).24 The total horizontal hand force was then normalized to the maximum available friction force. If friction was limiting it was expected that this value would be equal to 100%.

Statistical Analysis

A repeated-measures analysis of variance was used to examine the effect of direction (downward and pulling) and frequency (five, three, and one exertion per minute) on percentage of psychophysically acceptable force. Pairwise comparisons were used determine main and interaction effects, and effect sizes were approximated using partial eta squared. Significance was set at $P < .05$ for the repeated-measures analysis. Nonparametric Wilcoxon signed-ranks tests were conducted on each normalized dependent variable (corresponding to a possible limiting factor) as measured in each condition. The mean grouped response for each dependent measure was compared with a 100% criterion. If the measure was not different from, or was greater than the 100% criterion, it was inferred to be potentially limiting. To balance between the increased risk of type 1 error due to the number of comparisons and the increased risk of type 2 error by applying a conservative Bonferroni correction, significance was set at $P < .01$ for all Wilcoxon signed-rank tests. All statistical processing was completed using SPSS software (SPSS Inc., Chicago, IL, USA).

Results

The biomechanical analysis indicated that downward exertions were most likely limited by shoulder internal rotation strength as inferred from the shoulder joint internal rotation moment reaching the 100% criterion (Table 2), whereas pulling exertions were more likely limited by anterior-posterior balance as indicated by the balance point exceeding the 100% boundary condition (Table 2). In each scenario, friction did not reach the 100% criterion, indicating that friction was not the limiting factor any scenario. There was no significant interaction effect between direction and frequency ($F = 1.148$, $P = .332$, $\eta_p^2 = 0.076$) for the percentage of psychophysically acceptable force variable.

Workers chose significantly higher percentages of psychophysically acceptable force values when pulling (4% to 11% higher) as compared with pressing downward ($F = 5.443$, $P = .035$, $\eta_p^2 = 0.28$). Workers chose

<table>
<thead>
<tr>
<th>Variable</th>
<th>Down 5 (%)</th>
<th>Down 3 (%)</th>
<th>Down 1 (%)</th>
<th>Pull 5 (%)</th>
<th>Pull 3 (%)</th>
<th>Pull 1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow flex/ext strength</td>
<td>47.1 (47.7)</td>
<td>65.6 (39.2)</td>
<td>55.5 (36.2)</td>
<td>18.1 (17.6)</td>
<td>17.4 (20.3)</td>
<td>22.0 (27.5)</td>
</tr>
<tr>
<td>Shoulder rotation strength</td>
<td>91.9 (83.2)</td>
<td>98.6 (59.6)</td>
<td>104.5 (60.5)</td>
<td>20.0 (14.5)</td>
<td>19.8 (14.2)</td>
<td>32.9 (57.9)</td>
</tr>
<tr>
<td>Shoulder ab/adduction strength</td>
<td>30.5 (25.5)</td>
<td>41.5 (26.9)</td>
<td>44.3 (23.0)</td>
<td>16.6 (13.6)</td>
<td>17.9 (11.9)</td>
<td>18.5 (15.4)</td>
</tr>
<tr>
<td>Shoulder newest strength</td>
<td>53.5 (43.3)</td>
<td>59.9 (31.5)</td>
<td>64.0 (37.7)</td>
<td>36.6 (27.3)</td>
<td>35.4 (27.7)</td>
<td>42.1 (36.8)</td>
</tr>
<tr>
<td>Available friction</td>
<td>19.0 (20.7)</td>
<td>21.2 (20.3)</td>
<td>32.3 (28.6)</td>
<td>58.8 (30.6)</td>
<td>55.5 (28.2)</td>
<td>57.4 (33.1)</td>
</tr>
<tr>
<td>ML balance point boundary</td>
<td>22.5 (27.3)</td>
<td>26.0 (22.0)</td>
<td>29.4 (36.8)</td>
<td>17.0 (36.1)</td>
<td>34.4 (29.4)</td>
<td>18.5 (39.9)</td>
</tr>
<tr>
<td>AP balance point boundary</td>
<td>33.3 (35.3)</td>
<td>41.0 (42.1)</td>
<td>56.7 (53.4)</td>
<td>129.7 (76.6)</td>
<td>118.2 (68.6)</td>
<td>107.1 (59.7)</td>
</tr>
</tbody>
</table>
a significantly different percentage of psychophysically acceptable forces across different work frequencies ($F = 8.219, P = .005, \eta^2 = 0.370$). However, pairwise comparisons revealed that frequency only significantly affected the percentage of psychophysically acceptable force during downward conditions where the highest percent of psychophysically acceptable force was $68.0 \pm 17.3\%$ during exertions at once per minute and the lowest was $54.4 \pm 17.1\%$ at a frequency of five per minute (Figure 2). The percentage of psychophysically acceptable force during pulling exertions did not change between 1 and 3 exertions per minute, but decreased by 6% at a frequency of 5 exertions per minute.

Fatigue was unlikely, as no participants experienced decreases greater than 5% in their final maximal voluntary force exertions when compared with their initial maximal force exertions. This can be attributed to their ability to follow protocol and maintain a rating of perceived exertion of 2 or less throughout the scenario.

**Discussion**

The primary findings indicate that psychophysically acceptable hand forces are related to maximum voluntary force capacity and the underlying biomechanical factor limiting that capacity. As revealed by the biomechanical analysis, the two force directions had different biomechanically limiting factors (Table 2). These biomechanical constraints are consistent with previous research on similar types of exertions. Concurrently, the corresponding percentage of psychophysically acceptable force values also depended on the underlying biomechanically weakest link, where workers were willing to work closer to their maximal hand force when limited by balance than when limited by strength, which agrees with Fischer et al. Further, as frequencies increased from one exertion per minute, the percentage of psychophysically acceptable force was differentially affected, whereby a decrease was observed during strength-limited exertions, whereas balance exertions were not statistically different.

The exertions tested were likely limited by different biomechanical factors, which resulted in different effects on the percentage of psychophysically acceptable force as frequency was increased. This step-down decrease may be linked to specific joint strengths and endurance capacities, whereby frequency may have a larger effect in lower psychophysical outputs when limited by joints with lower endurance capabilities. A systematic review by Frey-Law and Avin reported on joint-specific intensity, and they were able to fit a power (log-log) relationship model to data from each joint allowing comparisons between different joints across intensities. Their analysis found that the ankle was the most fatigue-resistant with the highest endurance times, while the shoulder was the most rapidly fatigable, even at low intensities. The results from the meta-analysis support the findings reported here. Strength-limited exertions were determined to be limited by shoulder rotation strength (Figure 2), which was also reported to be the least fatigue resistant joint through meta-analysis. When maximal force is limited by muscular strength, workers may choose to work at a lower percentage of psychophysically acceptable force to protect themselves against fatigue, and may choose increasingly lower the percentage of psychophysically acceptable forces at increasingly higher frequencies during downward exertions, as the shoulder joint is the most sensitive to fatigue. Conversely, pulling exertions were limited by anterior-posterior balance, where balance would be achieved biomechanically using postural control muscles such as ankle strength. Since the ankle joint is demonstrated as the most fatigue-resistant joint, psychophysical limits may be chosen at a higher percentage of the maximum voluntary force, as fatigue may not occur as readily in the balance control muscles.

![Figure 2](image-url) — Psychophysically acceptable forces (%PAF) normalized to maximum voluntary force for downward and pulling exertions. Significant pairwise differences on % PAF during downward exertions due to frequency are represented by an asterisk (*) and the significant main effect of direction is represented by the letter Ψ. Frequency only significantly affected the percentage of psychophysically acceptable force during downward conditions, with the highest acceptable force during exertions at once per minute and the lowest at a frequency of five per minute.
Therefore, psychophysical limits during balance-limited exertions may be modulated by both a different fatigue mechanism (central fatigue) and by joint strengths that are more resilient to fatigue, such as the ankle joint.

This study prompts a fresh evaluation of the utility of previously accepted frequency-based modifiers used to guide acceptable limits for work. A comparison between the frequency effects to the percentage of psychophysically acceptable force during strength-limited exertions found in this study and the effect of the frequency multiplier for tasks above the waist from the National Institute of Occupational Safety and Health (NIOSH) Lift Guide reveals that both demonstrate similar decreasing force exposure limits with increasing frequencies. However, since balance-limited exertions did not show this same nonlinear decrease with increasing frequencies, it suggests that application of the NIOSH frequency multiplier may be overly conservative if the studied task is balance limited. Verily, an alternate modifier may be better suited for balance-limited tasks such as pushing and pulling.

Decreases in psychophysical outputs from other previously researched work-related tasks may be attributed to this fatigue sensitivity in strength-limited exertions. A similar decrease in psychophysically acceptable force outputs with increasing duty cycle using previously reported data has been identified, along with a recommendation that a logarithmic curve fit approach may be useful to scale the percentage of psychophysically acceptable force according to duty cycle and frequency. Considering that many of the tasks synthesized in this work were likely strength limited (vertical lifting, pinching, grasping, and finger pressing), the reported decreases in psychophysical force output may be attributed to fatigue sensitivity in the associated joints. More work is necessary to determine whether acceptable work limits should be modified to consider underlying biomechanical limitations.

There were inherent limitations in this study. Only one handle location relative to the participants was tested in the protocol, making it difficult to extend these findings to other scenarios, as changes in work location may influence worker outputs. Small uncertainties in the balance calculations and link segment modeling outputs likely resulted from intrinsic errors in the collection of the postural data, or the use of population-based anthropometric tables to estimate segment masses for segment calculations. Errors in marker placement were minimized through the use of rigid clusters on body segments. However, one strength of the current study was the use of participants with manual materials handler experience as the population pool. This supports the applicability of the results to industrial settings, as experienced individuals are more likely to exert forces that are representative of a full workday.

This study provides novel insights into the relationships among weakest biomechanical links, maximum voluntary force, and psychophysically acceptable forces. Understanding principles or rules that govern these relationships may help develop prediction models of psychophysically acceptable force thresholds for a variety of workplaces. Workers chose lower force outputs as a percentage of their maximum voluntary force when the exertion was strength limited, relative to when it was balance limited. Further, frequency affects the percentage of maximum voluntary force that a worker is willing to work at without undue pain or discomfort, where strength-limited exertions are more affected than those limited by balance. These findings are thus extremely relevant to practicing work task designers and evaluators.

Acknowledgments

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