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Relationships among static strength, dynamic strength, and psychophysically determined levels of acceptable force for a pushing task and foot pedal actuation task

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A R T I C L E I N F O

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A B S T R A C T

Static strength or psychophysical tests are commonly used to define the capabilities of a working population, but these data are not easily translated to the peak forces that users apply to products or the operational forces associated with product ease of use. This study investigated the relationships among static strength, peak forces from rapid exertions, and psychophysically determined levels of acceptable forces for 39 subjects depressing a foot pedal and pushing against a vertical surface. Peak forces were greater than static strength and psychophysically determined acceptable forces were less than static strength. The ratio of peak to static strength was greater for the pushing task than for the foot pedal task, likely because of the types of motor units recruited and the inertial effects of each exertion.

Relevance to industry: Engineers should be mindful when using published strength values to generate requirements for product design. The ratios among static strength, peak force, and psychophysical limits appear to vary based on task and could affect product safety, effectiveness, and ease of use.

1. Introduction

Accommodating the strength limitations of the worker is a key consideration when designing work that can be performed safely and productively (Waters et al., 1993). For this reason, a substantial body of ergonomics research has focused on defining the strength capability of the working population (e.g., Agrawal et al., 2009; Chaffin, 1974; Das and Wang, 2004; Peebles and Norris, 2003; Snook and Ciriello, 1991). Past research on strength capability has encompassed a large number of postures or activities and has employed a variety of measurement techniques (Chow and Dickerson, 2009; Dempsey and Ayoub, 1996; Gallagher, 2005).

Researchers have studied both static and dynamic activities to determine strength capabilities of workers (Aghazadeh and Ayoub, 1985; Chaffin et al., 1999). Much ergonomics research on strength capability has focused on static strength testing that requires subjects to produce a maximal force while adopting a fixed posture (Chaffin, 1975). These static exertions occur over a period of several seconds to allow contracting muscles to reach maximum strength (Kroemer and Marras, 1981; Ning et al., 2014; Zhou and Wiggermann, 2017). The fixed posture reduces variation due to movement speed or changing joint angles and these exertions are highly repeatable and relatively easy to collect (Essendrop et al., 2001). However, it is unclear how these strength measurements relate to the actual movements and forces exerted by workers in dynamic work settings.

Alternative to static testing, psychophysical methods have been used to determine acceptable load limits for dynamic physical activities that occur over the course of a work shift (Garg et al., 1982). In psychophysical testing, subjects repeatedly perform an activity at a frequency prescribed by researchers and the acceptable force or load is selected by subjects and recorded as the dependent variable (e.g., Ayoub et al., 1980; Snook and Ciriello, 1991). The advantage of these methods is that they are realistic; study subjects are free to adopt postures and perform movements just as workers would in the workplace (Giangiardi et al., 2016; Waters et al., 1993). However, findings from psychophysical studies are typically applicable strictly to the activity that was studied. Additionally, psychophysical studies can be difficult to conduct because they require a great deal of time from a relatively large number of participants to

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adequately describe the variation in the population.

Applying past research on strength capabilities poses a challenge to those who design products or work environments (Chaffin, 1997). In most circumstances a product is not designed merely to accommodate the upper limit of a user's strength but to operate with exertions that are acceptable to the user (Feyen et al., 2000; Kilbom et al., 1993). Such acceptable forces should not cause fatigue and will ensure that a product is easy to use. For example, if the handle of a car door actuated at the force equivalent to a user's static one-handed pull strength it would not be acceptable to most users.

Previous studies that have provided information about the relationship between static strength and acceptable forces have focused almost exclusively on lifting (Lee and Chen, 1996; Thompson et al., 1992). These studies have generally found significant relationships between static strength and the maximum acceptable weight of lift, but these correlations vary based on the isometric strength measurement technique and the parameters of the lift (lifting postures, box sizes etc.) (Garg et al., 1982). The range of correlation coefficients between isometric strength and maximum acceptable weight of lift were $r = 0.48$ to 0.79 (Garg et al., 1980), $r = 0.66$ to 0.85 (Garg et al., 1982), $r = 0.30$ to 0.73 (Rosecrance et al., 1991), and $r = 0.81$ to 0.86 (Lee and Chen, 1996). These studies included only males and with the exception of Rosecrance et al. (1991), all exclusively studied a university population. Several of these studies included fewer than 10 subjects (Garg et al., 1980; Garg et al., 1982; Garg and Banaag, 1988). Outside of these lifting applications, no research has explored the relationship between isometric strength and exertions that are acceptable to users when performing other occupational tasks.

Just as there is little knowledge relating strength capability to forces accepted by users, previous studies do not provide information that can be used to ensure that designs are robust to the maximal forces exerted by users. Continuing with the example of a car door handle, if the handle can withstand only the force equivalent to a user's static one-handed pull strength, it will frequently fail when subjected to peak forces from rapid exertions that might occur if a strong human jerks on the handle when the door is locked. The actual force generated can exceed static strength measures because of motivation not present in the lab or because of acceleration and inertial factors (e.g., Stevenson et al., 1990; Tupling et al., 1986) that are not reflected in static strength testing. Although researchers in sports science have compared static strength to athletic performance like jumping, throwing, or sprinting (see review articles: Juneja et al., 2010; Wilson, 1996) these activities are not applicable to most occupational activities or user product interactions. No studies have determined how traditional measures of static strength capability relate to such maximal peak forces.

The objectives of this research were to define the relationships among force limits determined through static strength testing, peak force testing, and psychophysical testing. These findings will provide insights for how designers can translate published strength guidelines into design requirements. Two whole body activities were studied: pushing horizontally using the hands against a flat surface and pressing down with the foot on a pedal. These activities are motivated by a healthcare application in which a worker transports a patient in a hospital bed or stretcher. It was hypothesized that the ratio of peak forces to static forces would be greater for pushing in which inertia of the entire body can be used to generate peak force than for actuating the foot pedal in which force is generated primarily by the leg and inertial effects are limited. Given that the pedal depressing task has not been previously studied, a secondary objective was to introduce normative values for this activity.

2. Methods

2.1. Subjects

Thirty-nine subjects (20 female) participated in the study. Nine of these subjects (6 female) were recruited specifically for their healthcare experience, having at least one year on the job as a nurse, nurse assistant, or hospital transporter. The other 30 subjects were not recruited based on work experience.

Subjects had a median age of 30 years (range 18–67 years), body mass of 77.1 kg (49–120 kg), and height of 172.7 cm (156.1–189.2 cm). More details of the physical attributes of the subjects are shown in Table 1. One participant was left foot dominant (indicated he would kick a ball with his left foot). All participants were free of injuries or conditions that affected their ability to step down a foot pedal or push against a vertical surface. Participants were asked to wear their own athletic shoes. All subjects signed an informed consent document reviewed by [IRB institution redacted for blind review].

2.2. Overview of testing

Two whole body activities were studied in this research: stepping down on a pedal and pushing against a vertical surface. Static strength and peak force from rapid exertions were measured for both the foot pedal activity and pushing activity for all 39 subjects. Additionally, the nine healthcare workers with experience operating foot pedals on hospital beds and stretchers were asked to evaluate the acceptable force to actuate a foot pedal.

2.3. Foot pedal force exertion

A fixture was built to simulate stepping on the brake pedal of a hospital bed. The injection molded plastic cover for a foot pedal was affixed to the top of a MC3A-1K six-axis load cell (AMTI; Watertown, MA, USA). The pedal and load cell assembly was positioned relative to a barrier 37 cm above the floor that simulated the underside of a hospital bed frame. The edge of the foot pedal was recessed 16 cm from the edge of the barrier and 19 cm above the floor (See Fig. 1). This position simulated a typical location for a brake pedal accessed with the foot from the side of a hospital bed.

Static strength was tested first, followed by the peak force testing and the psychophysical evaluation (for the healthcare workers). Two repetitions were tested for the static strength and peak force tests; the psychophysical evaluation was performed only once to prevent fatigue. All testing was performed on the right foot. The subject was required to rest at least 60 s between each trial.

For the static strength test, subjects were asked to place their foot on the pedal and press down for 5 s, building their force production for two seconds and then producing a constant maximal effort for an additional three seconds. A stopwatch was used to time the maximum effort during which time verbal encouragement was provided. Before the peak strength test, subjects were instructed to: “apply the greatest force possible for an instant in time, as if the pedal was stuck and you were trying to break it free.”

Psychophysical testing was conducted by placing weights on a lever arm connected to the foot pedal (see Fig. 2). The foot pedal was allowed to travel about 2.5 cm so that subjects could feel the pedal move as the gravitational force of the weights was overcome. Using the method of limits, the effective load on the pedal was systematically increased and then decreased in 2.27 kg increments and subjects tested the pedal to experience the load. A curtain was placed so that subjects could not see the weights. Before the evaluation, subjects were told: “Please indicate the force at which the resistance is no longer acceptable because it would cause fatigue or