Applied Ergonomics 43 (2012) 664–670

Contents lists available at SciVerse ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Effects of handle orientation and between-handle distance on bi-manual isometric push strength

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ARTICLE INFO

Article history:
Received 15 June 2010
Accepted 5 October 2011

Keywords:
Ergonomics design
Anthropometry
Strength testing
Cart
Manual vehicles

ABSTRACT

Hand–handle interface is seldom considered in contemporary upper limb biomechanical analyses of pushing and pulling strength. A laboratory study was designed to examine if handle rotation in the frontal plane (0°-horizontal, 45°, and 90°-vertical), anterior tilt (0°-parallel to the frontal plane, and 15°), and distance between two handles (31 and 48.6 cm) affect pushing strength and subjective rating of handle preference. A special testing station was constructed to elicit upper limb push exertions that involved minimal contribution of the torso and legs. Within the station, four load cells were used to measure the horizontal (forward pushing) and vertical components of the pushing forces. Thirty-one participants performed seated bi-manual pushing strength tests. Comparing to the reference handle configuration (horizontal, straight, and a 31-cm between-handle distance), the 45°-rotated and tilted handles with a 31-cm between-handle distance allowed 6.7% more pushing output, while the horizontal and tilted handles with a 31-cm between-handle distance resulted in 2.8% less. Subjective preference was correlated with normalized pushing strength ($r = 0.89$). Tilted handles, at 45°-rotated and vertical positions received highest subjective ratings of preference among all handle configurations. Men exerted greater pushing strength with the 48.6-cm handle distance while women's capacity was greatest with the 31-cm distance. The results demonstrated that handle rotation and tilt angles affected pushing strength and should be taken into consideration when evaluating or designing pushing tasks.

1. Introduction

Manual materials handling (MMH) jobs account for the majority of workers' compensation claims in the United States, both in terms of frequency and costs (Dempsey and Hashemi, 1999). It is estimated that pushing and pulling activities constitute nearly half of manual material handling tasks in certain industries (Baril-Gingras and Lortie, 1995). Pushing and pulling are involved in approximately 20% of low back injuries claims (Hoozemans et al., 1998) and are strongly associated with self-reported shoulder complaints (Hoozemans et al., 2002). Data on population push strength or psychophysical capacities have frequently been published (Chaffin et al., 1983; Ciriello et al., 2001; Keyserling et al., 1980; Kumar, 1995; Snook, 1978; Snook and Ciriello, 1991). However, these population strength or maximal acceptable load databases were typically collected on straight, horizontally oriented handles. The effect of handle interface on such databases is not known.

A plethora of studies have examined the forces required to move manual vehicles. Design factors such as wheel diameter and material, handle length and height, task factors such as load, and environment factors such as floor type and slope, have been evaluated in previous studies to assess the force required to maneuver the vehicles (Al-Eisawi et al., 1999a,b; Das et al., 2002; Haisman et al., 1972; Jansen et al., 2002; Jung et al., 2005; Kingma et al., 2003; Lee et al., 1991; Lin et al., 2010; Okunribido and Haslegrave, 1999). For example, Al-Eisawi et al. (1999b) measured the pull force required to initiate the movement of a 200-kg cart and found that as the cart wheel diameter increased from 51 to 153 mm, the force decreased from 28 to 11 kg. Lin et al. (2010) observed the sustained force to push a manually guided vehicle increased 31% when the handle height was lowered from 115 cm to 88 cm. Among all of the aforementioned studies, most of the hand trucks and pushcarts have straight handles parallel to the frontal plane of the operator. This may cause the wrist to deviate in the radial direction during a pushing task and may not allow operators to optimize force production during pushing.

Studies have shown that the handle interface can affect various upper extremity exertion capacities. The pulling strength was affected by different household handles and knobs (Fothergill et al.,

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0003-6870/$ – see front matter
doi:10.1016/j.apergo.2011.10.004

1992). The handle shape and design influence torque capacity (Shih and Wang, 1996). Drury and Deeb (1986a,b) presented the effects of box handle angle and position in lifting tasks on biomechanical and psychophysical measures. Handle configuration could affect hand exertion capacity through the change in adopted postures.

With regard to pushing strength, Jansen et al. (2002) evaluated pushing forces on three catering carts. The effects of, and the comparison between, vertical and horizontal handle positions did not yield any conclusive results due to limitations in study design, and the distance between handles was not controlled. Attempting to establish a predictive model of one-handed strength, Roman-Liu and Tokarski (2005) measured the effects of seven forearm joint angles on pushing strength and demonstrated that theoretically, pushing strength peaks when the wrist is in the neutral non-deviated position, and declined as the wrist became either radial or ulnar deviated. Okunribido and Haslegrave (2008) described the arm postures in isometric bi-manual pushing exertions. While focusing on the qualitative description of the strength buildup profiles and arm postures, the six handles under study consisted of variations of handle angles in three orthogonal planes. They concluded that the ability to allow various arm postures, especially that of the forearm, was important for push force production.

In contemporary biomechanical models, strength analyses, or exposure assessments, wrist posture is often considered inconsequential in determining push strength or capacity. Therefore, the purpose of this experiment was to examine the effects of different hand–handle interface designs (handle rotation and tilt) on operator bi-manual push capacity. The null hypothesis was that push strength was not affected by hand-handle interface design. The information is essential to provide alternative considerations for the design of manual vehicles.

2. Methods

2.1. Participants

Thirty-one healthy adults between 19 and 64 years of age, without any existing musculoskeletal or other health conditions that prohibited them from performing regular daily activities, participated in this study after giving the informed consent, which was approved by the research facility's Institutional Review Board. There were 14 female and 17 male participants. Their average (s.d.) age, body mass, and height were 38.5 (13.2) years, 69.4 (18.6) kg, and 166.0 (5.6) cm, respectively for the females, and were 34.8 (14.5) years, 77.5 (16.0) kg, and 175.4 (9.1) cm, respectively for the males.

2.2. Apparatus

The strength test station consisted of an aluminum frame with two uprights that were rigidly fixed to the ground (Fig. 1). An aluminum crossbar spanned the two uprights, and its height was adjustable. Two 4.0 cm diameter aluminum handles, whose surfaces were textured by sandblasting to minimize hand slipping, were mounted to the crossbar (Fig. 2A). Handle orientation was adjustable in two dimensions to allow different handle rotation (axis aligned with the direction of push) and tilt (axis perpendicular to the direction of push) configurations (Fig. 2A and B).

Four 100-kg-rated uniaxial load cells (Model AG100, Scaime S.A.S., France) were mounted to the crossbar, two at each end (Fig. 2C). The resolution of these load cells was 10 g and the measurement error was ±1.7 g. The load cells, which are designed to measure forces irrespective of point of load application, were located in such a way that the horizontal and vertical components of the pushing force applied by the participant at the handle could be resolved independently. After they were mounted, they were further calibrated with

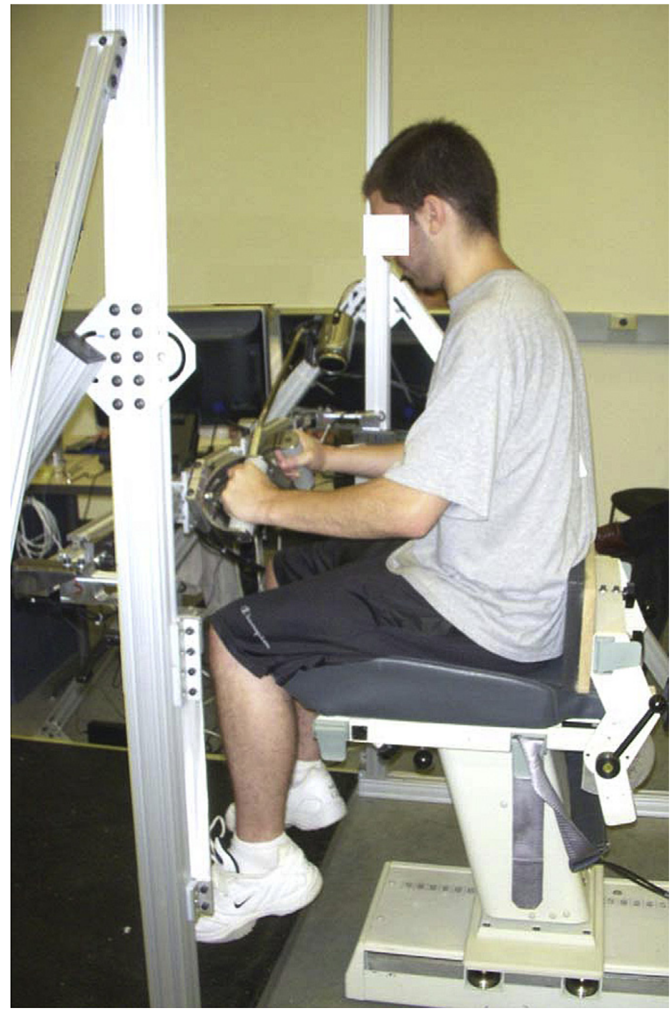

Fig. 1. Pushing strength test station. The handles were set at 45° rotation and 0° tilt (straight).

loads up to 311 N applied in both vertical and horizontal directions on the crossbar. The output from the four load cells was sampled at 100 Hz by a 16-bit A/D converter, and stored in a computer.

During pilot testing in a standing posture it became evident that pushing capacity was influenced by interaction of trunk and lower extremity postural strategies, participant weight and the friction available at the shoe–floor interface. In standing, pushing capacity was mostly limited by the available friction. To avoid confounding strength production by such factors, a seated protocol was developed. The seating system of an isokinetic muscle testing apparatus (System 2, Biodex Medical Systems, USA) was adapted for the protocol. The seating system was selected because it was designed to be sufficiently rigid to avoid flexure during strength testing trials. Seat height was adjusted so that when seated the participant's lower extremities were unsupported, and feet were clear of the ground, thus preventing lower extremity contribution to the pushing effort. The seat back rest was modified, so that support was provided only approximately as high as the iliac crests. This configuration minimized use of the trunk to provide leverage, which would be possible with a full-length back support.

2.3. Study design

This study employed a 3 × 2 × 2 full factorial design. The handle factors were rotation angle in the frontal plane (0°-horizontal, 45°,