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# Biomechanical evaluation of exoskeleton use on loading of the lumbar spine

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## ABSTRACT

The objective of this study was to investigate biomechanical loading to the low back as a result of wearing an exoskeletal intervention designed to assist in occupational work. Twelve subjects simulated the use of two powered hand tools with and without the use of a Steadicam vest with an articulation tool support arm in a laboratory environment. Dependent measures of peak and mean muscle forces in ten trunk muscles and peak and mean spinal loads were examined utilizing a dynamic electromyography-assisted spine model. The exoskeletal device increased both peak and mean muscle forces in the torso extensor muscles ($p < 0.001$). Peak and mean compressive spinal loads were also increased up to 52.5% and 56.8%, respectively, for the exoskeleton condition relative to the control condition ($p < 0.001$). The results of this study highlight the need to design exoskeletal interventions while anticipating how mechanical loads might be shifted or transferred with their use.

## 1. Introduction

Work-related musculoskeletal disorders (MSDs) continue to represent a major problem in modern occupational environments. Among all MSDs reported, low back disorders (LBDs) and shoulder injuries are by far the most prevalent (Holmstrom and Engholm, 2003; Widanarko et al., 2012, 2014; Wijnhoven et al., 2006). The Bureau of Labor Statistics indicates that between 2014 and 2015, work-related MSDs resulted in a median of 12 lost work days per incident, with low back and shoulder complaints making up 40% and 15% of the total cases, respectively (BLS 2016). These MSDs represent an immense economic burden, in which the direct cost of treatment of LBDs annually in the United States totals over $50 billion (Davis et al., 2012), and the direct cost of treating shoulder injuries totals to over $7 billion (Meislin et al., 2005).

Though workers in occupational environments are exposed to a wide range of exposures, the effects of using heavy hand tools to perform tasks such as drilling, countersinking, riveting, bucking, and swaging has received considerable attention. Hand tools may need to be used in unfavorable postures such as is seen in overhead work, asymmetric exertions, or kneeling (Burdorf et al., 1991). It is no surprise, then, that workers subjected to hand tool use have noted high rates of low back and shoulder injuries (Stenlund et al., 1993; Keyserling et al., 1991).

In response to musculoskeletal complaints related to hand tool use, various interventions have been introduced into occupational environments, including cranes and other lift assist devices. Unfortunately, among their many advantages, these devices also have significant costs. Their use can be both time and space consuming, and workers tend not to use them if loads fall within their strength capacity or if extensive learning is required (Graham et al., 2009). As a result, wearable exoskeletons have recently been introduced as an alternative workplace intervention. Exoskeletons are a type of mechanical intervention that are designed to work in concert with the worker in order to provide support or enhance their capabilities, and it is conceivable that exoskeletons could make a greater impact than existing interventions. In fact, previous investigations have already shown that exoskeletal devices can be helpful in reducing the sum of joint torque in the upper arm (Sylla et al., 2014) or decreasing the effective load on the shoulder (Naito et al., 2007).

Despite the fact that numerous work-related exoskeletons are commercially available and have already been introduced into some occupational environments, there has been relatively little research examining the potential benefits, drawbacks, and trade-offs of exoskeleton use in an occupational workplace. Likewise, most of the studies that have been conducted are limited in some capacity by the methods used. A number of studies used electromyographic (EMG) data to evaluate the impact of exoskeleton use, but the EMG data oftentimes was not normalized or modulated for muscle length and velocity or was just averaged across subjects (Abdoli-Eramaki et al., 2006; Bosch et al., 2016; Graham et al., 2009; Naito et al., 2007; Kobayashi and Nozaki, 2007). Numerous studies examined kinematic measures, but these were frequently confined to just the sagittal plane or purely static assessments (Abdoli-Eramaki et al., 2006; Abdoli-Eramaki et al., 2007;

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Heydari et al., 2013; Ulrey and Fathallah, 2013a, 2013b; Graham et al., 2009; Bosch et al., 2016; Sadler et al., 2011). Finally, those studies that used a biomechanical modelling approach often used models that were static or were unable to account for passive muscle forces and muscle coactivity (Abdoli-Eramaki and Stevenson, 2008; Frost et al., 2009; Graham et al., 2009; Heydari et al., 2013; Naruse et al., 2003; Panizzolo et al., 2016; Ulrey and Fathallah, 2013a, 2013b; Abdoli-Eramaki and Stevenson, 2008; Wehner et al., 2009).

Moreover, to the authors' knowledge, no studies have examined biomechanical loading to other joints that the exoskeletons were not specifically designed to support. For example, several industries including shipbuilding and aerospace manufacturing have considered the use of or have already implemented exoskeletal interventions that were specifically designed to mitigate risk to the upper extremities (particularly the shoulders) during powered hand tool use. However, it remains unclear if these interventions simply sacrifice risk elsewhere, such as the low back. Back problems in particular represent the most disabling medical condition to affect mankind worldwide (Hoy et al., 2014) and are the primary reason workers under the age of 45 have activity limitations (Marras, 2008). Thus, the impact of exoskeleton use on the low back should at the very least be investigated, even if the exoskeleton was designed for applications in which the upper extremity is the main concern.

There is a significant void in the body of knowledge concerning the use of work-related exoskeletons that should be addressed before this class of intervention is safely employed in occupational environments. Thus, the objective of this study was to employ a biomechanical model to evaluate how the use of an exoskeletal intervention affects muscle force and spinal load measures in the low back during simulated hand tool use in a laboratory environment.

## 2. Methods

### 2.1. Approach

A laboratory study was conducted in an attempt to understand the biomechanical impact of using an exoskeleton during occupational work. In this case, a mechanical arm was connected to an exoskeletal vest to support a power tool during a simulated work task. Muscle forces in the power-producing muscles of the torso and lumbar spinal loads in compression, anterior/posterior (A/P) shear, and lateral shear were evaluated for two different tools with and without the exoskeletal vest and arm using an EMG-assisted dynamic biomechanical spine model. The biomechanical model employed has been described extensively in the literature with numerous publications documenting its implementation and validation (Dufour et al., 2013; Granata and Marras 1993, 1995a, 1995b, 2000; Marras and Granata, 1997; Granata et al., 1999; Knapik and Marras, 2009; Knapik et al., 2012; Marras et al., 2001, 2004, 2006; Marras et al., 2009). The model has also been recently updated to include curved muscle representations and new personalized active and passive muscle force algorithms (Hwang et al., 2016a, 2016b, 2017).

### 2.2. Subjects

Twelve male subjects were recruited from the local university population (age 25.3 ± 6.0 years, mass 81.9 ± 9.8 kg, and height 184.4 ± 5.2 cm). All of the subjects provided informed consent and had no reports of previous or current low back pain in the past 3 years and no prior low back surgery. This study was approved by the University's Institutional Review Board.

### 2.3. Study design

A repeated measures design was implemented for this investigation to evaluate independent measures of exoskeletal intervention (with and without an exoskeletal vest and arm), vertical exertion height (50%, 65%, and 100% of subject stature), and asymmetry (feet oriented at 0° and 45° away from the tool). The experimental design was carried out for each subject with two tools, a nutrunner (weight 4.54 kg) and a pneumatic impact wrench (13.61 kg). Selection of the independent variables investigated and their levels were made consistent with suggestions from an industrial partner to represent tasks common to aerospace manufacturing.

The authors note that the combination of trials (with and without the intervention) with the heavy tool at 100% of subject stature was excluded from the study design. Under these experimental conditions, the target vertical exertion height was outside of the vertical range of the mechanical arm of the exoskeletal intervention being tested. Thus, experimental conditions tested for the nutrunner (light tool) were representative of a 2 × 3 × 2 repeated measures design, while experimental conditions tested for the pneumatic impact wrench (heavy tool) were instead representative of a 2 × 2 × 2 repeated measures design.

The order in which the experimental conditions were encountered by subjects were first counterbalanced based upon exoskeletal intervention (with and without). Within each block, conditions were then randomized based upon tool weight, exertion height, and asymmetry. Two repetitions of each experimental condition were collected back to back.

#### 2.3.1. Independent variables

Independent variables included intervention, vertical exertion height, and asymmetry. The main effects attributable to these independent variables as well as potential intervention*height and intervention*asymmetry effects were assessed separately for each of the two tools. Effects that were found to be consistent across both tool weights were determined to be of greatest importance for discussion.

#### 2.3.2. Dependent variables

Dependent measures consisted of peak and mean muscle forces and peak and mean three-dimensional spinal loads for each trial. Muscle forces were estimated for the power-producing muscles of the torso, including the right and left erector spinae (ES), internal oblique (IO), latissimus dorsi (LD), external oblique (EO), and rectus abdominis (RA) muscles. Likewise, three-dimensional spinal loads (compression, A/P shear, lateral shear) were calculated at the superior and inferior endplates of the lumbar spine extending from T12/L1 to L5/S1.

All dependent measures were derived from simulations in the multibody dynamics solver, Adams (MSC Software, Santa Ana, CA, USA). The aforementioned biologically-driven biomechanical model utilized inputs of subject-specific anthropometry, MRI-derived muscle locations and sizes, full body kinematics, muscle activity for the power-producing muscles of the torso, and tissue material properties. Muscle forces were estimated via modulation of EMG activity with a gain ratio determined from model calibration, muscle location and cross-sectional area derived from Magnetic Resonance Imaging (MRI), and force-length and force-velocity relationships of the muscle (Jorgensen et al., 2001; Marras and Granata, 1997; Marras et al., 2001). Likewise, spinal loads were estimated via combination of the muscle force data with whole body kinetic loads, torso cross sectional area, muscle lines of action, muscle moment arms, vertebral angles, and other geometric information.

### 2.4. Apparatus and instrumentation

#### 2.4.1. Tools

Two different tools were employed for testing. The light tool (4.54 kg) condition utilized a right angle nutrunner (EA34LA19-80, STANLEY Engineered Fastening, New Britain, CT, USA.) The heavy tool (13.61 kg) condition utilized a pneumatic impact wrench (1 in. Industrial Pinless Air Impact Wrench, Central Pneumatic, Camarillo, CA, USA.) These specific tools were selected since they were both at the