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Load-embedded inertial measurement unit reveals lifting performance

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ABSTRACT

Manual lifting of loads arises in many occupations as well as in activities of daily living. Prior studies explore lifting biomechanics and conditions implicated in lifting-induced injuries through laboratory-based experimental methods. This study introduces a new measurement method using load-embedded inertial measurement units (IMUs) to evaluate lifting tasks in varied environments outside of the laboratory. An example vertical load lifting task is considered that is included in an outdoor obstacle course. The IMU data, in the form of the load acceleration and angular velocity, is used to estimate load vertical velocity and three lifting performance metrics: the lifting time (speed), power, and motion smoothness. Large qualitative differences in these parameters distinguish exemplar high and low performance trials. These differences are further supported by subsequent statistical analyses of twenty three trials (including a total of 115 total lift/lower cycles) from fourteen healthy participants. Results reveal that lifting time is strongly correlated with lifting power (as expected) but also correlated with motion smoothness. Thus, participants who lift rapidly do so with significantly greater power using motions that minimize motion jerk.

1. Introduction

Manual lifting of loads arises in activities of daily living as well as in the specialized tasks performed by industrial, agricultural and construction workers, athletes, warfighters, emergency responders, and in many other occupations. Such lifting tasks are a well-known risk factor in low back pain. As reviewed in Song et al. (2016), the lifetime prevalence of low back pain in the US alone exceeds 60% (Krismer and van Tulder, 2007) and incurs annual costs exceeding $100 billion (Katz, 2006). Numerous studies explore the underlying mechanisms and lifting conditions implicated in injuries to the lower back; see, for example (Freivalds et al., 1984; Faber et al., 2009; Singh et al., 2014). Multiple biomechanical models of lifting (Freivalds et al., 1984; Singh et al., 2014) explore the lower back and/or shoulder loads during lifting tasks as well as the lifting motions that optimize lifting effort (Song et al., 2015, 2016), together with balance and spine loads (Xiang et al., 2012), and with variable joint stiffness (Hasan, 1986). Among many factors that contribute to injury risk are overexertion and fatigue as revealed by electromyographic data (Shair et al., 2017). Other factors include age and lifting speed, load, range, and technique; see, for example (Albert et al., 1999; Chen, 2000; Kollmitzer et al., 2002; Xiang et al., 2012; Song et al., 2015, 2016; Song and Qu, 2014a; Lee, 2015).

Prior experiments on manual load lifting consider both single hand lifting (Singh et al., 2014; Faber et al., 2009) and two hand lifting (Freivalds et al., 1984; Kollmitzer et al., 2002; Singh et al., 2014; Song and Qu, 2014a; Shair et al., 2017) using a variety of laboratory-based experimental methods. These methods rely principally on video analysis (Freivalds et al., 1984) and optoelectric cameras (Song et al., 2015, 2016; Lee, 2015; Song and Qu, 2014a; Chen, 2000) to deduce body segment pose and kinematics, and force plates to measure ground reactions (Freivalds et al., 1984; Singh et al., 2014; Song et al., 2015, 2016; Song and Qu, 2014a; Kollmitzer et al., 2002). Pertinent to this paper is the study by Song and Qu (2014a) that utilizes an eight-camera optoelectric motion capture system to measure both load and body segment kinematics during two-handed load lifting from floor to shelf heights. The motion capture data, which yield the position, velocity, and acceleration of the load and body segments, reveal significantly different lifting strategies for younger versus older participants. This experiment subsequently informed an optimization study of lifting (Song et al., 2016) that simultaneously considered minimal effort and maximum motion smoothness during lifting. Model results confirm that younger workers tend to minimize effort relative to older workers who tend to maximize load motion smoothness.

While the above laboratory-based methods successfully reveal lifting biomechanics, the conclusions drawn are necessarily somewhat limited by the laboratory conditions employed. Far greater ranges and

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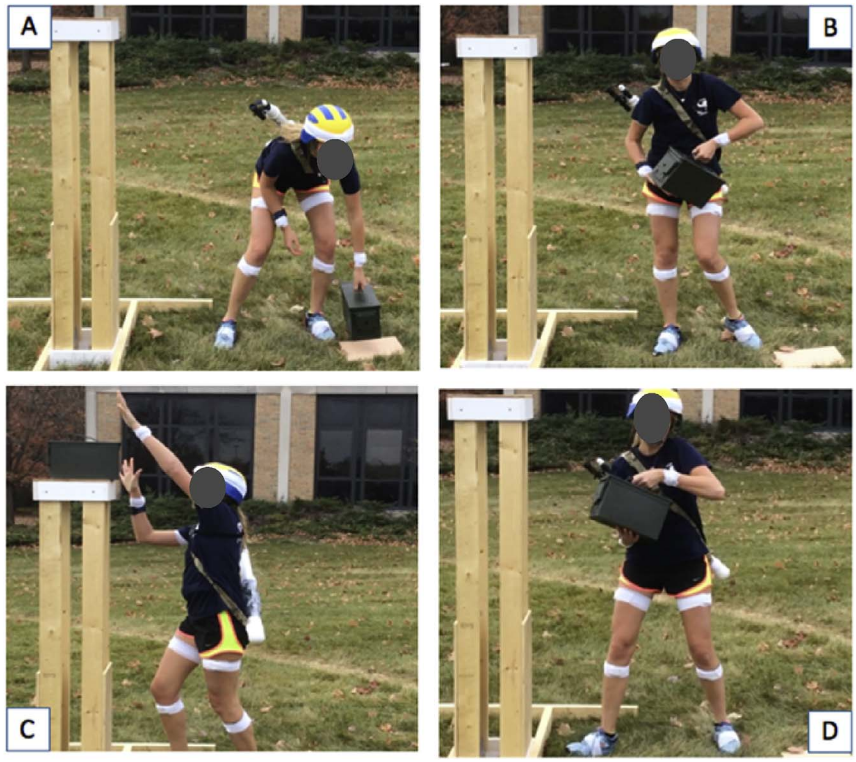

Fig. 1. Vertical load lift obstacle. **A**) Participant picks up the load from the ground (with load at the participant's left side); **B**) rapidly lifts the load upwards; **C**) places the load on stand (momentarily releasing from hands); **D**) rapidly lowers the load downwards and returns it to the ground (momentarily releasing from hands).

variations of lifting conditions exist outside the laboratory, for instance in the home, workplace, training facility, or field of play, where it is difficult if not impossible to use established laboratory measurement methods. A new measurement method, employing load-embedded inertial sensors, holds promise for studying lifting tasks in outdoor and other contextually-relevant environments. The major aims of this paper are to advance the use of miniature inertial measurement units (IMUs) embedded within the load to demonstrate both how lifting can be measured outside of the laboratory and how the measurements can quantify lifting performance.

Miniature embeddable and/or wearable IMUs, which contain MEMS accelerometers and angular rate gyros, are now routinely deployed in a wide range of human motion studies with examples focusing on human mobility (Ojeda and Borenstein, 2007; Rebula et al., 2013; Duong and Suh, 2017), balance training (Lee et al., 2012), human health (Nguyen et al., 2017), athlete performance (King et al., 2008; McGinnis and Perkins, 2012), activity and sleep monitoring (Johannsen et al., 2010; Jean-Louis et al., 2001), and warfighter performance (Davidson et al., 2016; McGinnis et al., 2016; Cain et al., 2016) among others. The use of IMUs for human motion tracking outside of laboratory environments potentially increases the validity of research conclusions. For example, Cain et al. (2016) consider human balance performance in the context of a challenging outdoor balance beam embedded within a larger obstacle course used to assess warfighter performance (Mitchell et al., 2016). Data harvested from an array of body-worn IMUs reveals the fundamental trade-off between speed and stability (balance) for participants traversing the beam with and without added equipment load. Also related to our paper are prior studies that deploy IMUs embedded in hand-held equipment, including athletic equipment (King et al., 2008; McGinnis and Perkins, 2012).

The objective of this paper is to demonstrate how IMUs embedded within loads can reveal lifting performance, including in environments outside the laboratory. To this end, we consider an example load lifting task, embedded in an outdoor obstacle course referred to as the Load Effects Assessment Program (LEAP) (Mitchell et al., 2016). The LEAP is used by military organizations worldwide for several purposes including a means to evaluate the effect of clothing and individual personal equipment on warfighter performance. Performance is assessed on twelve obstacles that include, for example, sprint and agility runs, stair and ladder climbs, window and wall climbs, among others. Important for this study, the LEAP also includes two lifting tasks where a load is lifted with two hands vertically and horizontally. This paper focuses on the vertical lifting task in which participants repeatedly lift and lower a load from ground level to approximately shoulder/head level, akin to prior studies of lifting from floor to shelf heights (see, for example (Song and Qu, 2014a; Song et al., 2016),). We open this paper by describing this vertical lifting task and the theory for using IMU data to quantify lifting performance in terms of three proposed lifting performance metrics; namely, the speed (time), power and smoothness of the lifting motion. We hypothesize that high performance is associated with short lifting times that are enabled by high lifting power and smooth lifting motion. A motivation draws from prior biomechanical models of lifting that associate smoother lifting motions with smaller loads on the lower spine (Freivalds et al., 1984; Hsiang and McGorry, 1997; Song et al., 2016).

2. Methods

2.1. Experimental procedure

Fourteen participants (4 female, 10 male; age = 20.7 ± 1.7 years; body mass = 73.2 ± 11.4 kg; height = 1.77 ± 0.08 m; mean ± standard deviation) for this study were recruited from club sports programs (rugby, triathlon and running) at the University of Michigan. The University of Michigan IRB approved the study, and all participants gave informed consent. Participants wore a military tactical vest, a helmet, and shouldered a mock rifle made of plastic. The participants completed an outdoor obstacle course that was a modified version of the Load Effects Assessment Program (Mitchell et al., 2016) as described above. One obstacle, which is the focus of this paper, was a