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Kinematic and ground reaction force accommodation during weighted walking

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ABSTRACT

Weighted walking is a functional activity common in daily life and can influence risks for musculoskeletal loading, injury and falling. Much information exists about weighted walking during military, occupational and recreational tasks, but less is known about strategies used to accommodate to weight carriage typical in daily life. The purposes of the study were to examine the effects of weight carriage on kinematics and peak ground reaction force (GRF) during walking, and explore relationships between these variables. Twenty subjects walked on a treadmill while carrying 0, 44.5 and 89 N weights in front of the body. Peak GRF, sagittal plane joint/segment angular kinematics, stride length and center of mass (COM) vertical displacement were measured. Changes in peak GRF and displacement variables between weight conditions represented accommodation. Effects of weight carriage were tested using analysis of variance. Relationships between peak GRF and kinematic accommodation variables were examined using correlation and regression. Subjects were classified into sub-groups based on peak GRF responses and the correlation analysis was repeated. Weight carriage increased peak GRF by an amount greater than the weight carried, decreased stride length, increased vertical COM displacement, and resulted in a more extended and upright posture, with less hip and trunk displacement during weight acceptance. A GRF increase was associated with decreases in hip extension ($|r| = .53$, $p = .020$) and thigh anterior rotation ($|r| = .57$, $p = .009$) displacements, and an increase in foot anterior rotation displacement ($|r| = .58$, $p = .008$). Sub-group analysis revealed that greater GRF increases were associated with changes at multiple sites, while lesser GRF increases were associated with changes in foot and trunk displacement. Weight carriage affected walking kinematics and revealed different accommodation strategies that could have implications for loading and stability.

1. Introduction

Walking while carrying an additional weight is a functional activity that is common in daily life, as well as during many occupational, sport, and military tasks. The negative effects of weighted walking include an increased risk of injury due to

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excessive musculoskeletal loading (Knapik, Harman, & Reynolds, 1996), increased risk of falling due to altered stability (Park, Hur, Rosengren, Horn, & Hsiao-Wecksler, 2010), and changes in gait that could result in a slip or trip event (Holbein-Jenny, Redfern, Gottesman, & Chaffin, 2007; Myung & Smith, 1997; Perry et al., 2010). Alternatively, weighted walking has been suggested to be a viable intervention for creating a positive stimulus for tissue remodeling to improve muscle strength and bone quality (Wendlova, 2011). The manner in which a person accommodates to the addition of weight during walking might influence whether he or she has a positive or negative outcome.

Accommodation refers to the changes in kinematic, kinetic and neuromuscular performance characteristics that are used to respond to the increased weight. Accommodation can be similar among individuals, as in a generalized response, or specific to an individual, as in an accommodation strategy that incorporates the individual's morphological, biomechanical, and perceptual uniqueness (James & Bates, 1997). For example, several studies have reported a generalized response in which peak vertical ground reaction force (GRF) magnitude (both non-normalized and normalized) increased proportionally with the increase in carried weight during walking when data were averaged across subjects (Birrell, Hooper, & Haslam, 2007; Harman, Han, Frykman, & Pandorf, 2000; Polcyn et al., 2002). However, it has also been shown that individuals can accommodate to weighted walking using strategies that increase, do not change or even decrease peak vertical GRF magnitudes even though the weight carried increases (James, Atkins, Dufek, & Bates, 2014). The kinematic characteristics that accompany these often different peak GRF responses during weighted walking are not well understood, although body geometry at initial ground contact and body motion after contact have been recognized to influence peak GRF magnitudes during normal running gait (Denoth, 1986).

There is an abundance of literature on weighted walking during military (Birrell & Haslam, 2009; Birrell et al., 2007; Harman et al., 2000; Majumdar, Pal, & Majumdar, 2010; Polcyn et al., 2002; Qu & Yeo, 2011), occupational (Myung & Smith, 1997; Park et al., 2010), and recreational backpacking (Kinoshita & Bates, 1983; Simpson, Munro, & Steele, 2012; Wiese-Bjornstal & Dufek, 1991) activities. Although most studies have reported similar peak GRF responses for averaged data, kinematic responses have been more variable. For example, some studies reported no changes in the kinematics of ankle (Birrell & Haslam, 2009; Harman et al., 2000; Smith, Roan, & Lee, 2010; Tilbury-Davis & Hooper, 1999) or knee (Harman et al., 2000; Holt, Wagenaar, LaFiandra, Kubo, & Obusek, 2003; Majumdar et al., 2010; Simpson et al., 2012; Smith et al., 2010; Tilbury-Davis & Hooper, 1999) motion during walking with the addition of weight, while other studies have reported either increases or decreases in motion of these same joints (Birrell & Haslam, 2009; Harman et al., 2000; Majumdar et al., 2010; Polcyn et al., 2002; Qu & Yeo, 2011; Quesada, Mengelkoch, Hale, & Simon, 2000; Silder, Delp, & Besier, 2013; Smith et al., 2010). However, hip joint changes seem to be more consistent. Studies that have examined hip joint kinematics have generally reported increased motion in various planes with the addition of weight (Birrell & Haslam, 2009; Harman et al., 2000; Majumdar et al., 2010; Polcyn et al., 2002; Qu & Yeo, 2011; Smith et al., 2010). It is not known which kinematic changes might be associated with changes in peak GRF during weighted walking or under which circumstances increases or decreases in joint motion might be expected, especially since research methodologies and individual subject strategies can vary widely. Kinematic accommodation strategies also would likely be affected by the specific requirements of the task, and would be a function of the location and magnitude of the weight carried. For example, individuals would be expected to exhibit different kinematic accommodations when weights are carried in a back versus a front pack, unilaterally slung over one shoulder, carried in one hand or two hands, carried with or without arm swing restriction, or carried on the lower extremity. The changes in peak GRF would likely correspond to the specific changes in body configuration and motion, which result from differences in muscle forces and joint kinetics.

Additional knowledge about the kinematic characteristics of accommodation that are associated with changes in peak GRF during weighted walking might improve understanding about accommodation strategies, which strategies might be likely to result in specific peak GRF responses, and potential anatomic sites (joint and segment systems) that might involve control mechanisms or be targeted for intervention to enhance positive or reduce negative outcomes. Therefore, the purposes of the study were to examine the effects of weight carriage on kinematics and peak GRF during walking, and explore the relationships between peak GRF and kinematic accommodation variables to gain a better understanding about which joint and segment system changes might be associated with changes in peak GRF. Additionally, rather than examining a specialized military, occupational or recreational task, the goal was to examine a task in which the amount of weight carried and the mode of carriage would have a broad application to daily life. It was hypothesized that the weight carriage task would evoke kinematic accommodations consistent with a need to maintain total body stability, increase stiffness of joint/segment systems to support the body under increased load, and accommodate to physical restrictions of motion at the hip and trunk due to the location of weight carriage. It was additionally hypothesized that observed changes in joint/segment kinematics would be related to concurrent changes in peak GRF, as a reflection of the alterations in total body center of mass (COM) motion, and that these relationships would differ within classified sub-groups of subjects, thereby revealing kinematic accommodation strategies that explain different peak GRF responses.

2. Methods

2.1. Subjects

Twenty healthy men and women (10 each; M ± SD age 27.8 ± 6.8 yr, height 1.73 ± 0.11 m, and mass 72.3 ± 16.6 kg) participated in the study. Volunteers were screened to exclude those who had previous surgeries, injuries or other health