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Prediction of calcaneal bone competence from biomechanical accommodation variables measured during weighted walking

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ABSTRACT

Carrying weight while walking is a common activity associated with increased musculoskeletal loading, but not all individuals accommodate to the weight in the same way. Different accommodation strategies could lead to different skeletal forces, stimuli for bone adaptation and ultimately bone competence. The purpose of the study was to explore the relationships between calcaneal bone competence and biomechanical accommodation variables measured during weighted walking. Twenty healthy men and women (10 each; age 27.8 ± 6.8 years) walked on a treadmill at 1.34 m/s while carrying 0, 44.5 and 89 N weights with two hands in front of the body. Peak vertical ground reaction force and sagittal plane angular displacements of the trunk and left lower extremity during weight acceptance were measured and used to quantify accommodation. Calcaneal bone stiffness index T-score (BST) was measured using quantitative ultrasound. Correlation and stepwise multiple regression were used to predict calcaneal BST from the accommodation variables. Accommodations of the foot and ankle explained 29 and 54% ($p \leq .015$) of the variance in calcaneal BST in different regression models. Statistical resampling using 1000 replications confirmed the strength and consistency of relationships, with the best model explaining 94% of the variance in calcaneal BST. Individuals who change foot and ankle function when carrying heavier weight likely alter the control of gravitational and muscular forces, thereby affecting calcaneal loading, bone adaptation and bone competence. These novel findings illustrate the importance of gait accommodation strategies and highlight a potential clinical consequence that requires further investigation.

1. Introduction

Walking while carrying additional weight is a common functional activity that has been associated with increased musculoskeletal loading (Birrell & Haslam, 2008; Birrell, Hooper, & Haslam, 2007; Dames & Smith, 2016; Harman, Han, Frykman, & Pandorf, 2000; James, Atkins, Dufek, & Bates, 2014; Xu et al., 2016), but not all individuals accommodate to weight carriage in the same way (James, Atkins, Yang, Dufek, & Bates, 2015; James et al., 2014). Although excessive loading can contribute to injury (Knapik, Harman, & Reynolds, 1996), under controlled conditions weighted walking has been suggested as a practical

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intervention for improving muscle strength and bone quality (Wendlova, 2011). Different biomechanical accommodations to weight carriage could lead to different musculoskeletal forces and consequently different stimuli for bone adaptation. Consistent with tissue adaptation theories such as Wolff's Law (Chen, Liu, You, & Simmons, 2010), Mechanostat theory (Frost, 2003), Daily Stress Stimulus theory (Qin, Rubin, & McLeod, 1998) and Physical Stress Theory (Mueller & Maluf, 2002), mechanical signals from gravitational (Judex & Carlson, 2009) and muscular (Robling, 2009) forces regulate bone remodeling and therefore influence bone competence. Bone competence is operationally defined as a bone's ability to resist fracture in the presence of skeletal forces and is determined mechanically by structural properties, material properties, and bone mineral mass and density, all of which are influenced by tissue adaptation (Bouxsein, 2005; Cole & van der Meulen, 2011; Davison et al., 2006; Donnelly, 2011; Felsenberg & Boonen, 2005; van der Meulen, Jepsen, & Mikic, 2001).

The way a person accommodates to weight carriage specifically, and perhaps other gait perturbations more generally, could influence bone competence through a pathway that alters the control of gravitational and muscular forces leading to an altered stimulus for bone adaptation. Previous research has shown that individuals can exhibit different strategies for accommodating to weighted walking resulting in different ground reaction force (GRF) magnitudes and kinematic displacements (James et al., 2014, 2015) suggesting that inter-individual variability in the coordination of muscular forces may result in different skeletal forces when accommodating to a given weight. Load accommodation strategies have also been observed during running (Simpson, Bates, & McCaw, 1988) and landing after a jump (Caster & Bates, 1995; James, Bates, & Dufek, 2003), and might represent a more general class of compensatory neuromuscular behaviors in the presence of gait perturbation.

Since skeletal forces are a stimulus for tissue adaptation, it is plausible that different strategies used to accommodate to weight carriage during walking might be related to bone competence. Weight carriage is common in daily life and examples include carrying books, portable electronic devices, groceries, plates or trays of food and drink, children, household items, as well as many various objects and implements used in occupational, recreational, sport, and military activities. Individuals who accommodate to weighted walking using strategies that chronically increase or decrease skeletal forces could exhibit different amounts of bone competence. However, it is not known to what extent accommodation to weight carriage during walking and bone competence are related. A meaningful relationship would support the hypothesis that an accommodation strategy is a manifestation of the control of gravitational and muscular forces that load the skeleton (James et al., 2014), and therefore could ultimately affect bone adaptation. Additionally, the way people accommodate to weight carriage during walking could more generally reflect how they accommodate to other common gait perturbations in daily life thereby increasing their chronic exposure to altered skeletal forces. Knowledge about the relationships between load accommodation strategies and bone competence could lead to the development of novel gait re-training countermeasures for improving or slowing the decline in bone competence in people who are at risk. Therefore, the purpose of the study was to explore the relationships between a common clinical measure of calcaneal bone competence and biomechanical variables measured during the accommodation to weighted walking. Based on the bone adaptation theories that link dynamic loading to bone mass and quality, it was hypothesized that biomechanical measures of accommodation to weight carriage during walking would be related to bone competence, perhaps also suggesting a more general relationship between gait accommodation and other types of perturbations. The observation of such a relationship would provide the preliminary quantitative evidence necessary to justify further investigation into a potential cause-effect relationship between gait accommodation and bone competence.

2. Methods

2.1. Subjects

A cross-sectional sample of 20 healthy men and women (10 each; M ± SD age 27.8 ± 6.8 yr; height 1.73 ± 0.11 m; mass 72.7 ± 16.6 kg) participated in the study. The age range was 21–41 years, 12 subjects were less than 30 years, seven subjects were 30–40 years, and one subject was over 40 years of age. Volunteers were excluded if they reported previous surgeries, injuries, or other impairments that would have prevented them from walking normally on a treadmill or carrying weight. Volunteers who did not speak English and pregnant women were also excluded. The study was approved by the Institutional Review Board for the Protection of Human Subjects at the affiliated University. All subjects gave written informed consent to participate.

2.2. Procedures

Data for the current study were obtained as part of a larger study that included multiple weight carriage conditions (James et al., 2014, 2015). The specific procedures relevant to the current study are summarized here. Subjects walked on a treadmill at 1.34 m/s while carrying 0, 44.5, and 89 N (0, 4.5, and 9.1 kg) weights attached to the wrists with the hands clasped in front of the body without arm swing (Fig. 1). The weights were presented in a random order based on selection from a table of random numbers (Portney & Watkins, 2009). Vertical ground reaction force (vGRF) data were measured using an instrumented treadmill (100 Hz; Gaitway, Kistler Instrument Corporation, Amherst, New York, USA). Sagittal plane kinematic data in two dimensions from the trunk and left side foot, leg and thigh (two reflective markers each placed proximally and distally and parallel to the anatomical axis of each segment) were obtained using a single camera motion capture system (120 Hz; Motus 9.2, Vicon Motion Systems, Centennial, Colorado, USA). The marker trajectories were interpolated using a cubic spline so that the number of samples obtained at 120 Hz matched the number of samples obtained from the treadmill force platforms at 100 Hz over the same time interval. Data from the instrumented treadmill and motion capture systems were synchronized using a common analog signal from a separate force platform (Model 4060–10, Bertec Corporation, Columbus Ohio, USA) that was generated when contacted by one of the investigators and sent