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The effects of different carrying methods on locomotion stability, gait spatio-temporal parameters and spinal stresses

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ABSTRACT

Manual material handling (MMH) contributes to a large percentage of musculoskeletal disorders. One of its fundamental activities is load carrying that can be accomplished in several strategies, with each one imposing different types of stresses on the musculoskeletal system. Therefore, the first goal of this study was to determine the effect of different carrying methods on walking stability using motion capture analysis. Second, to analyze gait adaptations to stresses associated with load carrying in order to prevent falling. Third, to investigate the effect of these stresses coupled with human body adjustment on the forces at the L5/S1 disc. Thirty participants carried 10 and 30 lbs loads via frontal, lateral, bilateral, and posterior carriages. Frontal and lateral methods generated the most unstable conditions compared to the others. The unstable locomotion forced the gait parameters to be significantly altered in order to maintain stability. Additionally, the postures maintained in these conditions resulted in significantly high compression and shear forces acting at the L5/S1 disc when compared to the other carrying methods. Moreover, heavier weights exacerbated the effect on the dependent variables. Notably, bilateral and posterior carrying methods provided results comparable to the unloaded walking baseline. In conclusion, to reduce the potential risks associated with load carrying, the recommendation to split the load between both hands using bilateral carrying method or carrying it posteriorly should be taken into account while designing MMH activities.

Relevance to Industry: Injuries due to falls in the workplace are common issues among many workers. A major factor to these incidents is load carrying that can be accomplished with different postures. The human body adopts different compensation strategies in terms of gait patterns, and trunk adjustments. Those types of adaptive strategies may compromise dynamic stability, potentially leading to falls, and stresses on the spine. Investigating the effects of different carrying methods examined in this study can be used in designing manual material carrying tasks in order to reduce the potential risk associated with load carrying.

1. Introduction

The manual material handling (MMH) task of carrying is fundamental in many occupational activities. At the same time, load carrying may expose the musculoskeletal system to both traumatic and chronic injuries. For instance, carrying loads is recognized as the first primary occupational factor contributing to loss of balance, resulting in over 30% of fall injuries (Andersson and Lagerlöf, 1983). Also, injuries to the lower back caused by carrying activities account for 33% of the total injuries in work environment (NIOSH, 1994).

As many human movements, control of locomotion stability is a complex task that requires the interaction between sensory, nervous, and motor systems to regulate the body's center of mass (CoM) in an accurate and efficient way. Maintaining gait stability becomes more challenging when it is coupled with MMH activities, since the load carried alters the location of the CoM. Consequently, the human body adopts compensation strategies, such as alterations of gait patterns and trunk adjustments. All these changes may compromise the dynamic stability, potentially leading to fall, and increase the mechanical load on the lower back (Bressel et al., 2009), which may lead to disc degeneration (Iatridis and ap Gwynn, 2004). To date, the information on the effects of load carrying on dynamic stability and lower back biomechanics is very limited. A few studies have investigated walking

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stability while carrying loads in the form of back packs (Qu, 2013) or double pack (Liu et al., 2007) in order to simulate military occupational activities. Additionally (Holbein and Redfern, 1994), compared walking stability in the medial-lateral direction while carrying loads in different strategies. Similarly, compression and shear forces on the lower back while carrying a load in one hand or splitting it between both hands have been measured (Rose et al., 2013). Also, shear force acting on the lumbar spine have been measured only for the cases of frontal, lateral and posterior carriages (Rose et al., 2013).

The objective of this study was to further elucidate the effects of magnitude and method of load carrying on both walking stability and spine biomechanics. This was done by conducting a motion capture analysis to yield, for any experimental condition examined, gait stability and spatio-temporal parameters, and forces acting on the lumbar spine.

2. Methods

2.1. Participants

Twenty males (age 27.3 ± 2.64 y.o., BMI 24.89 ± 3.92 kg/m^2), and 10 females (age 24.3 ± 3.5 y.o., BMI 21.79 ± 2.51 kg/m^2) participated in the study. The experimental protocol was approved by the Institutional Review Board of the University of Miami. All subjects were provided written informed consent before participating in the study. Subjects who had a history of falls within the past 6 months, history of dizziness, tremors, alcoholism, neurological disorders, diabetic symptoms, vestibular disorders, or back pain were excluded from the study.

2.2. Experimental protocol

Prior starting the experiments, the subjects were briefed about the task to complete and suited with 41 reflective markers for motion capture analysis (see 'Motion Measurements'). The experiment consisted in walking at self-selected pace along a straight line for a 4 m walkway embedded with 4 force-plates (Kistler®, Winterthur, Switzerland). While walking, subjects carried loads of 10 lbs or 30 lbs. These loads were selected based on a pilot study. Carrying modalities were frontal, lateral and bilateral carriage using a 15″x 6″x 6″ box, and posterior carriage using a custom designed backpack, as shown in Fig. 1. For frontal carriage, subjects were instructed to carry the load at about waist level without supporting it against the body, and at self-chosen horizontal distance from the torso. In lateral carriage, participants carried the load with their dominant hand. For bilateral carriage, the loads were split in half between each box. For each load weight and carrying modality, subjects completed 3 trials. In addition, 3 trials were completed while walking without carrying load. These trials served as baseline measurements for comparison purposes. Motion data were acquired via Vicon® Motion Capturing System (Oxford Metrics, United Kingdom) using Nexus® software (version 2.5) and integrating 10 cameras at a sampling rate of 120 Hz. Data analysis was performed to yield walking stability measures, gait spatio-temporal parameters and forces acting on L5/S1 intervertebral disc, see below.

2.3. Motion Measurements

Motion analysis was performed using the 15-segment model (Vicon's Plug-In Gait model) which employs 39 reflective markers distributed across the full body. Two additional markers were added on the 5th metatarsal of each foot, in order to obtain the actual area of contact with the ground while walking. This information was used to determine the base of support (BoS), see below.

When the CoM lies at or near the center of the base of support (CBoS), the human body is more stable than when it is near the edges of the BoS (Whiting and Rugg, 2006). In this study, in order to quantify walking stability during load carrying, the deviation of the extrapolated center of mass (XCoM) from the CBoS was calculated. The XCoM has been previously introduced by (Hof et al., 2005), and adds the linear function of the velocity of the CoM to its position (Iqbal and Pai, 2000; Hof et al., 2007):

$$XCoM = CoM + \frac{V_{CoM}}{\sqrt{\frac{g}{l}}}, \tag{1}$$

where, V_{CoM} is the velocity of the CoM (m/s), g is acceleration of gravity, and l is leg length (m). The choice of using XCoS in place of the CoM is motivated by the fact that the direction of the velocity of a system plays a fundamental role in stability: even when the CoM falls within the BoS, a system may be unstable if the velocity is directed outward the CBoS; diametrically, stability can be achieved even if the CoM is outside the BoS, as long as the velocity is directed towards the CBoS (Singh and Koh, 2009).

In equation (1) the CoM refers to the system composed of the subject together with the load carried. Its expression is provided by the following relation:

$$CoM_{system} = \frac{Weight_{Load} \times Load's\ CoM + Weight_{Body} \times Body's\ CoM}{Weigh_{Load} + Weight_{Body}}, \tag{2}$$

where the CoM of the subject's body was directly provided by the standard Vicon's Plug-In Gait model (Zatsiorsky et al., 1990), while the CoM of the load was obtained by attaching two markers on the box (for frontal, lateral and bilateral carrying) or on the backpack (for posterior carrying).

Each gait cycle consists of 2 double support (DS) phases (i.e. standing on both limbs), and 2 single support (SS) phases (i.e. standing on a single limb). Therefore, the proposed measures quantify walking stability in DS, and SS separately by finding the maximum deviation of the XCoM from the CBoS in the anterior-posterior (A/P) and medial-lateral (M/L) directions:

$$Gait\ Stability\ in\ DS\ phase = max_i(|XCoM - CBoS|) \quad i = 1,2, \tag{3.i}$$

$$Gait\ Stability\ in\ SS\ phase = max_i(|XCoM - CBoS|) \quad i = 1,2. \tag{3.ii}$$

Fig. 1. Carrying methods investigated: (A) Frontal, (B) Lateral, (C) Bilateral, and (D) Posterior.