



The effect of evenly distributed load carrying on lower body gait dynamics for normal weight and overweight subjects

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ABSTRACT

The carrying of extra weight can cause significant injuries. This extra weight can be in the form of an external load carried by an individual or excessive body weight carried by an overweight individual. This study attempts to define the differences in lower body gait patterns caused by either external load carriage, excessive body weight, or a combination of both. Twenty-three subjects generated 115 trials of motion capture data for each loading condition. Path lengths of the phase portrait and the ranges of joint motions (hip, knee and ankle) were used to quantify subgroup differences. The study found significant gait differences due to external load carriage and excessive body weight. Within each class of normal weight and overweight subjects, differences were found in the hip and ankle path lengths when a subject carried an evenly distributed external load. This implies that these joints may be more prone to injury due to external load carriage.

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1. Introduction

Load carrying is a common cause of injuries to the knee and lower back [1,2]. This has motivated previous studies that characterize the human effects of load carrying including the effect on gait patterns. According to these studies, the duration of the double stance increased with increased loads, while the single stance duration decreased (in 10 healthy males [3] and in 15 boys [4]). Significant gait differences were observed between loaded and unloaded walking. These differences were dependant on whether the load was a backpack or double-pack. With a backpack load, forward leaning of the trunk is a natural behavior to help keep the center of mass over the feet. It was found that the forward inclination considerably increased with load weight to minimize energy cost [5]. This minimization of energy expenditure resulted in the decrease of vertical positions at the knee and ankle with the added weight [6]. Several published studies indicated that pelvic rotation reduced and ankle rotation increased in the sagittal plane under loaded conditions [3,5]. These studies also showed that knee flexion after impact was greater when carrying loads in order to absorb increased impact forces.

Excessive body weight has also been linked to large number of health problems such as cardiovascular disease, stroke, hyperten-

sion, and diabetes as well as numerous gait related injuries [7]. A limited amount of work has been done to investigate the injury related gait kinematics of overweight individuals. The kinematic deviations include slower velocity, shorter step length, increased double support time, decreased knee range of motion, and larger ground reaction forces compared to normal weight individuals [8–11].

Body mass index (BMI) is a standard measure of obesity level that is highly correlated to an individual's amount of body fat. BMI is based on height and weight and applies to both men and women [12]. In this work BMI is used to separate subjects into normal weight and overweight categories. This follows the standard convention (BMI > 25 kg/m² overweight, BMI < 25 kg/m² normal weight).

Little work has been done to study the effects of external load carriage and excessive body weight. The previous studies focus on external load carriage by normal weight individuals using mostly linear spatial–temporal measurements such as double stance time, stride frequency and trunk inclination [29]. Recently, Haddad et al. [13] examined the intralimb and interlimb adaptations with a unilateral leg load. Continuous relative phase (CRP) analysis was used to evaluate limb coordination. The advantage of using phase analysis is that it can convert four variables (two positions and two velocities) into one measurement. Phase analysis can also be used to show coordination between two oscillating components [30] which can give insight into the control of a system. This makes phase analysis very useful for investigating human movement and its complexity using a reduced set of measurements or metrics. The path length of the phase portrait has been used to determine the

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effectiveness of the postural control system in controlling the lower body stability and steadiness similar to distance measures of center of pressure (COP) in sway balance control tests [14,31]. To the best of our knowledge, gait adaptations due to external loads have not been compared using measures extracted from phase portraits in normal weight vs. overweight subjects in order to quantify gait differences within these groups.

The present study investigated continuous relative phase analysis to quantify gait adaptations due to external loads for overweight and normal weight groups. Our primary hypothesis was that external loads will affect the lower body movements of the two groups differently. Establishing gait differences between BMI classes due to external loads can be useful for determining maximum acceptable occupational load conditions as function of BMI.

2. Methods

2.1. Subjects and experimental setup

Twenty-three subjects, 16 normal weight (BMI < 24.99 kg/m²) and seven overweight (BMI > 25 kg/m²), were selected in order to provide a significant amount of data for statistical analysis. These subjects generated a total of 115 treadmill trials for each loading condition. All subjects gave their informed consent prior to participation as defined by the Committee for Participants of Investigative Projects at the Virginia Polytechnic Institute and State University. The only statistically significant difference between two groups is weight related variables, i.e. weight, the weight of the load as a percentage of the subject body mass (% BM), and BMI. The subject demography is summarized in Table 1. To determine a subject's preferred walking speed, the treadmill was started and the velocity gradually increased so as to achieve a subject's most comfortable walking speed. This walking speed was used for the two loading conditions.

A total of 23 reflective markers [15,16] were attached to the subjects' anatomical landmarks (top of the head, base of second toe, malleolus, epicondyle, greater trochanter, clavicle, styloid process of ulna, lateral epicondyle of humerus, greater tubercle, acromion, anterior portion of temporal bone, and center of the calcaneus) to capture subjects' three-dimensional motion using a ProReflex system (Qualisys, Gothenburg, Sweden) at the sampling rate of 120 Hz. However, in this study only lower body data were analyzed to focus on changes in lower body kinematics. Treadmill walking was performed for 30 s sessions with subjects wearing a 12.5-kg vest, with mass evenly distributed on the front and back, and without any external load (unloaded walking). The vest was attached to the subjects' body using two shoulder straps and three side straps so that it did not obstruct any upper or lower body movements. Five trials were repeated in each load condition and the order of external load conditions in each subject was completely randomized to reduce any order effects. A rest period of 1–5 min was given between each 30 s walking session.

2.2. Analysis

Consecutive left heel contacts determined the period of one stride in this study. Thus, one stride includes both a left and a right step. Left heel contacts were determined using the vertical velocity changes of heel markers to identify gait periods [17]. Two consecutive left strides were averaged for the analysis in order to reduce the variability of the measurements from stride to stride. Then, the kinematic data were interpolated to 100% and filtered using a low pass, fourth-order Butterworth filter with 7 Hz cutoff frequency. All angles were calculated from the subject's sagittal plane marker positions. Hip angles were defined from horizontal to the thigh segment. Knee angles were determined between the thigh segment and the shank segment, and ankle angles were between the shank segment and the foot [18]. Sagittal plane joint ranges of motion (ROM) were calculated as the difference between peak flexion and peak extension [19] at hip, knee and ankle joints (Hip ROM, Knee ROM and Ankle ROM). Segmental angular velocities were

calculated from the sagittal plane angles using a first central difference method [13]. These joint angles and velocities were then used to compute continuous relative phase from the position–velocity phase portrait. From the resulting phase-planes, the phase angle at each time was calculated relative to the right horizontal using Eq. (1) [20].

$$\psi(t) = \tan^{-1} \left(\frac{\dot{\theta}(t)}{\theta(t)} \right) \quad (1)$$

2.3. Path length (PL) of phase portrait

From the resulting phase-planes, path length (PL) (Eq. (2)) is estimated as the sum of the straight line distances between consecutive points for hip, knee and ankle phases (PL_{Hip}, PL_{Knee} and PL_{Ankle}). These values were used to quantify the magnitude and velocity of joint angular movement as function of time over a gait cycle.

$$PL = \sum_{i=1}^{n-1} \sqrt{(\theta(i+1) - \theta(i))^2 + (\dot{\theta}(i+1) - \dot{\theta}(i))^2} \quad (2)$$

Variations between the phase of the angular movement and angular velocity are captured by this metric. Specifically, the path length is a measure of the overall relationship between the joint angular position and velocity throughout the gait cycle. The path length serves as a measure that can reveal the complicated phase relationships of each joint throughout an entire gait cycle.

2.4. Statistical analysis

Two-way analysis of variance (ANOVA), BMI by load, was used and results were considered to be significant at the $p < 0.05$ level of confidence. A least significant difference (LSD) test was used to determine the differences between each group. Statistical analyses were completed using the SPSS statistical package (v.13, SPSS Inc., Chicago, IL).

3. Results

Two-way analysis of variance (BMI by load) indicated no significant ($p > 0.05$) two-way interaction for lower body movements, implying that the overall trend in these responses was similar in normal weight vs. overweight individuals. No significant effect of load was found in the knee path length, and knee and ankle ROMs (Table 2). However, there were statistically significant increased path lengths of ankle and hip joints ($p < 0.001$), and hip ROM ($p < 0.05$) in the loaded walking condition for all subjects. Additionally, there was a statistically significant increase in hip ROM between normal and overweight individuals irrespective of the loading condition (Fig. 1).

Fig. 2 illustrates the overall experiment, broken down into the specific groups and loading conditions studied. Each of the statistical tests conducted between the groups and loading conditions is labeled as A–F. Individual results for each comparison in Fig. 2 are:

A: Comparison between two BMI groups over all external loading conditions found a statistically significant increase in hip ROM for overweight individuals (Table 3).

B: Comparison between two BMI groups for the unloaded walking condition found no statistically significant difference ($p > 0.05$) in gait variables.

Table 1

Data for the 23 subjects used in the study (mean ± standard deviation). Bold text indicates a statistically significant difference ($p < 0.05$) between normal and overweight groups.

Variable	Normal weight ($n = 16$)	Overweight ($n = 7$)	p -Value
Age (years)	21.59 ± 3.14	25.17 ± 4.67	0.12
Height (m)	1.74 ± 0.08	1.75 ± 0.08	0.94
Weight (kg)	67.08 ± 8.50	89.95 ± 18.68	0.02
% BM	18.62 ± 2.05	15.67 ± 4.08	0.01
BMI (kg/m ²)	22.04 ± 2.10	29.20 ± 3.42	0.01

n , number of subjects; % BM, the weight of the load as a percentage of the subject body mass; normal weight, BMI < 24.99 kg/m²; overweight, BMI > 25.00 kg/m².

Table 2

ANOVA results (mean ± standard deviation) from pooled loading conditions between unloaded and loaded walking conditions for all subjects. Bold text indicates a statistically significant difference ($p < 0.05$) between unloaded and loaded walking conditions.

Variable	Unloaded	Loaded	p -Value
PL _{Ankle}	0.6856 ± 0.0642	0.7515 ± 0.0593	0.001
PL _{Hip}	1.3713 ± 0.1283	1.5031 ± 0.1185	0.001
PL _{Knee}	2.5602 ± 0.2131	2.6418 ± 0.2234	0.211
Hip ROM (°)	38.6058 ± 3.5124	41.8693 ± 3.0355	0.019
Knee ROM (°)	60.3562 ± 5.0004	57.9842 ± 6.4828	0.172
Ankle ROM (°)	28.5638 ± 4.0134	29.9843 ± 5.0475	0.297

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