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Effects of load carriage and footwear on spatiotemporal parameters, kinematics, and metabolic cost of walking

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ABSTRACT

Gait patterns are commonly altered when walking or running barefoot compared to shod conditions. Although controversy exists as to whether barefoot conditions result in lower metabolic costs, it is clear that adding load to the body results in increased metabolic costs. The effects of footwear and backpack loading have been investigated separately, but it is unclear whether manipulating both simultaneously would cause similar outcomes. Twelve healthy individuals (7 female, 5 male) with no obvious gait abnormalities participated in this study (age = 24 ± 2 years, height = 1.73 ± 0.13 m, and mass = 71.1 ± 16.9 kg). Steady state metabolic data and 3D motion capture were collected during treadmill walking at 1.5 m s^{-1} in four conditions: Barefoot Unloaded, Shod Unloaded, Barefoot Loaded, and Shod Loaded. Barefoot walking elicited shorter stride lengths, stance and double support times, as well as a slight (≈1%), but not significant, decrease in metabolic cost. Loading increased metabolic costs of walking but did not elicit spatiotemporal changes in either footwear condition. Lower limb kinematic differences were noted in response to both loading and footwear. Changes in spatiotemporal parameters observed when walking barefoot were not exacerbated by the addition of a backpack load. This suggests that the increased metabolic demand associated with the load is met with a similar spatiotemporal pattern whether a person wears a supportive shoe or not. Thus, the discomfort associated with foot strike while barefoot that promotes spatiotemporal changes seems to be independent of load.

1. Introduction

Backpack loads of 10% or greater of body mass are common among the college student population [1]. Two-thirds of students in a recent survey reported daily backpack use [1] and walked an average of 9.04 miles weekly, most of which while carrying a backpack [2]. Loads as small as 12% of body mass have been shown to negatively influence pedestrian behaviors. For example, reduced walking speeds and reduced distances to an oncoming vehicle while crossing a street have been observed [2]. Additionally, lower extremity injury and/or low back pain may be consequences of habitual load carriage [1,3]. With the significant distances and time spent walking with a backpack weekly, it is important to understand the unique responses of college-aged individuals to loaded walking. However, few studies have investigated load carriage in this population using loads similar to those that these individuals experience on a daily basis.

Wang, Pascoe and Weimar [4] simulated the effect of typical backpack loads by adding 15% of body mass to backpacks in a group of college students. It was reported that while loaded single support time and step frequency decreased, whereas double support time increased. The increased double support time may be an attempt to increase stability when a load is applied to the trunk [5], while the decreased single support time presumably reduces the support contribution required by an individual leg [4]. Grabowski, Farley and Kram [6] suggested that the additional musculoskeletal effort required to maintain an upright body position and to generate forces necessary to propel the body during loaded walking are major contributors to the noted increases in metabolic cost of walking with an extra load. Martin and Nelson [3] suggested that an increase in support time may also increase the risk of injury to the lower limbs.

Controversy exists in the literature about the effects of barefoot running on metabolic cost in part due to methodological differences across studies. For example, Hanson, Berg, Deka, Meendering and Ryan [7] have reported reductions in metabolic costs during barefoot running, while Divert et al. [8] report no differences between barefoot and shod running. van Engelen et al. [9] reported a 3.5% reduction in metabolic cost while walking

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barefoot compared to shod, but this difference was not significant. This suggests that even during walking there may be a potential effect on metabolic costs if the shoes are removed.

Barefoot locomotion conditions have also been shown to lead to alterations in locomotion mechanics [10]. Based on our observations, college students commonly wear unsupportive footwear that also have minimal cushioning between the foot and ground at contact. Observed spatiotemporal differences while walking barefoot, compared to shod, include: reduced speed, step length, double support time, and total support time [11]. Increased step frequency and single support times have also been reported during barefoot walking [11]. Zhang, Paquette and Zhang [12] reported that barefoot walking results in a higher loading rate than shod walking, which likely influences the adopted spatiotemporal gait characteristics presented above. Specifically, it is presumed that shortening the stride length reduces the discomfort experienced at foot strike without the cushioning of a standard shoe [13]. It is currently unknown if these spatiotemporal differences would be further altered by a load when walking barefoot.

Given the noted gait adjustments made under novel conditions (i.e., loaded or barefoot) it was of interest to understand what effects these promote while simultaneously experienced. For example, adding a backpack load while walking shod increases stance time [14], but changing to barefoot walking from shod walking decreases stance time [13]. It is unclear how stance time will respond when the shoe condition and load condition are simultaneously manipulated given the opposite effects of these conditions individually. The addition of a backpack load while barefoot may potentially increase the discomfort of initial contact and accentuate pain-reducing strategies and modify gait mechanics beyond those noted in barefoot walking without a load. However, the effect of carrying heavy loads without a supportive shoe on walking kinematics, spatiotemporal parameters, and economy is still unclear.

Thus, the purpose of this study was to investigate the simultaneous effects of loading and footwear changes on gait mechanics and walking economy. We hypothesized that loading, regardless of footwear, would elicit shorter stride lengths, longer stance times, longer double support times and increased metabolic costs. In contrast, we hypothesized that walking barefoot, regardless of load, would have the exact opposite effect on these measures. Therefore, it was our expectation that adding a backpack load to individuals walking barefoot would result in spatiotemporal patterns and metabolic costs similar to those of shod unloaded walking. Our first two hypotheses are based on previous findings from the literature where barefoot and load effects have been reported by themselves. Our last hypothesis, is simply a combination of the first two hypotheses with an expectation that barefoot and load effects observed individually will cancel each other out when experience simultaneously.

2. Methods

2.1. Participants

Twelve individuals (7 female, 5 male) participated in this study (age = 24 ± 2 years, height = 1.73 ± 0.13 m, and mass = 71.1 ± 16.9 kg). All participants were healthy, recreationally active and free of any notable gait abnormalities. The university's Institutional Review Board approved this study and all participants provided informed written consent prior to participation.

2.2. Experimental protocol

Anthropometric data (including body mass and height) were collected based on VICON's full body plug-in-gait model with medial markers on the knee and ankle to better identify knee and ankle axes [15]. Reflective markers were placed on various anatomical locations using double-sided tape based on the plug-in-gait model. Participants then walked on a level treadmill (Woodway, Waukesha, WI) at 1.5 m s^{-1} for 6-min under four conditions: Barefoot Unloaded (BU), Shod Unloaded (SU), Barefoot Loaded (BL), and Shod Loaded (SL). This model of treadmill was selected because its rubberized slats allowed steady state barefoot walking to be accomplished without blister formation or undue discomfort. A moderately higher walking speed than previously used [10] was selected in an effort to increase the demands on the system so that alterations in movement patterns would be more apparent. A backpack equal to 15% of the participant's body mass was worn during the two loaded conditions. A single textbook was placed in the pack against the participant's back to provide a solid, flat surface before adding lead weights until the desired mass of the backpack was achieved. Participants performed the shod conditions using their own athletic shoe (mean shoe mass = 272 ± 68 g). The order of conditions was individually randomized and a brief rest was provided between successive walking bouts. The rest period was based on the time it took to change from one condition to the next and only lasted a couple of minutes. Randomization of all conditions across all participants was used in attempt to minimize any fatigue effects in this study. During all walking trials, metabolic (ParvoMedics, Sandy, UT) and motion (100 Hz) (VICON, Englewood, CO) data were collected. For metabolic data collection, expired gasses were passed into the gas analyzer via a hose and mouthpiece. A nose plug was worn to force all expired gasses to enter the mouthpiece. Motion data were collected during the last two minutes of each walking trial, which is where steady-state metabolic responses also occurred.

2.3. Data analysis

Mean rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) over the last 2-min of each 6-min trial [9,16] were used to estimate average rate of energy consumption [17]:

$$\dot{E} = (3.9)\dot{V}O_2 + (1.1)\dot{V}CO_2 \quad (1)$$

where $\dot{E}$ is energy cost in kcal/min, and $\dot{V}O_2$ and $\dot{V}CO_2$ in L/min. $\dot{E}$ was converted to units of J/s and normalized to body mass. Metabolic cost was not normalized to any additional mass added to the body. We felt not accounting for the additional passive mass reflected best the real world metabolic consequences of walking with additional mass.

For spatiotemporal and kinematic measures, marker data were processed using VICON Nexus. Marker coordinate data were filtered using a 4th Order, recursive digital Butterworth filter with a cut-off frequency of 6 Hz. Joint kinematics were determined using the built-in plug-in-gait model in VICON Nexus. Velocities were derived using finite difference approximations.

Foot contact events (i.e., heel strike and toe-off) for each leg were visually identified during post-processing by a single researcher. This researcher identified heel strike as the first frame in which the heel marker stopped moving downwards. Toe off was identified as the first frame in which the toe marker began moving upwards. The foot contact events were then used to determine spatiotemporal measures during the trial, which included stance time, double support time, and swing time. Stride time was determined as the sum of stance and swing times for a given leg. Stride length was determined based on the walking velocity relationship:

$$\mathrm{SL} = V \times \mathrm{ST} \quad (2)$$

where SL represents stride length in m, V represents the walking velocity (1.5 m s^{-1}), and ST represents stride time in seconds.