RESEARCH ARTICLE

Inclined Weight-Loaded Walking at Different Speeds: Pelvis-Shoulder Coordination, Trunk Movements and Cost of Transport

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ABSTRACT. Although studied at level surface, the trunk kinematics and pelvis-shoulder coordination of incline walking are unknown. The aim of this study was to evaluate the speed effects on pelvis-shoulder coordination and trunk movement and the cost of transport (C) during unloaded and loaded (25% of body mass) 15% incline walking. We collected 3-dimensional kinematic and oxygen consumption data from 10 physically active young men. The movements were analyzed in the sagittal plane (inclination and range of trunk motion) and the transverse plane (range of shoulder and pelvic girdle motion and phase difference). The rotational amplitude of the shoulder girdle decreased with load at all speeds, and it was lower at the highest speeds. The rotational amplitude of the pelvic girdle did not change with the different speeds. The phase difference was greater at optimal speed (3 km.h⁻¹, at the lowest C) in the loaded and the unloaded conditions. The trunk inclination was greater with load and increased with speed, whereas the range of trunk motion was lower in the loaded condition and decreased with increasing speed. In conclusion, the load decreased the range of girdles and trunk motion, and the pelvis-shoulder coordination seemed to be critical for the incline walking performance.

Keywords: backpack, metabolic cost of incline walking, phase difference, slope, trunk coordination

Movements of the head, trunk, and pelvis occur in a coordinated manner to minimize variations in mechanical energy during walking (Van Emmerik & Wagenaar, 1996). Walking with load requires a different type of motion control compared to walking without load at level: The pelvic rotation is smaller during walking with load, resulting in a decrease in stride length and an increase in stride frequency and hip excursion (LaFiandra, Wagenaar, Holt, & Obusek, 2003; Martin & Nelson, 1986; Wagenaar & Beek, 1992). The trunk inclination is greater during walking with increasing load (Goh, Thambyah, & Bose, 1998; Hong & Cheung, 2003). The energy demand also changes because the walking metabolic rate is directly related to external load. Likewise, the cost of transport (C) is affected by the external load with the optimal speed (where the C is lowest) occurring independently of carriage load, around 4.5 km.hr⁻¹ (Bastien, Willems, Schepens, & Heglund, 2005; Saibene & Minetti, 2003).

On the other hand, incline reduces the optimal speed in comparison to level walking (Gomeñuka, Bona, da Rosa, & Peyré-Tartaruga, 2014). Postural adaptations are specific, and the control parameters are different during level and gradient walking. A positive gradient above 10% (6°) induces a progressively flexed posture of the hip, knee, and ankle at initial foot contact as well as a progressive forward tilt of pelvis and trunk. Thus, it is necessary to move the center of gravity ahead of the base of support to assist the forward propulsion of the body (Leroux, Fung, & Barbeau, 2002). The trunk movement and pelvis-shoulder coordination have been neither measured nor related to metabolic cost of walking during loaded and inclined conditions.

Alteration in the walking speed reflects systematic changes in temporal parameters, kinematics, and kinetics of the lower limb (Kavanagh, 2009). At each walking speed, there is an optimal stride frequency, corresponding to the freely chosen stride frequency, which minimizes the C (Saibene & Minetti, 2003). Changes in length and stride frequency are observed during the transport of loads and result, among other factors, in alterations in the coordination of the shoulder and the pelvis. The rotation of the pelvis in the transverse axis helps to increase the stride length (Wagenaar & Beek, 1992). Therefore, the load carriage is expected to increase the walking stride frequency as a consequence of reduction in the rotation of the pelvis and stride length.

The coordination between the rotation of the shoulder and the pelvis is dependent on the walking speed (Van Emmerik & Wagenaar, 1996). An increase in the walking speed is associated with a transition from a more in-phase relationship of the shoulder and the pelvis (rotating in the same direction at the same time) to a more out-of-phase relationship (rotating in opposite directions). To the best of our knowledge, the trunk coordination has not been investigated during walking with loads on slope terrain. At level walking, the speed affects the angular amplitude of the pelvis and the shoulder resulting in a better pelvis-shoulder coordination with increasing speed. Likewise, at low speeds, there is the trend for a lower pelvic rotation due to the shorter stride length (Taylor, Goldie, & Evans, 1999). Therefore, the aim of this study was to evaluate the effects of speed on the pelvis-shoulder coordination, trunk
movement, and C of 15% incline and loaded (backpack load, 25% of body mass [BM]) walking.

We hypothesized that the scapular and pelvic girdles would be in counter-rotation (out of phase, close to 180°) not just for higher speeds, as on level surface, but at all speeds due to the inevitable adjustments in postural control strategies. Recent study has found increased electrocortical activity in adults while walking on an incline compared with walking on the level (Bradford, Lukos, & Ferris, 2015). We also hypothesized that general oscillations of trunk would be lower at loaded condition as a consequence of the greater forward trunk tilt and, consequently, to control the metabolic cost of moving the loaded trunk during incline walking.

Methods

Subjects

Participants comprised 10 young healthy men 23.1 ± 2.9 years old, 1.78 ± 0.06 m tall, and 71.6 ± 6 kg BM, each carrying about 17.9 ± 1.5 kg (25% of BM) of load and all healthy, nonathlete undergraduates. All the subjects were informed about the study and signed an informed consent. This study was approved by the ethics committee of the Federal University of Rio Grande do Sul (Brazil).

Experimental Design

The present study was designed as observational. During the first visit, individuals were familiarized with all protocols, backpack, and treadmill. The second and third visits were conducted (randomized): walking with a loaded backpack (25% of BM) with a hip belt or walking without a backpack. The visits were separated by about 2–4 days. The five submaximal tests were randomized at each visit.

Data Collection

The subjects performed five different walking speeds (1, 2, 3, 4, and 5 km.h⁻¹), on the treadmill (BH Fitness, Explorer Pro Action, Vitoria-Gasteiz, Spain) at a 9° positive inclination under simultaneous metabolic and kinematic measurements.

In all tests, the heart rate (Polar, Kempele, Finland), end-tidal partial pressure of oxygen, end-tidal partial pressure of carbon dioxide, oxygen uptake (VO₂), carbon dioxide output, and ventilation minute (MEDGRAPHICS MGC, St. Paul, MN) were measured continuously. Besides, the respiratory exchange ratio was also monitored achieving values lower than one.

For each speed tested, the experiment began and ended with measurement of the standing VO₂ (6 min, at loaded and unloaded conditions). All trials lasted 6 min to allow for steady-state metabolic measurements. The rest time between tests was maintained until the VO₂ reached the resting values.

Marker-based kinematic data was collected with four cameras at 50 Hz sampling frequency (JVC GR-DVL 9800, Wayne, NJ). We registered the three-dimensional kinematics at the fourth minute in all walking tests synchronizing the video cameras using DVIDEOW 5.0 software (Dvideow movement analysis system, Laboratory of Biomechanics, Institute of Computing UNICAMP, Campinas, Brazil; Figueroa, Leite, & Barros, 2003).

For the kinematic variables, we used an 18-point anatomical model (Pontzer, Holloway, Raichlen, & Lieberman, 2009), with reflective markers placed on the fifth metatarsal, calcaneus, lateral malleolus, femoral epicondyle, greater trochanter, acromion, lateral epicondyle of the humerus, ulnar middle point-radius, and temporal bone, located on both sides of the body.

Kinematic Analysis

The leaning angle of the trunk refers to the angle, sagitally oriented, and formed by the line connecting the shoulders and the hips and the horizontal line passing through the hips. Values greater than 0° represent a forward lean, whereas values less than 0° represent backward leaning of the trunk. The range of trunk motion refers to the range of angular motion that was observed in one complete stride (Hong & Cheung, 2003).

The angular amplitude of the shoulder girdle and the pelvic angle were calculated as the difference between the maximum and the minimum angular position of the girdles, transversely oriented in the stride cycle (Taylor et al., 1999).

We determined the coordination pattern between the pelvic and shoulder girdles, investigating the discrete transition from counterclockwise to the clockwise rotation at each girdle transversely oriented. The difference between the discrete transitions of pelvic girdle rotation (t pelvis) and shoulder girdle rotation (t shoulder), and normalized by the stride period, was calculated as the phase difference (Pontzer et al., 2009):

\[
\text{Phase difference} = \frac{360° \times (t \text{ pelvis-t shoulder})}{\text{stride period}}
\]

(Equation 1.)

The in-phase pattern is characterized by values around 0° (i.e., pelvis and shoulder–thorax move concomitantly and in the same direction), and an out-of-phase pattern is characterized by values around 180° (i.e., pelvis and shoulder–thorax move in opposite directions).

For all variables analyzed, the data shown are the average results of 15 stride cycles (Figure 1). All kinematic variables were calculated to identify the orientation of the trunk in the global reference system. The cutoff frequency was determined separately for each test using the residual
analysis of the difference between filtered and unfiltered data (Winter, 2005) in a customized algorithm (LabView Version 10, National Instruments, Austin, TX).

Cost of Transport

The walking economy was denoted by the cost of transport, \( C \), expressed in J.kg\(^{-1}\).m\(^{-1}\). For that, we divided the net metabolic rate (gross — stand metabolic rate) by speed and, we converted oxygen milliliters to Joules regarding combustion enthalpy of substrates resulting from oxidation observed indirectly from respiratory exchange ratio (Péronnet & Massicotte, 1991).

Statistical Analysis

The data were assessed for normality using the Shapiro-Wilk test. All values are reported as mean and standard deviation. We used a two-way analysis of variance (ANOVA) for repeated measures to verify the interaction between speed and load. When we detected interaction between these variables (speed \( \times \) load), a one-factor
repeated measures ANOVA was performed to verify the main effect of the speeds (1–5 km.hr⁻¹) on the cost of transport and kinematics variables. We used the Bonferroni test to locate the difference. For comparison between the two load conditions (backpack and no backpack), we used paired t tests. Statistical significance was set at an alpha level of .05 (SPSS version 17).

**Results**

The kinematical and metabolic data showed a normal distribution. Figure 2 shows the differences between the walking with and without load. We found an interaction between load and speed (p = .05) and a greater range of pelvic girdle motion at low speeds during walking with load (Figure 2A).

The range of shoulder girdle motion remained lower at loaded condition across all speeds (p < .05). The differences varying from 17% at 1 km.hr⁻¹ to 44% at 4 km.hr⁻¹ speed (Figure 2B).

The sagittal inclination of the trunk was markedly higher at all speeds of walking with load compared to without load (Figure 2C), showing the critical influence of the load on the pattern of gradient walking. Although both conditions show an increase of trunk inclination in function of speed, there was an interaction between load and speed (p < .05), indicating that the backpack not only affects the trunk position but more intensively at higher speeds. On the other hand, the range of trunk motion was lower during walking with load at all speeds (Figure 2D).

The shoulder and pelvic girdles coordination are in an out-of-phase pattern for all speeds and load conditions at the 9° incline. Although the shoulder-pelvic coordination appears to be similar, the phase difference between the shoulder and the pelvis girdles was higher during walking without load (Figure 3). Interestingly, walking at incline adding a load of 25% of BM changed the coordination pattern of girdles from an anticipatory shoulder movement (at unloaded condition) to a delayed shoulder movement (at loaded condition) with respect to the pelvis movement.

Figure 4 reveals a U-shaped C-speed curve accompanied by an inverted U-shaped phase difference-speed curve. Specifically, the curves show that the lowest values of C with and without load were at 3 km.hr⁻¹ and that the highest values of the phase difference occurred at intermediate walking speeds. These findings were found in both loaded and unloaded conditions at inclined walking (Figure 4).

![Figure 2](image-url) **Figure 2.** Trunk movement adaptations in human walking to speed changes at the 9° incline, with and without 25% of body mass load. (A) The range of pelvic girdle motion (pelvic amplitude), (B) range of shoulder girdle motion (shoulder amplitude), (C) trunk inclination, and (D) range of trunk motion with the backpack (gray) and no backpack (black) at the five different speeds. Data shown as M ± SD. *p < .05, **p < .01, ***p < .001.
Discussion

Our results indicated significant differences in movement and control patterns of the trunk while walking with load compared to walking without the load on the incline. Differently of level walking, where the pelvic-shoulder coordination is in-phase at low speeds (Van Emmerik & Wagenaar, 1996), during incline walking the coordination pattern is out-of-phase across all speeds, independently of load condition. Moreover, the load in backpacks used here (25% of BM) appears to have a critical additional effect on movement patterns of the trunk on the incline, specifically with a more flexed trunk and, consequently, with a lower range of trunk motion (sagittally, and related to range of shoulder girdle motion).

Confirming our first hypothesis, the phase relation between pelvic and shoulder or thoracic rotations is out of phase across all speeds and load conditions during walking on the incline. Postural adjustments are necessary on inclines, for example, the total external momentum is increased due to inevitable upward movement of the swinging leg (Silverman, Wilken, Sinitski, & Neptune, 2012). Also, changes in foot placement, joint kinematics, and ground reaction forces will result in differences in the movement control patterns, even affecting the electrocortical activity (Bradford et al., 2015) during incline. Our findings indicate that the task of carriage load seems to be a major factor intensifying some postural adjustments on positive gradients.

The lowest $C$ of this study occurred at intermediate velocities close to 3 km.hr$^{-1}$ for both unloaded and loaded conditions. During level walking, the U-shaped $C$-speed curve is explained by the pendulum-like mechanism (Sai-bene & Minetti, 2003). It has been argued that at positive gradients, the metabolic cost of walking does not seem to be totally related to pendular mechanism, specifically at high speeds (Gomeñuka et al., 2014). Collectively, the trunk coordination and movement patterns seem to play a role in order to explain the metabolic cost. The trunk inclination increase with increasing speed at gradients and, therefore, trunk muscles are more activated with load and at inclines (Bobet & Norman, 1984; Pellegrini et al., 2015).

According to LaFiandra, Holt, Wagenaar, and Obusek’s (2002) model, the dynamic relationship during gait between the upper and the lower body may be modeled as two segments connected by a torsional spring. If we assume that the pelvis remains fixed, and the upper body rotates on it in the transverse plane, a sort of stored energy in the spring can contribute as an energy-saving mechanism in gradient. Increasing the range of girdles motion or the stiffness of the torsional spring, the amount of torque stored in the spring will increase. It was observed an increase in stiffness with increased walking speed, suggesting that a passive-elastic mechanism of the trunk may contribute substantially to human walking, especially with a larger trunk rotation (Kubo, Holt, Saltzman, & Wagenaar, 2006). LaFiandra et al.’s (2002) model, combined with the pendulum mechanism of walking (Cavagna, Thys, & Zamboni, 1976), could explain the metabolic optimization on incline walking.

The amplitude of the pelvic angle was lower during walking with load at slower speeds. Besides the effects on trunk movement aforementioned, the angular amplitude of the pelvis is classically one of the major determinants of gait (Saunders, Inman, & Eberhart, 1953) and has a good agreement with stride length and vertical displacement of...
the body center of mass (Kerrigan, Riley, Lelas, & Della Croce, 2001). On slopes, the role of pelvic rotation on metabolic cost via vertical whole-body movement is still unknown. Further research is needed to test the relationship between the energetics and mechanics to give a conclusive response on walking performance on the incline.

In agreement with the findings of Sharpe, Holt, Saltzman, and Wagenaar (2008), the subjects showed a trunk’s coordination pattern markedly different when using a loaded backpack with a hip belt, which contributed to a lower range of trunk motion. The trunk inclination seems to be affected directly by both load and gradient. Therefore, it may explain the greater magnitude of inclination found in the present study compared to that reported by Hong and Cheung (2003). Another study with children observed greater trunk forward lean and a lower range of motion in accordance with an increase in the load (Li, Hong, & Robinson, 2003), corroborating the findings in the present study where both the tilt and the angle increased as the amplitude of the trunk decreased in loaded walking. These data confirm the rationale that carrying a backpack modifies the natural posture and that this modification is accentuated in slopes. Therefore, the risk factors of back pain, postural discomfort, and lower back injuries are increased.

The angular amplitude of the trunk in the frontal plane is altered due to load carriage. In a comparative study of Nepalese porters and Caucasian mountaineers, Minetti, Formenti, and Ardigo (2006) reported that the Nepalese had a lower and more consistent oscillation of the trunk and lower C, which was explained by lower co-contractions. The trunk stability affects the C, as observed in Nepalese porters, suggesting that training using loads during walking helps to increase this stability. The present study found an increase in the C with load, in accordance with the study by Abe, Muraki, and Yasukouchi (2008), who found that the metabolic demand during loaded walking increases linearly with the load mass. Nevertheless, walking with loads decreases the range of trunk motion and increases the stability of the trunk, contributing to sustaining the lower C at an intermediate speed. The interlimb coordination remains unchanged adding loads on body segments at level walking (Donker, Daffertshofer, & Beek, 2005). Conversely, the backpack loading at gradient shows critical differences on coordination patterns of human walking.

A possible limitation in the present study design that could influence the analysis of the findings is that the assessments of coordination were performed during treadmill walking. Further study of trunk muscle activity related to coordination pattern during incline walking would also benefit from testing LaFiandra et al.’s (2002) model. Another limitation is that the present results are only related to a unique descriptor variable of trunk coordination. Because of other parameters as continuous relative phase and variability in relative phase, future researchers should extend the present findings to a wider look on trunk coordination pattern in incline walking.

**Conclusion**

The movement patterns analyzed were altered with loads of 25% BM during 9° incline walking. The shoulder rotation was influenced inversely by the increase in the load and the speed. The load in backpack affected the pelvis–shoulder coordination on the incline, changing the unloaded movement pattern from a shoulder-pelvis temporal sequence to pelvis-shoulder ones.

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