WALKING IN SIMULATED HYPER-GRAVITY

Stephen M Cain[1] and Daniel P Ferris[1]

[1]Human Neuromechanics Laboratory, The University of Michigan, Ann Arbor, MI, USA
E-mail: smcain@umich.edu

INTRODUCTION

The relationship between human walking mechanics and metabolic cost is remarkably elusive. Grabowski et al. (2005) used added mass and simulated reduced gravity to examine how bodyweight and body mass independently affect the metabolic cost of walking. They found that adding mass without bodyweight (via reduced gravity) resulted in about 45% of the increased metabolic cost found with just added mass. They concluded that normal load carriage increases metabolic cost due to both increasing forces to support bodyweight and increasing forces to redirect the center of mass at step-to-step transitions.

We studied humans walking in simulated increased gravity to determine if metabolic cost of walking in hyper-gravity would result in smaller increases in metabolic cost than load carriage. Because subjects in hyper-gravity would likely not experience the increased collision costs associated with added mass, we hypothesized that the metabolic cost of walking in hyper-gravity would be lower than the metabolic cost of walking with increased weight. In addition, we used inverse dynamics to determine if joint mechanical work increased in proportion to gravity.

METHODS

Three healthy adult subjects (1 male, 2 female, mean body mass 56.1 kg) walked at 1.25 m/s under five different gravity levels (1G, 1.1G, 1.2G, 1.3G, and 1.4G). The order of the trials was randomized and each trial lasted 7 minutes.

Hyper-gravity was simulated by applying a near-constant downward force to the subject using a custom designed hyper-gravity simulator (Fig. 1). We supplied force by stretching lengths of rubber tubing with a hand winch. The tubing was stretched far enough to make small length changes negligible, keeping tubing tension nearly constant. We transferred the force to the subject by connecting the tubing to aircraft cable, routing the cable through low friction pulleys, and attaching the cable to a belt worn by the subject. Each subject wore a backpack hip belt designed to comfortably transfer vertical loads to the pelvis without interfering with gait. The cable was attached to both the left and right sides of the hip belt to provide a balanced downward force. The cable providing the downward force to the right side was connected to the cable connected to the left side, allowing the subjects to move freely to the right and left without experiencing centering forces.

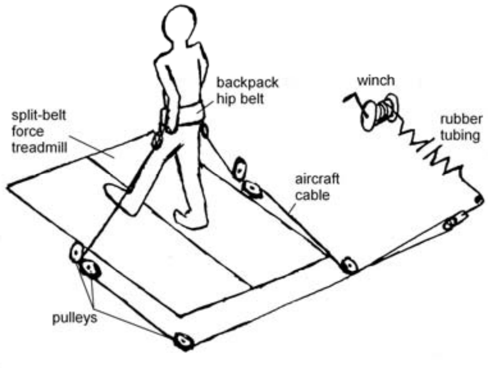

Figure 1: The hyper-gravity simulator.

We collected joint kinematics, electromyography (EMG), metabolic cost, and ground reaction forces while subjects walked on a custom split-belt force treadmill. We recorded electromyography (EMG) of 8 lower limb muscles. We calculated root-mean-squared (RMS) values for the EMG signals for stance phase. Using the kinematic and kinetic data, we used inverse dynamics to calculate joint moments, powers, and works. We used the Brockway (1987) equation to calculate metabolic rates and subtracted standing metabolic rate from each trial to determine net metabolic rate.

RESULTS AND DISCUSSION

Contrary to expectations, we found that the metabolic cost of walking in hyper-gravity was similar to the metabolic cost of walking with load carriage (Fig. 2). The respective sums of the positive and negative joint powers (ankle, knee, and hip together) increased proportionally with gravity (Fig. 3). However, the increased work was not distributed evenly across the joints. Positive work rates of the ankle and hip and negative work rate of the hip increased greater than gravity (a 40% increase in gravity resulted in a >40% increase in work rate). The work rate at the knee did not change. As gravity level increased, vastus medialis, vastus lateralis, and rectus femoris muscles showed increased activity just after heel strike and just before push off. EMG RMS of these muscles increased linearly with gravity (a 40% increase in gravity resulted in a 100% increase in RMS).

SUMMARY/CONCLUSIONS

The results indicate that increases in metabolic cost due to hyper-gravity cannot be explained by increases in joint work rates alone. It is likely that the cost of generating force to support body weight is significant during walking in hyper-gravity.

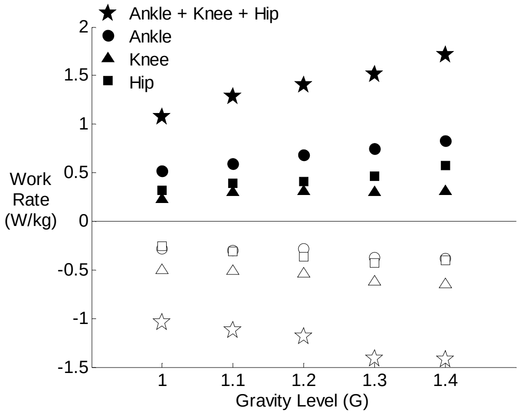

Figure 2: Average positive (filled symbols) and negative (unfilled symbols) work rates for the ankle, knee, and hip of both legs over one complete stride (left heel strike to left heel strike) for different levels of simulated gravity.

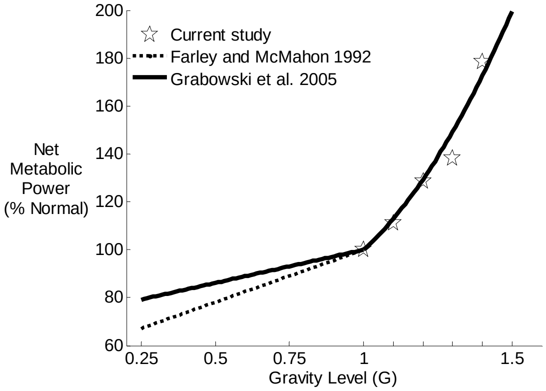

Figure 3: Net metabolic power (as a percentage of normal, 1G) versus gravity level. Results from Farley and McMahon (1992) and Grabowski et al. (2005) are included for comparison. The data from Grabowski et al. for gravity levels >1G are the metabolic cost of walking with load carriage, not the effect of only increased gravity.

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