EFFECT OF INCLINE ON WALKING MECHANICS, ENERGETICS AND NEUROMUSCULAR CONTROL

Amy Silder, Scott Delp and Thor Besier
1Stanford University, Stanford, CA, USA
2University of Auckland, Auckland, New Zealand
Email: silder@stanford.edu

INTRODUCTION

Identifying the relationship between mechanical work and metabolic cost is essential to improve our understanding of the mechanisms by which humans select various gait patterns. In recent years, muscle models have been refined to account for energy consumption [1,2] and used in conjunction with whole body simulations to estimate the metabolic cost of normal human walking [2,3]. Yet, our knowledge of different locomotion patterns, such as walking up an incline, is limited, primarily due to a lack of comprehensive experimental data. Such data would provide the foundation for deciphering the mechanical determinants of energetic cost. The purpose of this study was to systematically evaluate lower extremity kinematics, kinetics, muscle activities, and energetics as a function of surface incline.

METHODS

Thirteen healthy subjects (35±8y, 68±12kg, 1.77±0.10m) provided informed consent to participate in this study. Each subject completed three five-minute walking trials on a split belt instrumented treadmill (Bertec Corp.) at surface inclines of 0%, 5% and 10%. Subjects completed each trial at his/her preferred level ground walking speed (1.28±0.12m/s). Steady-state oxygen uptake was measured (K4b2, COSMED) and analyzed during the final minute of each condition.

Whole body kinematics (100Hz) and ground reaction forces (GRFs) (2000Hz) were measured over five strides using an eight-camera motion capture system (Vicon). A 31-degree of freedom whole body model was scaled to the size and mass of each subject [4]. A global optimization inverse kinematics routine was used to compute lower extremity joint angles. Inverse dynamics was then used to compute lower extremity joint moments and powers.

Muscle activities were measured on the left limb from the soleus, medial gastrocnemius, tibialis anterior, vastus medialis, vastus lateralis, rectus femoris, and the medial and lateral hamstrings. Electromyographic (EMG) signals were band-pass filtered (30-500Hz) and full wave rectified. Root mean square (RMS) activities were computed from the average signal across five gait cycles.

Oxygen consumption, spatiotemporal, kinematic, kinetic, and EMG data were compared across inclines using a one-way repeated measures ANOVA with significance set at p<0.05.

RESULTS

Oxygen consumption increased 40±8% (0 to 5%) and 31±6% (5 to 10%) with each increase in incline (p<0.01). No significant changes in stride length, stride frequency, or the magnitude of peak GRFs were detected. Peak hip flexion angle, stance and swing phase knee flexion angles and ankle plantarflexion angle all increased with incline (p<0.01) (Fig. 1).

During the first half of stance, the peak hip extension moment and power increased an average of ~16% and ~65% between 0% and 10% incline, respectively (p<0.01). At this same time, the peak knee extension moment decreased ~30% between 0% and 10% incline (p<0.01) (Fig. 1). During the second half of stance, the knee flexion moment increased ~58% across inclines (p<0.01). Knee power absorption and generation both increased with incline (p<0.01). Smaller, though significant changes were measured at the ankle, with the peak plantarflexion moment and power generation increasing ~14% and ~25%, respectively, from 0% to 10% incline (p<0.01) (Fig. 1).

RMS muscle activity increased with incline for the soleus, gastrocnemius, and medial and lateral hamstrings (p<0.05). All other muscles showed small, but insignificant increases in activity as incline increased.
DISCUSSION

Similar to observations made during inclined running, walking up an incline resulted a change in hip and knee joint function [5]. Although joint angles were similar approaching toe-off, increased incline resulted in a more anteriorly directed GRF, thereby dramatically altering joint moments. Most notably, the hip extensors took on a dominant role, with greater hip power generation as incline increased. The knee flexion moment increased throughout stance phase, and when coupled with a greater range of motion, energy absorption during the first half of stance and power production during the second half of stance both increased. These findings were supported by increased hamstring muscle activity.

Numerous factors contribute to the ~84% increase in oxygen consumption between 0% and 10% incline. A complete understanding of the interaction between the mechanical and metabolic changes cannot be inferred with an experimental approach alone [2]. Nevertheless, several observations can be made from the data presented here. In particular, the ankle plantarflexors have been shown to be the primary contributors to forward progression during level walking [2,6]. With increasing incline, we observed relatively larger changes in hip and knee power generation, compared to the ankle. Given that peak hip extension angles were similar across incline and elastic energy contributions at the hip derive primarily from stretching the hip flexors during late stance [7], the proximal shift in power likely results in less passive energy storage and return, compared to level walking. Furthermore, larger angular excursions across all joints necessitate higher average musculotendon velocities and therefore create the potential for higher energetic costs.

In conclusion, we have presented comprehensive data describing how incline alters neuromuscular control, energetic cost, and lower extremity joint kinematics and kinetics. Musculoskeletal modeling simulations using these data will aid in our understanding of how specific muscles contribute to these observed changes in joint kinetics and the increased energy cost of inclined walking.

REFERENCES


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