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Mechanical work performed by the individual legs during uphill and downhill walking

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ABSTRACT

Previous studies of the mechanical work performed during uphill and downhill walking have neglected the simultaneous negative and positive work performed by the leading and trailing legs during double support. Our goal was to quantify the mechanical work performed by the individual legs across a range of uphill and downhill grades. We hypothesized that during double support, (1) with steeper uphill grade, the negative work performed by the leading leg would become negligible and the trailing leg would perform progressively greater positive work to raise the center of mass (CoM), and (2) with steeper downhill grade, the leading leg would perform progressively greater negative work to lower the CoM and the positive work performed by the trailing leg would become negligible. 11 healthy young adults (6 M/5 F, 71.0 ± 12.3 kg) walked at 1.25 m/s on a dual-belt force-measuring treadmill at seven grades ($0, \pm 3, \pm 6, \pm 9^{\circ}$). We collected three-dimensional ground reaction forces (GRFs) and used the individual limbs method to calculate the mechanical work performed by each leg. As hypothesized, the trailing leg performed progressively greater positive work with steeper uphill grade, and the leading leg performed progressively greater negative work with steeper downhill grade ($p < 0.005$). To our surprise, unlike level-ground walking, during double support the leading leg performed considerable positive work when walking uphill and the trailing leg performed considerable negative work when walking downhill ($p < 0.005$). To understand how humans walk uphill and downhill, it is important to consider these revealing biomechanical aspects of individual leg function and interaction during double support.

1. Introduction

The motion of the body's center of mass (CoM) is well-characterized mechanically as an inverted pendulum during the single support phase of level-ground walking (Cavagna et al., 1977; Farley and Ferris, 1998). This analogy describes the conservative exchange between the kinetic and gravitational potential energies of the CoM during single support, requiring little external mechanical work from the legs. In contrast, considerable mechanical work must be performed to transition from one period of single support to the next (Donelan et al., 2002; Adamczyk and Kuo, 2009). At the end of single support, the CoM velocity is directed downward and forward. During double support, the collision of the leading leg with the ground dissipates mechanical energy. The trailing leg can replace this dissipated energy by generating mechanical power to restore and redirect the CoM velocity upward and forward. Thus, when walking over level-ground, the leading and trailing legs respectively perform substantial negative and positive external work simultaneously during double support. However, no study to date has investigated the work performed by the individual legs during uphill and downhill walking.[1]

Unlike level walking, humans must perform net positive work to walk uphill and net negative work to walk downhill in order to raise or lower the body's CoM with each step. Pioneering studies estimated the net positive or negative work performed from the minimum change in potential energy necessary to raise or lower the CoM (Margaria, 1938; Cotes and Meade, 1960). Later, Minetti et al. (1993) quantified mechanical work during uphill and downhill walking using the total mechanical energy change of the CoM, reporting and characterizing positive and negative work during a step. While valuable, these studies employed techniques that neglect the simultaneous positive and negative work performed by each of the individual legs during double support (Alexander, 1980). Donelan et al. (2002) developed the "individual limbs method" (ILM) to quantify this simultaneous mechanical work. In short, the ILM computes mechanical work using the velocity of the CoM and the separate forces exerted by the leading and trailing legs. Using the ILM,

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[1] Note that we use the common phrasing "work performed by the legs" throughout this manuscript, recognizing that the legs generate forces and it is these forces that perform mechanical work.

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Donelan et al. (2002) found that during level-ground walking, traditional calculations underestimate mechanical work by ~33%.

How does the mechanical work performed by the individual legs change to walk uphill or downhill? Gottschall and Kram (2006) showed that inverted pendulum exchange of mechanical energy is largely preserved during the single support phase of uphill and downhill walking. However, we believe that considerable mechanical work must be performed by the individual legs during double support. To walk uphill, humans presumably reduce the negative work performed by the leading leg and increase the positive work performed by the trailing leg to overcome gravity. In contrast, to walk downhill, humans presumably increase the negative work performed by the leading leg to resist gravity and decrease the positive work performed by the trailing leg. The dominant and distinct functions of the leading and trailing legs (braking and propulsion, respectively) could remain the same when walking uphill and downhill. Indeed, other studies have demonstrated that uphill walking is characterized by greater peak propulsive and smaller peak braking ground reaction forces (GRFs), and downhill walking is characterized by greater peak braking and smaller peak propulsive GRFs exerted by the individual legs (Kuster et al., 1995; Redfern and DiPasquale, 1997; Gottschall and Kram, 2006; Lay et al., 2006; McIntosh et al., 2006).

Our goal was to quantify the mechanical work performed by the individual legs during uphill and downhill walking at various grades. We hypothesized that during double support, (1) with steeper uphill grade, the negative work performed by the leading leg would become negligible and the trailing leg would perform progressively greater positive work to raise the CoM, and (2) with steeper downhill grade, the leading leg would perform progressively greater negative work to lower the CoM and the positive work performed by the trailing leg would become negligible. To test these hypotheses, we had subjects walk at a steady speed on a dual-belt, force-measuring treadmill on the level and at a range of uphill and downhill grades.

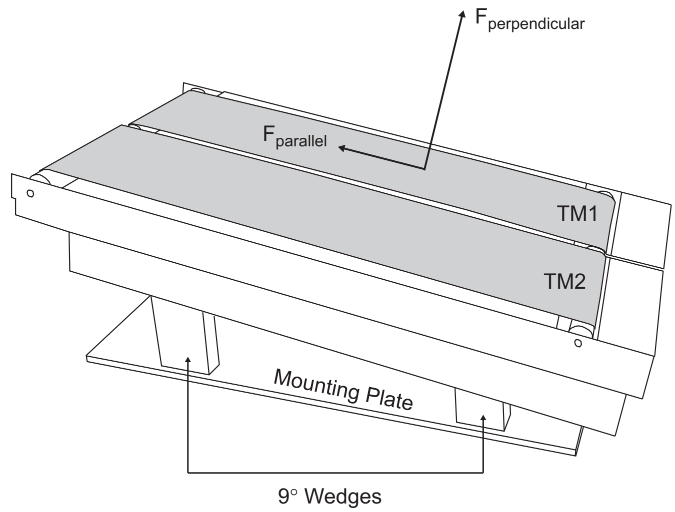

Fig. 1. Dual-belt force measuring treadmill mounted at 9°. A force platform mounted under treadmill TM1 recorded the perpendicular, parallel, and medial–lateral components of the ground reaction force produced by a single leg. The inner edges of the left and right treadmill belts were separated by less than 2 cm.

2. Methods

2.1. Subjects

Twelve healthy young adults volunteered. All were experienced treadmill users. Subjects gave written informed consent before participating as per the University of Colorado Institutional Review Board. Because of a measurement error, we successfully collected data for eleven young adult subjects (6 M/5 F, mean ± standard deviation, age: 25.7 ± 4.5 years; height: 1.76 ± 0.10 m; mass: 71.0 ± 12.3 kg).

2.2. Experimental protocol

Subjects completed experimental sessions on four separate days. At the start of each session, subjects walked on a motorized treadmill (model 18–60, Quinton Instruments, Seattle, WA) calibrated to 1.25 m s^{-1} and level for 5 min to warm-up. Subjects then walked at 1.25 m s^{-1} for 2 min on a dual-belt force-measuring treadmill, either level, or both uphill and downhill at one of three grades (3°, 6°, 9°; i.e., 5.2%, 10.5%, 15.7%).

2.3. Ground reaction forces

Previously, Gottschall and Kram (2005) mounted one side of our force-measuring treadmill (Kram et al., 1998) on custom-made aluminum wedges fixed at 3°, 6°, and 9° to study sloped running mechanics. To measure individual foot ground reaction forces (GRF), we constructed a second set of these wedges to angle both sides of the treadmill in parallel (Fig. 1). A force platform (ZBP-7124-6-4000; Advanced Mechanical Technology, Inc., Watertown, MA) secured under one side of the dual-belt treadmill recorded the GRF components perpendicular, parallel, and lateral to the treadmill surface. We changed the treadmill belt velocity to allow subjects to walk both uphill and downhill at each determined grade. We recorded right leg GRFs while the subjects walked uphill and left leg GRFs while the subjects walked downhill.

We collected 30 s of GRF data at 1000 Hz during each walking trial (Motion Analysis Corp., Santa Rosa, CA). We digitally filtered the ground reaction forces using a recursive fourth-order Butterworth low-pass filter with a cutoff frequency of 20 Hz. We determined the timing of gait cycle events (heel-strikes and toe-offs) using a 50-N threshold for the perpendicular GRFs and computed the average GRF profiles over 15 consecutive strides per condition. Assuming symmetry (Seeley et al., 2008), we phase-shifted the stride averaged GRF data by 50% and reversed the polarity of the lateral forces to emulate the forces produced by the contralateral leg. The identified gait cycle events provided the average timing of single and double support within a stride, and the average stride frequency (SF) and stance time (t_{stance}).

2.4. Individual limb work

To calculate the external mechanical work performed on the CoM by each leg (Donelan et al., 2002), we first calculated the instantaneous CoM velocity in each direction (perpendicular, parallel, and lateral to the treadmill surface) by integrating the whole body CoM accelerations with respect to time and adding integration constants adjusted for hill locomotion (Cavagna, 1975).

$$v_{z,CoM} = \int \frac{F_{z,res} - mg\cos\theta}{m} dt \quad (1)$$

$$v_{y,CoM} = \int \frac{F_{y,res} - mg\sin\theta}{m} dt \quad (2)$$

$$v_{x,CoM} = \int \frac{F_{x,res}}{m} dt \quad (3)$$

In Eqs. (1)–(3), F_{res} is the resultant GRF from both legs, v_{CoM} is the velocity of the CoM, and the subscripts z, y, and x denote directions perpendicular, parallel, and lateral to the treadmill surface, respectively. Also, θ is the treadmill grade, with uphill grades positive and downhill grades negative. We calculated the constants of integration by knowing that the average parallel velocity was equal to the nominal treadmill velocity, and that the average perpendicular and lateral velocities were zero.

We determined individual limb mechanical power as the dot product of the CoM velocity and the individual limb GRFs (Donelan et al., 2002). Fig. 2 displays these mechanical power constituents (CoM velocity and GRFs) during level, uphill, and downhill walking. We then calculated double support positive (W^{+}_{ILM}) and negative (W^{-}_{ILM}) individual limb work by integrating individual limb power with respect to time, restricting the integral to the intervals during double support over which the integrand was positive (POS) or negative (NEG), respectively.

$$P_{ds,trail} = \vec{F}_{trail} \cdot \vec{v}_{CoM} = F_{z,trail} v_{z,CoM} + F_{y,trail} v_{y,CoM} + F_{x,trail} v_{x,CoM} \quad (4)$$

$$P_{ds,lead} = \vec{F}_{lead} \cdot \vec{v}_{CoM} = F_{z,lead} v_{z,CoM} + F_{y,lead} v_{y,CoM} + F_{x,lead} v_{x,CoM} \quad (5)$$

$$W^{+}_{ILM} = \int_{POS} P_{ds,trail} dt + \int_{POS} P_{ds,lead} dt \quad (6)$$

$$W^{-}_{ILM} = \int_{NEG} P_{ds,trail} dt + \int_{NEG} P_{ds,lead} dt \quad (7)$$