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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, ± 3, ± 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.

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}).

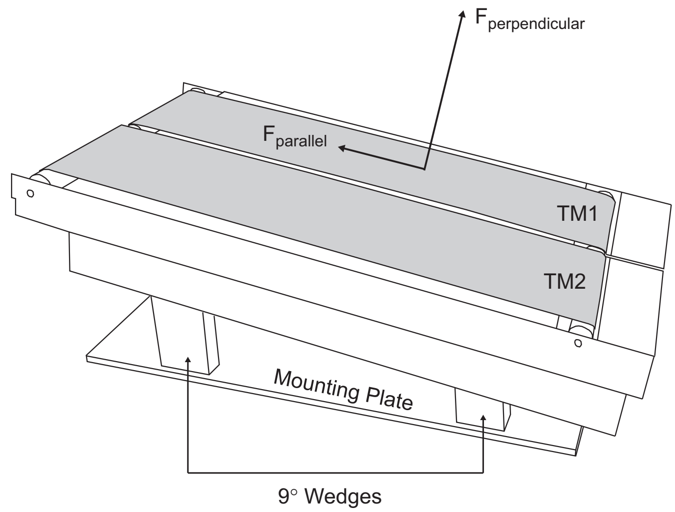

Fig. 1. Dual-belt force measuring treadmill mounted at 9°. A force platform mounted under treadmill TM1 recorded the perpendicular, parallel, and medial–lateral components of the ground reaction force produced by a single leg. The inner edges of the left and right treadmill belts were separated by less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

2.4. 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).

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

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

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

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.

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

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

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

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

In these equations, $\vec{F}_{trail}$ and $\vec{F}_{lead}$ are the ground reaction forces produced by the trailing and leading legs during double support, respectively. $P_{ds,trail}$ and $P_{ds,lead}$ are the double support mechanical powers generated/absorbed by the trailing and leading legs, respectively. Additionally, we computed positive and negative individual limb mechanical work for single support and over a complete step using similar methods but considering also the GRF exerted during single support, restricting these integrations to the time intervals of interest. Finally, for comparison with prior research (Margaria, 1938; Minetti et al., 1993), we calculated the positive (W^+_{CLM}) and negative (W^-_{CLM}) combined limbs mechanical work by considering only the resultant GRF from both legs.

$$W^+_{CLM} = \int_{POS} (\vec{F}_{res} \cdot \vec{v}_{CoM}) dt \tag{8}$$

$$W^-_{CLM} = \int_{NEG} (\vec{F}_{res} \cdot \vec{v}_{CoM}) dt \tag{9}$$

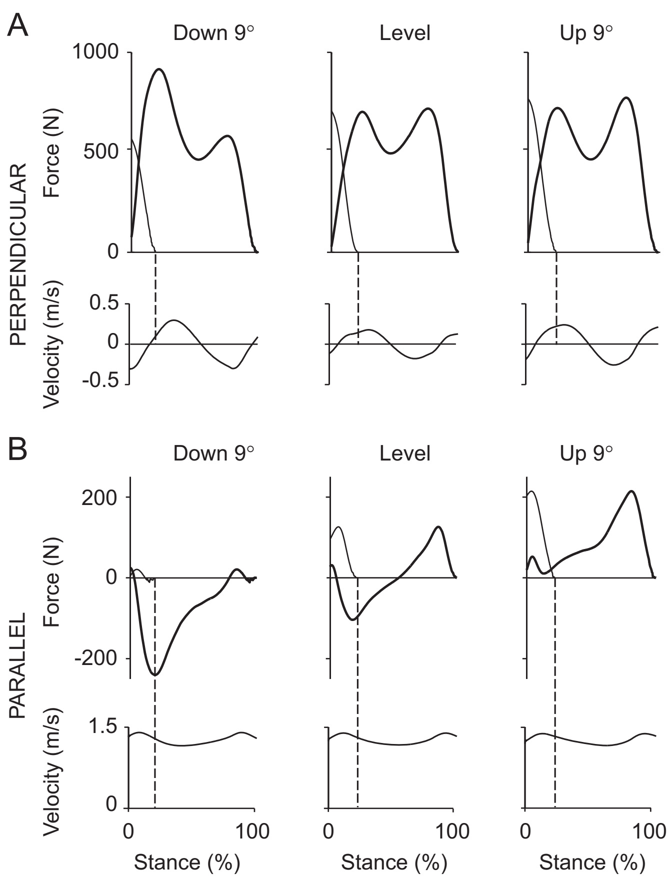

Fig. 2. Average perpendicular (A) and parallel (B) ground reaction forces (GRFs) and center of mass velocities during the stance phase of level, uphill (+9°), and downhill (−9°) walking. Vertical dashed lines indicate the instant of trailing leg toe-off. During double support, thick lines represent the leading leg GRFs and thin lines represent the trailing leg GRFs.

2.5. Statistical analysis

We calculated mean values of stride frequency, stance time, and all mechanical variables over 15 consecutive strides per subject. A repeated measures ANOVA tested for significant main effects of grade with a criterion of $p<0.05$. When a significant main effect was found, we performed post-hoc comparisons with a Bonferroni adjusted level of significance (0.05/10 = 0.005). To assess how uphill and downhill walking differed from level walking, planned post-hoc contrasts were focused between level and all uphill and downhill walking conditions. We evaluated the difference between individual limbs (W_{ILM}) and combined limbs (W_{CLM}) mechanical work performed over a stride at each grade using paired-samples t-tests and a $p<0.05$ criterion.

3. Results

We observed prominent, and progressive shifts in the functions of the individual legs with uphill and downhill grade. Our results confirmed that when walking over level ground, the leading and trailing legs simultaneously absorb and generate mechanical power during double support, respectively (Table 1, Fig. 3). In contrast, the leading and trailing legs *both* contributed progressively more to power generation with steeper uphill grade and to power absorption with steeper downhill grade. Stride frequency (p=0.20, 0.27, 0.64) and stance time (p=0.07, 0.02, 0.17 for +3, +6, +9°, respectively) during uphill walking were not significantly different from level walking (Table 2). Compared to level walking, subjects took modestly faster strides and spent less time in stance when walking downhill at grades steeper than 3° ($p<0.005$).

3.1. Uphill walking

The negative work performed by the leading leg during double support diminished with steeper uphill grade (decreased by 98% at +9°) and the trailing leg performed 62% greater positive work at +9° (W^+_{trail}: mean ± s.d., 0.21 ± 0.03 at 0° vs. 0.34 ± 0.05 J/kg/step at +9°, $p<0.005$) (Fig. 4A). Unlike level walking, the *leading* leg performed considerable positive work during double support at each uphill grade (W^+_{lead}: 0.01 ± 0.01 at 0° vs. 0.14 ± 0.04 J/kg/step at +9°, $p<0.005$). In fact, when walking up 9°, the leading leg accounted for 28% of the double support positive work. Single support positive work increased progressively from 0.07 ± 0.03 J/kg/step during level walking to 0.61 ± 0.06 J/kg/step at +9° ($p<0.005$) (Fig. 4B). The total individual limb positive work performed over a step increased by 276% with steeper uphill grade, from 0.29 ± 0.03 J/kg/step during level walking to 1.09 ± 0.10 J/kg/step at +9° ($p<0.005$) (Fig. 4C). The corresponding negative work decreased by 93%.

3.2. Downhill walking

The leading leg performed 255% greater negative work at −9° (W^-_{lead}: −0.09 ± 0.03 at 0° vs. −0.32 ± 0.06 J/kg/step at −9°, $p<0.005$) and the positive work performed by the trailing leg diminished with steeper downhill grade (decreased by 98% at −9°) (Fig. 4A). Unlike level walking, the *trailing* leg performed

Table 1
Mean (s.d.) values of double support individual limb mechanical work per step (J/kg/step).

		−9°	−6°	−3°	0°	3°	6°	9°
W^+	Trail	0.00 (0.01)	0.00 (0.00)	0.06 (0.02)	0.21 (0.03)	0.21 (0.05)	0.29 (0.06)*	0.34 (0.05)*
	Lead	0.00 (0.00)	0.00 (0.00)	0.02 (0.01)	0.01 (0.01)	0.02 (0.02)*	0.13 (0.04)*	0.14 (0.04)*
W^-	Trail	−0.10 (0.04)*	−0.08 (0.03)*	−0.01 (0.01)*	0.00 (0.00)	−0.01 (0.01)	0.00 (0.00)	0.00 (0.00)
	Lead	−0.32 (0.06)*	−0.22 (0.04)*	−0.13 (0.03)*	−0.09 (0.03)	−0.01 (0.01)	0.00 (0.00)	0.00 (0.00)

Asterisks (*) indicate significantly greater than level walking ($p<0.005$).

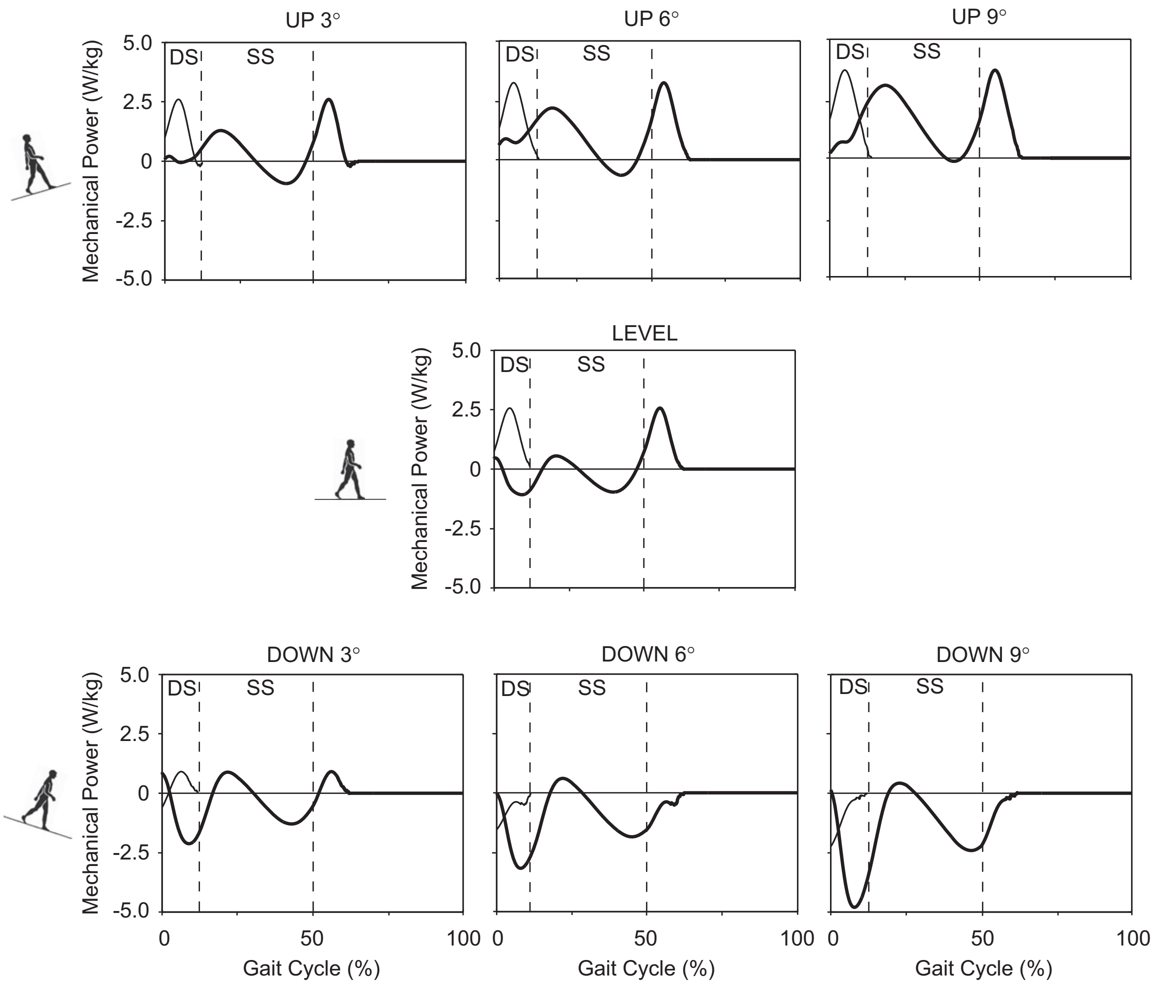

Fig. 3. Average individual limb mechanical power over a complete gait cycle normalized to body mass. Vertical dashed lines indicate the periods of double support (DS) and single support (SS) during the stance phase. During double support, thick lines represent leading leg mechanical power and thin lines represent trailing leg mechanical power.

Table 2
Mean (s.d.) values of stride frequency and stance time across grades.

	−9°	−6°	−3°	0°	3°	6°	9°
SF (Hz)	1.00 (0.07)*	0.97 (0.07)*	0.94 (0.07)	0.94 (0.07)	0.92 (0.07)	0.93 (0.07)	0.93 (0.07)
t_{stance} (s)	0.60 (0.03)*	0.62 (0.03)*	0.64 (0.03)	0.66 (0.03)	0.68 (0.07)	0.67 (0.07)	0.67 (0.07)

Asterisks (*) indicate significant difference from level walking.

considerable negative work during double support at each downhill grade (W^{-}_{trail}: $< -0.01 \pm 0.01$ at 0° vs. -0.10 ± 0.04 J/kg/step at −9°, $p < 0.005$). When walking down 9°, the trailing leg accounted for 24% of the double support negative work. Single support negative work increased progressively from -0.17 ± 0.04 J/kg/step during level walking to -0.57 ± 0.06 J/kg/step at −9° ($p < 0.005$) (Fig. 4B). The total individual limb negative work performed over a step increased by 283% with steeper downhill grade, from -0.26 ± 0.03 J/kg/step during level walking to -0.99 ± 0.07 J/kg/step at −9° ($p < 0.005$) (Fig. 4C). The corresponding positive work decreased by 84%.

3.3. ILM vs. CLM mechanical work

Similar to Donelan et al. (2002), we found that the combined limbs method underestimated the positive and negative external work performed over a step during level walking by 25% and 28%, respectively ($p < 0.05$) (Table 3). When walking uphill or downhill at 3°, the leading and trailing legs respectively performed some simultaneous negative and positive work during double support. Thus, the combined limbs method also underestimated the external work performed over a step when walking at ±3° ($p < 0.05$). The magnitudes of mechanical work calculated using the ILM and CLM converged at uphill and downhill grades steeper than ±3°.

4. Discussion

As hypothesized, with steeper uphill grade, the negative work performed by the leading leg during double support became negligible and the trailing leg performed progressively greater positive work. Also as hypothesized, with steeper downhill grade, the leading leg performed progressively greater negative work during double support and the positive work performed by the trailing leg became negligible. More remarkably, unlike the double support phase of level-ground walking, the leading leg performed considerable positive work to walk uphill and the trailing leg performed considerable negative work to walk downhill. Our findings reveal that in healthy human walking, during double support both legs contribute progressively more to power generation with steeper uphill grade and to power absorption with steeper downhill grade.

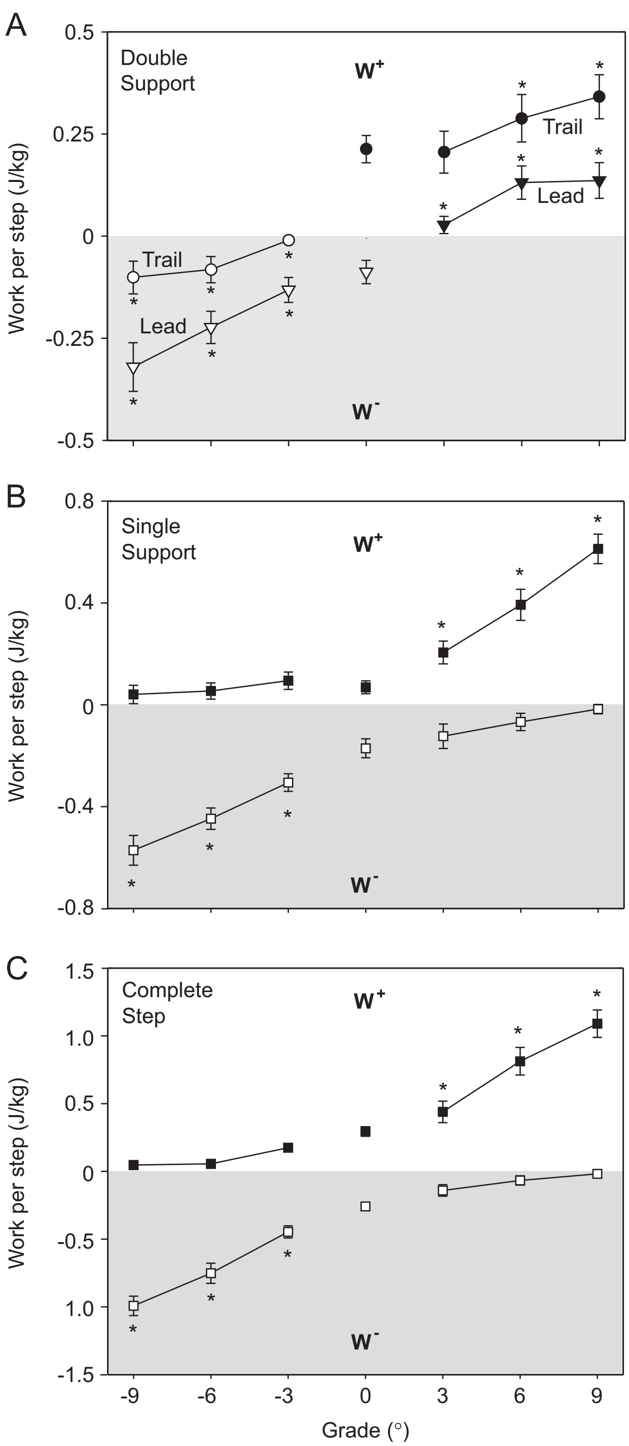

Fig. 4. Average (standard deviation) positive (W^+) and negative (W^-) individual limb external mechanical work performed (A) by the trailing and leading legs during double support, (B) during single support, and (C) over a complete step normalized to body mass. Double support negative and positive work became negligible with steeper uphill and downhill grade, respectively, and are omitted for clarity (see Table 1 for values). Symbols distinguish mechanical work performed by the leading (triangles) and trailing (circles) legs during double support from that performed during single support or summed over a complete step (squares). Asterisks (*) indicate significantly greater than level walking ($p < 0.005$).

We found general agreement between our findings and those reported previously for level-ground walking (Donelan et al., 2002). In the present study, the leading and trailing legs respectively performed greater than 99% of the negative work and 94% of the positive work performed during double support. As discussed previously (Donelan et al., 2002), this follows from the substantial contribution of the opposing parallel forces during double support to the mechanical power generated and absorbed by the individual legs. However, this is not the case during the double support phase of uphill and downhill walking.

Unlike level walking, the individual legs do not simultaneously exert large opposing parallel forces when walking at uphill or downhill grades steeper than $\pm 3^\circ$ (e.g., Fig. 2). With steeper uphill grade, the leading and trailing legs both exert progressively greater propulsive forces during double support. As a result, we find that across the range of uphill grades from $+3^\circ$ to $+9^\circ$, the leading leg performs 11–31% of the double support positive work to walk uphill, assisting the trailing leg in raising the CoM with each step. With steeper downhill grade, although the parallel velocity of the CoM is relatively large compared to the perpendicular velocity, the parallel force exerted by the trailing leg becomes negligible. Further, compared to level walking, the perpendicular CoM velocity remains negative for a greater proportion of double support when walking downhill. The relatively large perpendicular force exerted by the trailing leg and the negative perpendicular CoM velocity contribute to the trailing leg absorbing considerable mechanical power during downhill walking. Thus, we find that across the range of downhill grades from -3° to -9°, the trailing leg performs 7–27% of the double support negative work to walk downhill, assisting the leading leg in lowering the CoM with each step.

Previous studies of the mechanical work performed during uphill and downhill walking considered only the summed contribution of both legs to raise and lower the CoM (Margaria, 1938; Cotes and Meade, 1960; Minetti et al., 1993). Here, we used the ILM to uncover additional biomechanical aspects of leg function during uphill and downhill walking. However, these new findings neither contradict nor invalidate earlier seminal studies of uphill and downhill human locomotion. As during level walking, the traditional combined limbs method significantly underestimates the performance of mechanical work when the individual legs simultaneously perform positive and negative work during double support. But, at grades steeper than $\pm 3^\circ$, the calculated magnitude of external work performed over a complete step using the CLM coincides with ILM measures. Thus, the leading and trailing legs only perform simultaneous positive and negative work at very modest uphill and downhill grades.

One possible limitation of our study is that the total mechanical work performed on the body includes internal work performed to accelerate and decelerate the limbs relative to the CoM is not quantified by the ILM (Cavagna and Margaria, 1966). However, Minetti et al. (1993) found that internal work is largely invariant with uphill and downhill grade and should not influence the interpretation of our findings. A more notable limitation of our study is that the actual work performed by muscles cannot be directly inferred from measures of external mechanical work. Further, we measured the GRF exerted by a single leg and computed individual limb work during double support by assuming symmetry. Other authors have confirmed the bilateral symmetry of GRF measurements during walking (Seeley et al., 2008; Burnett et al., 2011). Finally, in this study we emphasized the period of double support as a first examination of the step-to-step transition during uphill and downhill walking. However, as

Table 3
Mean (s.d.) values of ILM vs. CLM mechanical work per step (J/kg/step).

		−9°	−6°	−3°	0°	3°	6°	9°
W^+	ILM	0.05 (0.03)	0.06 (0.03)	* 0.17 (0.03)	* 0.29 (0.03)	* 0.44 (0.08)	0.81 (0.10)	1.09 (0.10)
	CLM	0.04 (0.04)	0.05 (0.03)	0.11 (0.03)	0.22 (0.04)	0.43 (0.09)	0.81 (0.10)	1.09 (0.10)
W^-	ILM	−0.99 (0.07)	−0.75 (0.07)	* −0.45 (0.04)	* −0.26 (0.03)	* −0.14 (0.04)	−0.07 (0.03)	−0.02 (0.02)
	CLM	−0.99 (0.08)	−0.75 (0.07)	−0.38 (0.05)	−0.19 (0.04)	−0.13 (0.05)	−0.07 (0.03)	−0.02 (0.02)

ILM: Individual limbs method; CLM: Combined limbs method.
Asterisks (*) indicate significant difference between ILM and CLM ($p < 0.05$).

Adamczyk and Kuo (2009) recently demonstrated in level walking, redirecting the CoM velocity during the step-to-step transition begins before and ends after double support. Further analysis could characterize the CoM velocity redirection during the step-to-step transition of uphill and downhill walking.

In summary, our findings reveal that for the double support phase of walking, both the leading and trailing legs simultaneously contribute progressively more to power generation with steeper uphill grade and to power absorption with steeper downhill grade. We conclude that during double support (1) the leading leg performs positive work during uphill walking, assisting the trailing leg to raise the CoM with each step and (2) the trailing leg performs negative work during downhill walking, assisting the leading leg to lower the CoM with each step.

Conflict of interest statement

The authors have no conflicts of interest to disclose.

Acknowledgments

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