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The relative contributions of sagittal, frontal, and transverse joint works to self-paced incline and decline slope walking

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ABSTRACT

Positive and negative work are generated at the lower limb joints in order to locomote over various terrains. Joint work quantifies the changes in energy that are necessary to adapt gait to environmental demands. The aim of this study was to quantify 3D joint work at the hip, knee, and ankle during slope walking. Work was calculated for ten males (23.9 ± 1.1 years) walking at a self-selected speed on inclines and declines (−20, −12, −6, 0, 6, 12, 20 degrees). Sagittal positive work significantly increased at the hip, knee, and ankle for incline walking (for example, hip positive work increased 153%, 280%, and 453% for 6, 12, and 20 degrees, respectively; knee and ankle positive work also increased) ($p \le 0.05$), in order to raise and propel the body forward. Sagittal negative work increased significantly at the hip, knee and ankle for decline walking (for example, knee negative work increased 193%, 355%, and 496% for −6, −12, and −20 degrees, respectively; hip and ankle negative work also increased) ($p \le 0.05$), in order to control body descent. These substantial changes in work will be especially challenging for people with compromised strength due to age and disease. Furthermore, changes in work were not limited to the sagittal plane: 46% of the total hip joint work occurred in the frontal and transverse planes for six degree decline walking. Thus, decline walking placed greater demands on the hip ab/adductors and rotators, and this may be related to the greater risk of falls observed for descent versus ascent.

1. Introduction

More than 30% of the population aged above 65 in the USA falls at least once during a year (Centers for Disease Control Prevention, 2006). The risk of falling is increased when facing increased locomotor challenges such as stairs and slopes (Honeycutt and Ramsey, 2002). Incline walking is inevitable in daily living and places more demands on the locomotor system than level walking (Hong et al., 2014; Lay et al., 2006; Leroux et al., 2002; Sheehan and Gottschall, 2012). Walking up slopes has a higher risk of falling than walking up stairs with a similar incline (Sheehan and Gottschall, 2012), and increased joint loading when walking down slopes may result in pain or injuries (Schwameder, 2004). Since it is impractical to remove slopes from the community, it is important to understand how gait is adapted to accommodate slopes.

Gait analysis of slope walking has been studied extensively, with measures ranging from spatiotemporal measures (e.g. Sun et al. (1996)) to 3D kinetics (e.g. Silverman et al. (2012)). In general, while the support moment increased for both incline and decline walking, the joint moment patterns were different for the two slope directions (Lay et al., 2006). Furthermore, angular momentum is more tightly controlled on declines, likely due to higher risk of falling (Silverman et al., 2012). Many slope studies have utilized treadmills (Franz et al., 2012; Khandoker et al., 2010; Kimel-Naor et al., 2017; Ortega and Farley, 2015) – which results in a fixed speed – but kinetic differences have been noted between treadmill slopes and overground slopes (Lee and Hidler, 2008; Riley et al., 2007). Gait adaptations to overground slopes during self-paced walking have yet to be adequately characterized (Kimel-Naor et al., 2017).

Kinetic analyses of slope walking have largely been limited to 2D analyses, with the following exceptions: 3D external moments and joint moments (Silverman et al., 2012), and 3D total joint power (McIntosh et al., 2006). As expected, the majority of the work is in the sagittal plane during slope walking, but the 3D individual joint powers and work have not been fully identified. In the frontal plane, the ankle and hip moments act to control the trunk and pelvis medial-lateral motion, and these joint powers are likely important contributors to slope walking. For example, during level

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walking, hip joint work in the frontal plane contributes 23% of the total hip work in order to control the pelvis and the trunk against gravitational forces (Eng and Winter, 1995). The demand against gravitational forces will be increased in decline walking and hip frontal work will be especially important in controlling the pelvis and trunk against this higher demand. Furthermore, it is expected that hip frontal powers will be an important contributor for generating energy during incline walking. Quantification of 3D joint work during slope walking will provide new knowledge regarding control of locomotion, and may lead to new insights regarding the cause of falls, rehabilitation approaches, prosthetic design, and control of biped robots.

The purpose of this study is to quantify the 3D joint work, including positive and negative work, during incline and decline, and to quantify the contribution of each plane to the total work done at each joint. We hypothesized that the sagittal joint work will be modified on slopes with increased positive work for incline and increased negative work for decline walking. We hypothesized that the sagittal work will provide the majority of the total work. We also hypothesized that frontal hip work will contribute at least 30% of the total hip work in decline walking.

2. Methods

2.1. Participants

Ten healthy young adults (10 males; 23.9 ± 1.1 years; 67.64 ± 4.76 kg; 175 ± 4.35 cm), without any known impairments that might influence locomotion, volunteered for the study. Each participant signed an informed consent form approved by the Institutional Review Board of Beijing Sport University.

2.2. Protocol

Twenty-nine retroreflective markers were placed according to a modified Helen Hayes Marker Set (Vaughan et al., 1999). Five practice trials and three walking trials were completed for each gradient (+20°, +12°, +6°, 0°, −6°, −12°, −20°), providing a range of challenge that is similar to previous research (e.g. Alexander and Schwameder (2016), Kawamura et al. (1991), Lay et al. (2006), Redfern and DiPasquale (1997)). The level condition was completed first, and the remaining six conditions were performed in block randomized order. Participants walked at a self-selected speed. The force plate (Kistler 9281CA, Switzerland) was mounted on vertical struts (Lay et al., 2005) and placed in the center of the 3.2 m walkway. The walkway was framed with rigid aluminum and surfaced with plywood. A scissor-lift changed the height of one end of the walkway (Fig. 1) until the desired angle was attained. The angles were later confirmed to be within ±0.5 degrees of the desired angle with the motion analysis system. If foot contact with the force platform was incomplete, or if the participant targeted the platform, the trial was repeated. The ground reaction forces (GRF) were sampled at 1000 Hz and kinematic data were sampled at 200 Hz using an 8 camera 3D Optical Capture system (Motion Analysis Raptor-4, USA).

Fig. 1. The walkway set-up.

2.3. Data processing

For each gradient, the force plate was digitized in Cortex (version 2.6, Motion Analysis Corporation, Santa Rosa, CA), and the software transformed the GRFs of the force plate to align with the global reference system. The kinematic data were filtered using a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency of 8 Hz in Cortex, and GRF data were filtered using a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency of 15 Hz in Matlab (version 9.0, The MathWorks, Inc., Natick, MA) (Bisseling and Hof, 2006; Hong et al., 2015). Gait events were identified as follows: First right heel contact and toe-off were identified with the vertical GRF (10 N threshold), and second right heel contact was identified visually. Spatiotemporal measures of stride length, cadence, and speed were calculated from first to second right heel contact. Joint angles were calculated with the neutral standing position representing 0 degrees for each joint, and the joint coordinate systems were set according to ISB definitions (Wu and Cavanagh, 1995; Wu et al., 2002). Joint moments were calculated according to the methods of Vaughan et al. (1999) and Winter (1980) and normalized to body mass. Joint powers were calculated as the dot product of the joint angular velocities and joint moments (Eng and Winter, 1995). Positive and negative joint work (PJW and NJW) indicate energy generation and absorption, respectively (Winter, 1991), thus PJW and NJW were calculated by integrating the power curves over one stride (Fig. 2) for each trial as follows

$$\mathbf{PJW} = \int power\ dt \text{ when power was positive (hatched region in Fig. 2)} \quad (1)$$

$$\mathbf{NJW} = \left| \int power\ dt \right| \text{ when power was negative (dotted region in Fig. 2)} \quad (2)$$

3D joint work was calculated (Eng and Winter (1995)) as follows

$$\mathbf{3D\_PJW} = \mathbf{PJW}\ \text{sagittal} + \mathbf{PJW}\ \text{frontal} + \mathbf{PJW}\ \text{transverse} \quad (3)$$

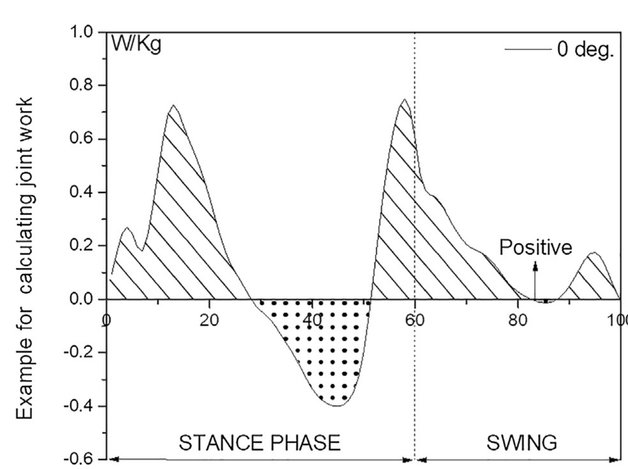

Fig. 2. Exemplar joint power to demonstrate positive work (area of hatched region) and negative work (dotted region).

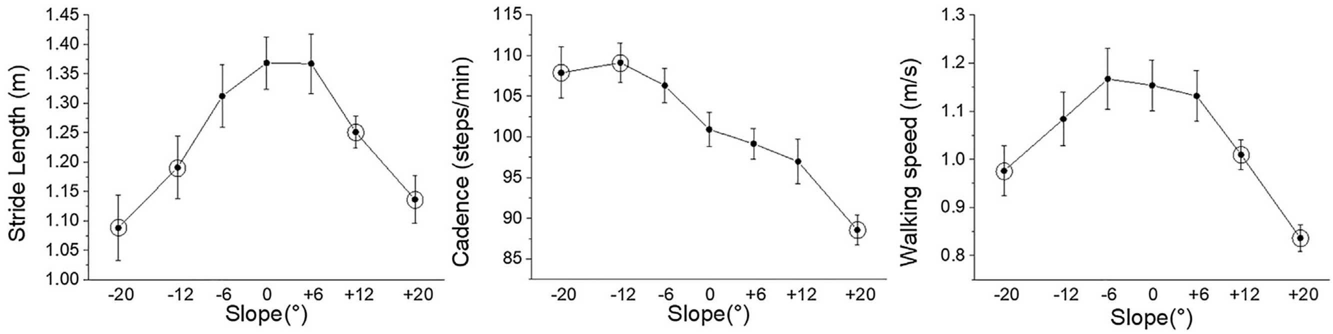

Fig. 3. Spatiotemporal parameters as a function of slope gradient. Circles distinguish significant differences ($p \le 0.05$) between each slope condition and level gait.

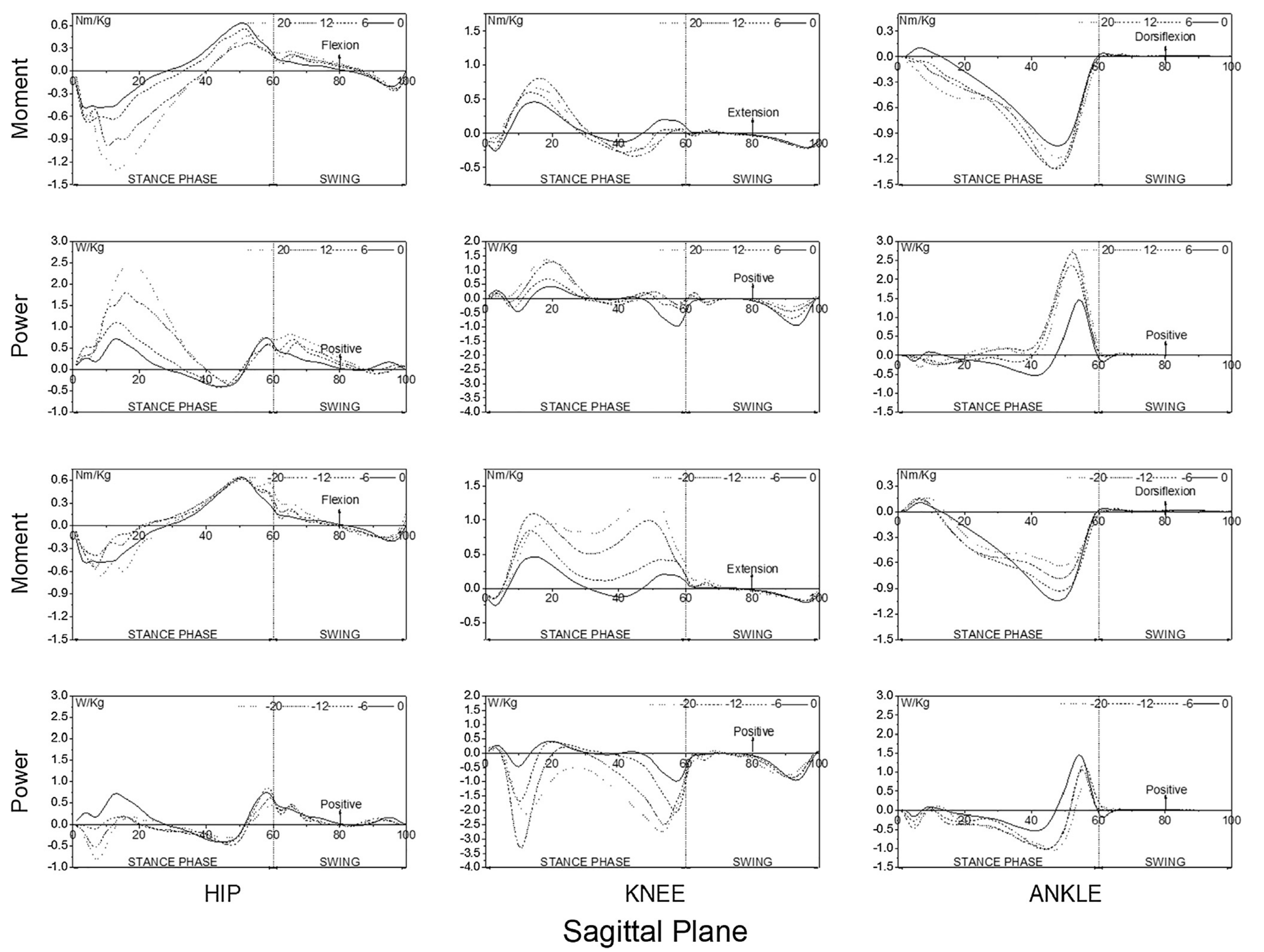

Fig. 4. Sagittal joint moments and powers as a function of the gait cycle, normalized to mass. Gait cycle was time-normalized to 60% for stance and 40% for swing phase for plotting purposes only. Incline walking is in the top two rows, decline walking in the bottom two rows.

$$3\mathbf{D\_NJW} = \mathbf{NJW}\ \text{sagittal} + \mathbf{NJW}\ \text{frontal} + \mathbf{NJW}\ \text{transverse} \quad (4)$$

An alternate work analysis identifies the 3D power bursts (e.g. H1-F, A2-S, etc.) (Eng and Winter (1995)). However, individual differences are evident in the power bursts in level walking (Vardaxis et al., 1998), and differences will likely be compounded by the slope manipulation. Thus, due to the subjective decisions associated with power burst detection, a power burst analysis was not completed. Changes in speed as a function of gradient were observed (Fig. 3), which would mean that changes in work may be related to changes in gradient and/or changes in speed. Therefore, the work calculated in each trial was normalized to the speed of that trial (Silverman et al., 2012). Finally, the joint work in each plane was expressed as a percent of the total work at that joint. The values for the three trials were averaged for each subject at each slope.

A repeated-measures one-way ANOVA ($p \le 0.05$) was used to determine if the measures were affected by the slope manipulation (7 levels: −20, −12, −6, 0, 6, 12, and 20), with $p \le 0.05$. When a sig-

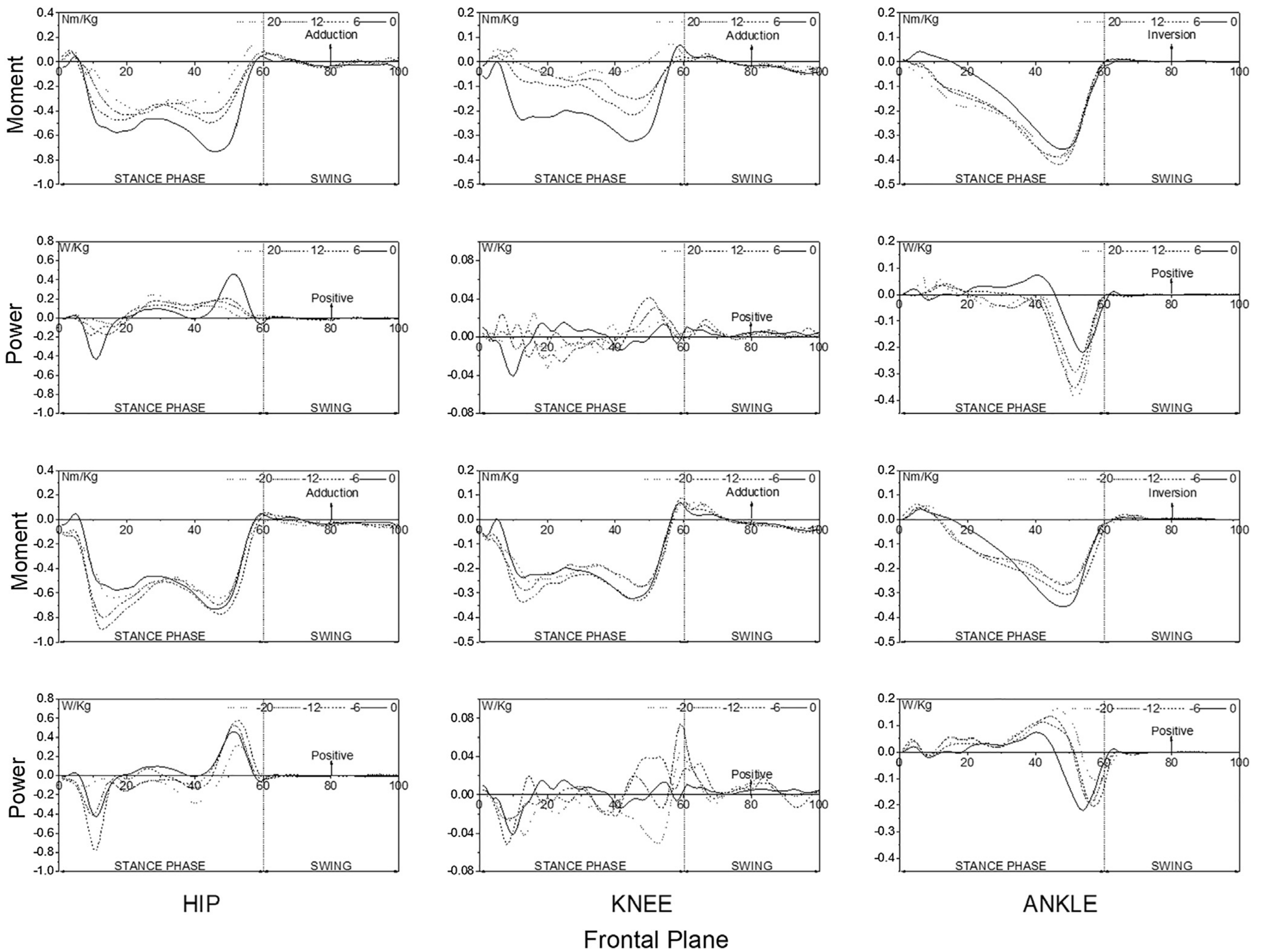

Fig. 5. Frontal joint moments and powers as a function of the gait cycle, normalized to mass. Gait cycle was time-normalized to 60% for stance and 40% for swing phase for plotting purposes only. Incline walking are in the top two rows, decline walking in the bottom two rows.

nificant effect for gradient was identified, pairwise comparisons were conducted with Dunnett's post hoc test between the level condition and each of the six slope conditions (Dunnett's post hoc accounts for multiple comparisons to baseline). To determine if work was different for incline versus decline, contrasts were conducted on the average work of the three incline conditions (6, 12, 20) versus the average work on the three decline conditions (−6, −12, −20). All statistical tests were performed using SAS 9.3 (version 9.3, SAS Institute, Cary, NC).

3. Results

The following spatiotemporal measures were significantly affected by the slope manipulation: Stride length ($F(6, 54) = 14.74$, $p < 0.001$), cadence ($F(6, 54) = 23.72$, $p < 0.001$), and speed ($F(6, 54) = 15.84$, $p < 0.001$) (Fig. 3). Post hoc analyses revealed that, relative to the level condition, stride length decreased with inclines and declines greater or equal to 12 degrees. Cadence was slower at 20 degrees, and faster when decline was greater or equal to −12 degrees. Walking speed decreased when incline was greater or equal to 12 degrees and decline at −20 degrees.

Time series of the moment of force and power curves are presented in Figs. 4–6. Mean, standard deviation, and statistical differences of the joint work normalized to speed are presented in Table 1, and described below.

3.1. Sagittal plane

In the sagittal plane, gradient significantly affected positive work at all three joints: hip ($F(6, 54) = 214.54$, $p < 0.001$), knee ($F(6, 54) = 22.87$, $p < 0.001$), and ankle ($F(6, 54) = 96.41$, $p < 0.001$). Similarly, gradient significantly affected negative work at all three joints: hip ($F(6, 54) = 11.82$, $p < 0.001$), knee ($F(6, 54) = 114.11$, $p < 0.001$), and ankle ($F(6, 54) = 53.18$, $p < 0.001$).

3.2. Frontal plane

In the frontal plane, gradient significantly affected positive work at the hip ($F(6, 54) = 2.56$, $p = 0.030$), and ankle ($F(6, 54) = 7.36$, $p < 0.001$). Gradient significantly affected negative work at the hip ($F(6, 54) = 20.48$, $p < 0.001$), knee ($F(6, 54) = 2.39$, $p = 0.040$), and ankle ($F(6, 54) = 12.60$, $p < 0.001$). .

3.3. Transverse plane

In the transverse plane, gradient significantly affected positive work at the hip ($F(6, 54) = 14.63$, $p < 0.001$), and knee (F(6, 54)

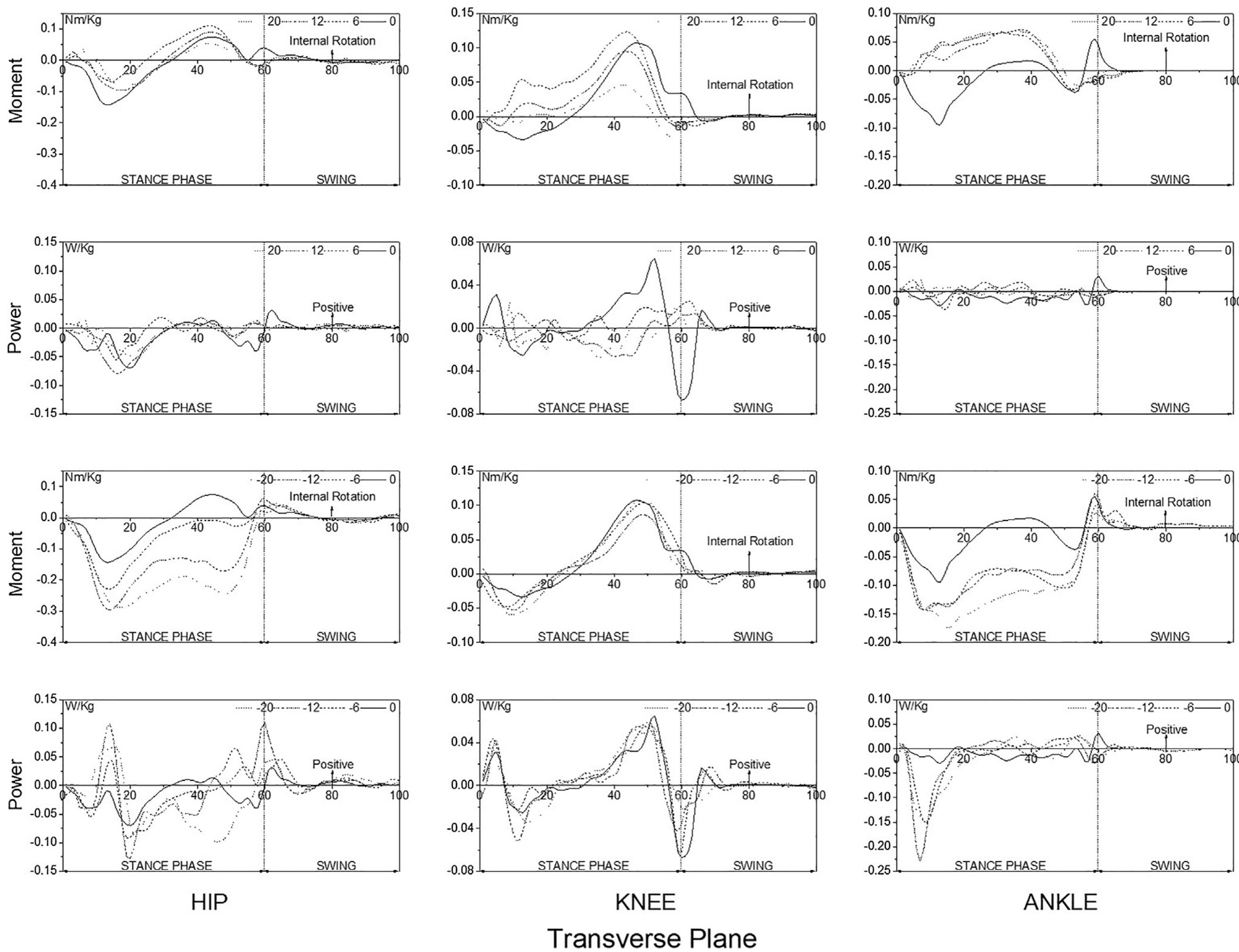

Fig. 6. Transverse joint moments and powers as a function of the gait cycle, normalized to mass. Gait cycle was time-normalized to 60% for stance and 40% for swing phase for plotting purposes only. Incline slopes are in the top two rows, decline gait in the bottom two rows.

= 2.68, $p = 0.024$).Gradient significantly affected negative work at the hip ($F(6, 54) = 10.92$, $p < 0.001$), and ankle ($F(6, 54) = 4.59$, $p < 0.001$).

3.4. Three-dimensional: combined sagittal, frontal, and transverse

When the three planes were combined (see equation in Fig. 2), gradient significantly affected positive work at all three joints: hip ($F(6, 54) = 152.52$, $p < 0.001$), knee ($F(6, 54) = 20.18$, $p < 0.001$), and ankle ($F(6, 54) = 61.49$, $p < 0.001$). Similarly, gradient significantly affected negative work at all three joints: hip ($F(6, 54) = 40.75$, $p < 0.001$), knee ($F(6, 54) = 119.81$, $p < 0.001$), and ankle ($F(6, 54) = 43.97$, $p < 0.001$).

3.5. Contrasts of incline versus decline

Contrasts indicated that in the sagittal plane and in the combined work (sagittal, frontal, and transverse), average positive work during incline gait was greater than average positive work during decline gait at all three joints (asterisks in Table 1, $p \leq 0.05$). Furthermore, average negative work was lower for incline than decline. While significant contrasts were observed for incline versus decline in the frontal and transverse planes, no clear patterns were observed (Table 1).

4. Discussion

Current knowledge regarding slope walking is extended in two ways: (1) subjects walked at a self-paced speed on an overground walkway (as opposed to a treadmill) and (2) the 3D mechanical work of the ankle, knee, and hip joints was quantified. The former is important, because this is more representative of everyday activities. The latter – quantification of mechanical work – allows us to more fully understand the function of the joint moments of force. The largest changes in mechanical work were observed in the sagittal plane, but large changes were also observed in the frontal and transverse plane. For example, sagittal work increased 496% at the knee during decline walking, and frontal work increased 320% at the ankle. As predicted for the sagittal plane, increased positive work was observed for incline walking and increased negative work was observed for decline walking. As predicted, the sagittal work provided the majority of the total work for all gradients and directions. However, the contribution of the other planes was not trivial: during decline walking, the frontal hip work contributed 32% of the total work, as predicted. Further, the contribution of the frontal and transverse planes to the total joint work at the hip was 46% for decline walking, highlighting the critical role played by the hip ab/adductors and hip rotators.

Incline walking resulted in a change in work in sagittal and frontal planes. Increased positive sagittal work at the three lower

Table 1
Mean (SD) of positive work and negative joint work (W) normalized to body mass (kg) and gait speed (m/s). Bolded mean values indicate significant difference between the gradient and level walking using Dunnett's post hoc comparisons.

		Gradient						
	3000	−20	−12	−6	0	6	12	20
Sagittal								
Positive	Hip*	**0.135** (0.036)	**0.125** (0.044)	**0.143** (0.050)	0.237 (0.056)	**0.363** (0.082)	**0.664** (0.119)	**1.074** (0.132)
	Knee*	0.031 (0.019)	0.049 (0.035)	0.071 (0.034)	0.076 (0.038)	0.134 (0.079)	**0.277** (0.108)	**0.354** (0.193)
	Ankle*	0.068 (0.047)	0.088 (0.042)	0.098 (0.057)	0.129 (0.032)	**0.313** (0.054)	**0.418** (0.094)	**0.473** (0.100)
Negative	Hip*	**0.137** (0.065)	**0.125** (0.050)	0.100 (0.043)	0.076 (0.037)	0.058 (0.028)	0.047 (0.029)	0.050 (0.030)
	Knee*	**1.261** (0.289)	**0.901** (0.174)	**0.489** (0.196)	0.254 (0.046)	0.173 (0.041)	0.140 (0.035)	0.118 (0.042)
	Ankle*	**0.349** (0.106)	**0.329** (0.075)	**0.259** (0.066)	0.128 (0.034)	0.078 (0.042)	**0.054** (0.026)	0.063 (0.031)
Frontal								
Positive	Hip	0.043 (0.025)	0.065 (0.041)	0.081 (0.043)	0.065 (0.021)	0.061 (0.020)	0.071 (0.025)	0.086 (0.035)
	Knee	0.012 (0.009)	0.016 (0.015)	0.017 (0.015)	0.016 (0.013)	0.012 (0.008)	0.012 (0.007)	0.013 (0.008)
	Ankle*	**0.048** (0.027)	**0.038** (0.034)	0.032 (0.031)	0.015 (0.007)	0.011 (0.005)	0.008 (0.005)	0.011 (0.008)
Negative	Hip*	**0.085** (0.030)	**0.087** (0.042)	**0.087** (0.022)	0.044 (0.016)	0.023 (0.012)	0.030 (0.015)	0.024 (0.018)
	Knee*	0.023 (0.010)	0.014 (0.008)	0.014 (0.005)	0.014 (0.009)	0.007 (0.010)	0.010 (0.015)	0.011 (0.016)
	Ankle*	0.016 (0.030)	0.021 (0.033)	0.022 (0.031)	0.029 (0.011)	0.041 (0.019)	**0.059** (0.030)	**0.075** (0.048)
Transverse								
Positive	Hip*	**0.025** (0.009)	**0.027** (0.011)	0.016 (0.008)	0.009 (0.006)	0.008 (0.003)	0.007 (0.004)	0.011 (0.005)
	Knee*	0.019 (0.014)	0.015 (0.016)	0.016 (0.009)	0.014 (0.008)	0.011 (0.005)	0.006 (0.004)	0.007 (0.007)
	Ankle*	0.011 (0.010)	0.010 (0.010)	0.009 (0.008)	0.009 (0.005)	0.007 (0.006)	0.006 (0.003)	0.007 (0.005)
Negative	Hip*	**0.044** (0.020)	0.030 (0.011)	0.024 (0.011)	0.020 (0.010)	0.012 (0.005)	0.018 (0.008)	0.016 (0.006)
	Knee	0.012 (0.009)	0.011 (0.007)	0.008 (0.005)	0.012 (0.011)	0.006 (0.004)	0.011 (0.008)	0.014 (0.011)
	Ankle*	0.030 (0.019)	0.026 (0.018)	0.019 (0.011)	0.018 (0.022)	0.008 (0.009)	0.006 (0.003)	0.009 (0.013)
3D								
Positive	Hip*	0.203 (0.040)	0.217 (0.077)	0.240 (0.081)	0.312 (0.049)	**0.432** (0.080)	**0.741** (0.125)	**1.172** (0.146)
	Knee*	0.062 (0.029)	0.080 (0.043)	0.104 (0.035)	0.106 (0.045)	0.156 (0.080)	**0.295** (0.107)	**0.374** (0.189)
	Ankle*	0.127 (0.070)	0.136 (0.071)	0.139 (0.085)	0.153 (0.029)	**0.330** (0.050)	**0.432** (0.096)	**0.492** (0.102)
Negative	Hip*	**0.266** (0.061)	**0.242** (0.061)	**0.211** (0.047)	0.139 (0.032)	**0.093** (0.026)	0.095 (0.030)	**0.090** (0.030)
	Knee*	**1.296** (0.293)	**0.926** (0.176)	**0.511** (0.200)	0.279 (0.054)	0.187 (0.045)	0.161 (0.039)	0.143 (0.062)
	Ankle*	**0.396** (0.104)	**0.376** (0.092)	**0.300** (0.085)	0.175 (0.041)	0.127 (0.041)	0.119 (0.040)	0.147 (0.066)

* Indicates significant difference between the contrast of average work for incline versus average work for decline.

limb joints raised and propelled the body forward, and increased negative frontal work at the ankle controlled medial-lateral displacement (Fig. 7). In order to understand the contribution of these changes in work to locomotor control, each significant effect (Table 1) is described in the context of observed changes in the average joint power time series (Figs. 4–6), as in Winter (1991). Higher hip and knee sagittal joint work occurred during early to mid-stance phase (0–40% of stride) to provide forward propulsion while also raising the body. During mid-stance phase (20–40%), the ankle power is negative for level gait, which acts to decelerate the forward rotating body (Winter, 1991); this control is not evident during incline walking (Fig. 4), allowing the body to rotate forward to facilitate forward motion. During late stance phase (40–60% of stride), the ankle sagittal joint work increased to continue the upward and forward propulsion. The decrease in cadence (Fig. 3) provided more time for each power burst, which in turn increased the work. Despite the substantial increases in positive work in the sagittal plane during incline walking, stride length and gait speed still decreased on the steepest inclines (Fig. 3). Maintaining stride length and speed would have required even greater increases in positive work and/or decreases in negative work. Likely, there is a trade-off between maintaining speed and minimizing metabolic costs. While the ankle invertors/evertors did not play a role at the shallowest incline (6°), negative ankle frontal work increased significantly at the steeper inclines (Fig. 7) during mid to late stance phase (40–60%, Fig. 5). Since the moment is evertor at this

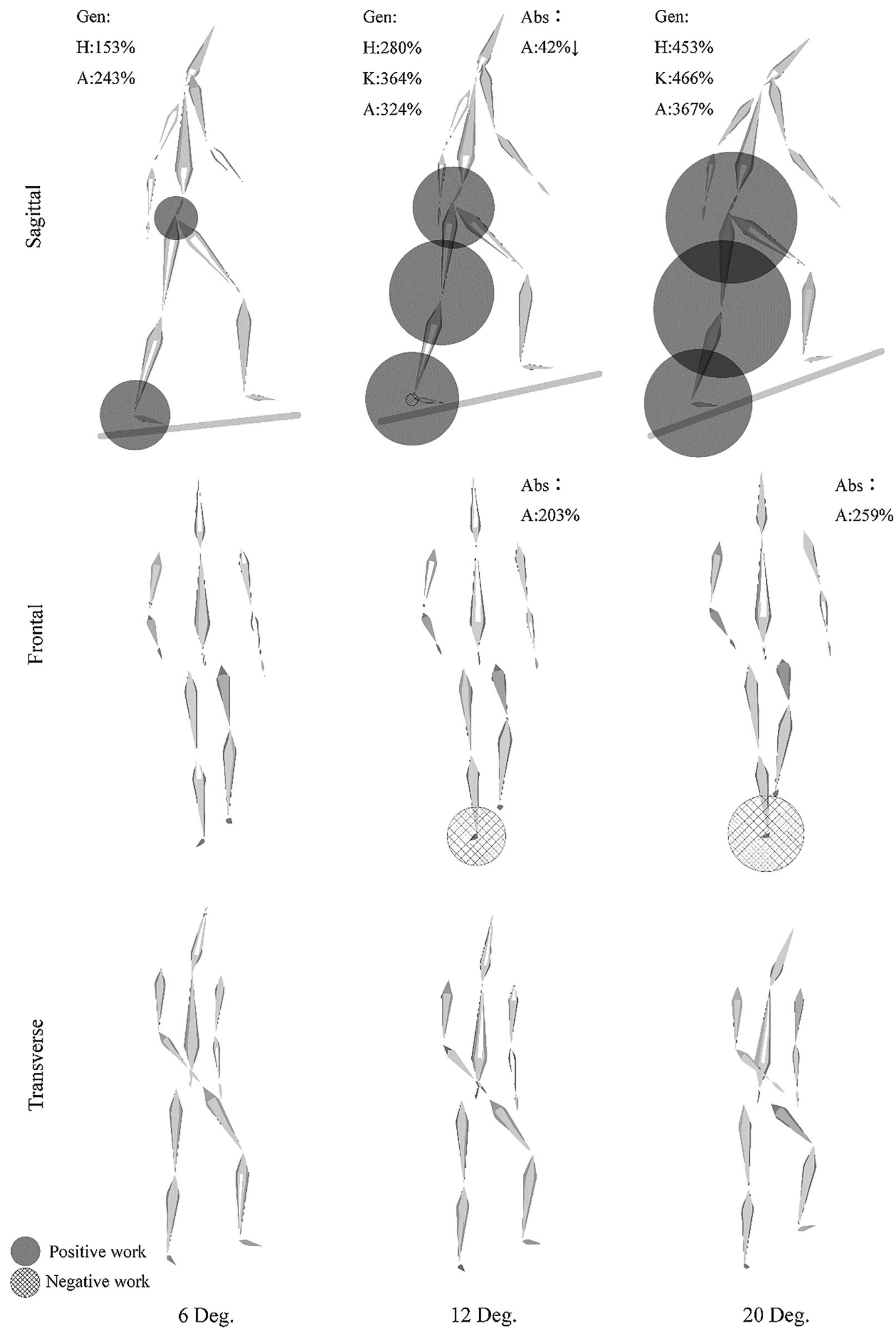

Fig. 7. Illustration of significant changes in joint work at each joint in each plane as a function of slope inclines. The area of the circles in the legend reflects a 100% change in work for gradient gait relative to level gait. Dark gray filled circles indicate positive work, and cross-hatch filled circles indicate negative work. Results were normalized for mass and gait speed.

phase, and the ankle is inverting (determined from joint angle time series, not shown), the ankle evertors are acting to control the medial displacement of the body during push-off. Overall, a large increase in positive work was observed to accomplish incline walking: For the shallowest incline, positive ankle sagittal work increased 243%, and for the steepest incline, positive knee sagittal work increased 466% (Fig. 7).

Decline walking resulted in higher negative sagittal work at all three joints to control body descent, and changes in positive and negative work at the ankle and hip in the frontal and transverse

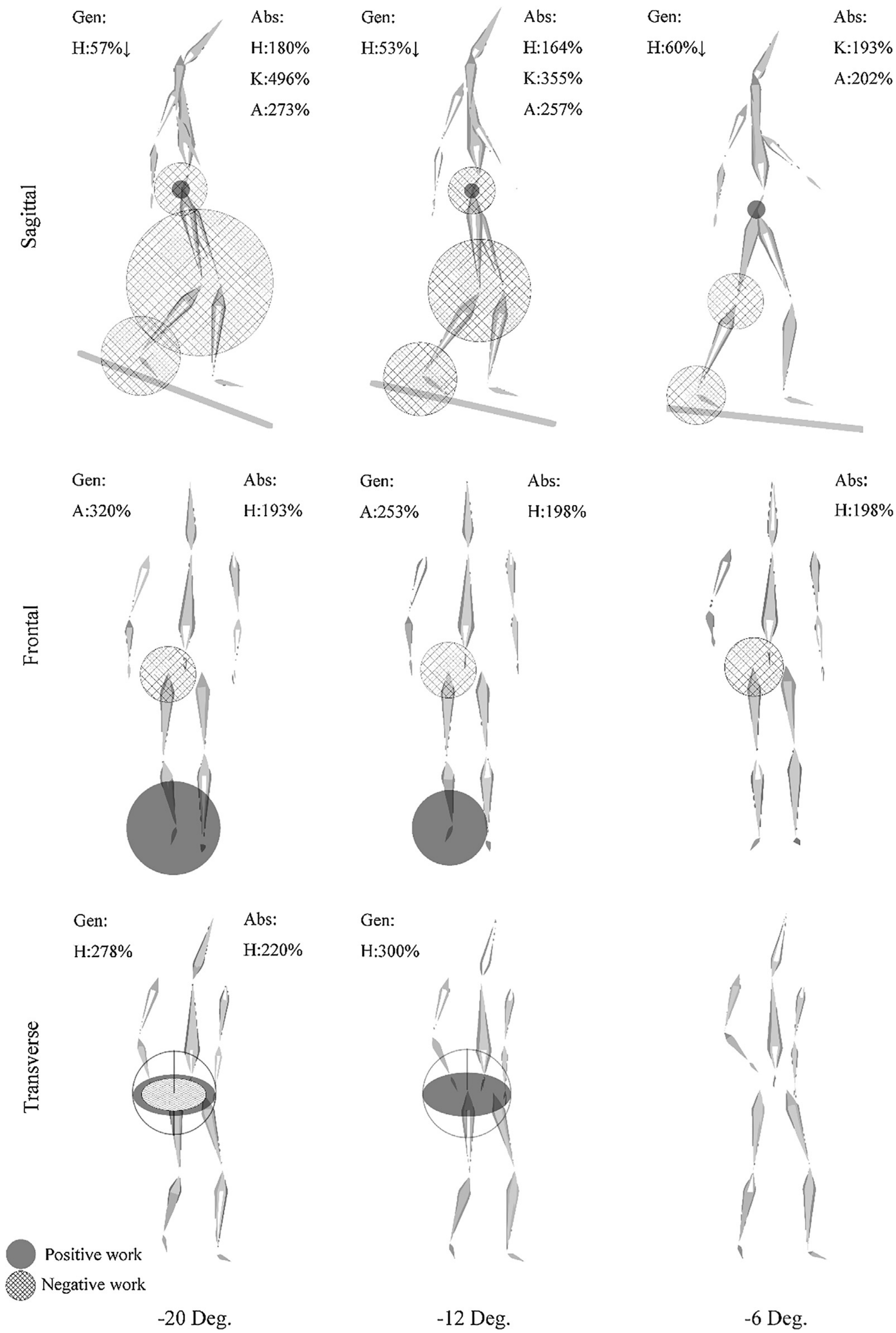

Fig. 8. Illustration of significant changes in joint work at each joint in each plane as a function of slope declines. The area of the circles in the legend reflects a 100% change in work for gradient gait relative to level gait. Dark gray filled circles indicate positive work, and cross-hatch filled circles indicate negative work. Results were normalized for mass and gait speed.

planes (Fig. 8). In the sagittal plane, larger hip and knee negative work during early stance phase (0–∼15%; Fig. 4) provide deceleration against gravitational forces and act to prevent lower limb collapse at weight acceptance following the larger downward displacement of the body (Leroux et al., 2002). In mid to late-stance phase (20–50%), higher negative ankle work reduces the forward rotation of the body over the ankle. Concurrently (20–30%), the hip has less positive work, since gravity is acting to pull the body forward and downward. During late stance phase (50–60%), the ankle has reduced push-off, due to the forward and downward activity of gravity. Concurrently (∼40–60%), the higher negative work at the knee absorbs more energy to control the backward

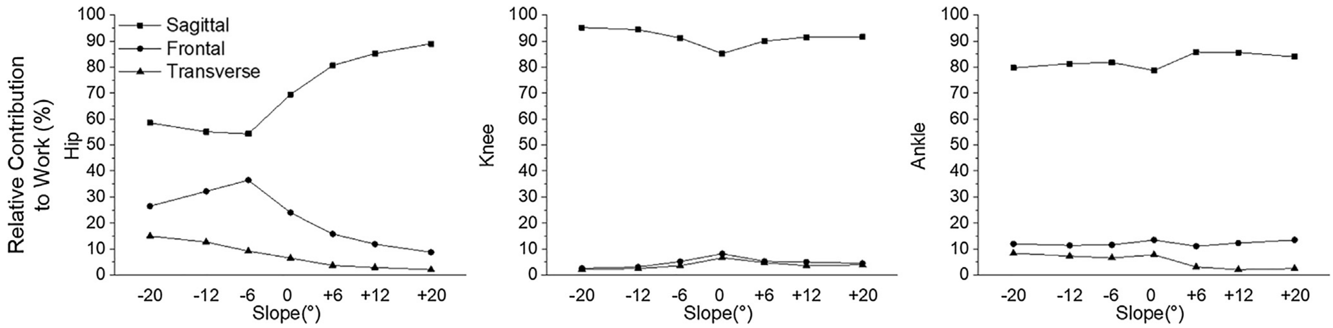

Fig. 9. The percent contribution of each plane to the total work at that joint as a function of slope gradient.

rotating shank, likely so that the knee is extended appropriately during swing phase. These kinetic changes reduced stride length and speed, but higher cadence was also observed during decline walking (Fig. 3). Increasing cadence reflects faster placement of each footfall in order to allow greater opportunities for the limbs to absorb the energy and prevent the body from accelerating down the decline. As demonstrated for incline walking, changes were not limited to the sagittal plane (Fig. 8). Frontal hip negative work increased through most of stance phase (Fig. 5) to control the dropping pelvis due to gravitational forces and to control mediolateral displacements (Allard et al., 1996; Eng and Winter, 1995). Concurrently, frontal ankle positive work increased during most of stance phase (Fig. 5), likely acting to keep the center of mass positioned over the stance foot. In the transverse plane, only the hip joint contributed to meet the increased demands from decline slopes. Hip transverse negative work increased during mid stance phase (20–40%) to control the rotation of the pelvis and trunk about the stance limb, and positive work increased during late stance and early swing phase (40–70%) to facilitate pelvis and trunk motion in (Fig. 6). Overall, decline walking was accomplished through large increases in both positive and negative work, and increased work was observed in all three planes (Fig. 8).

The most compelling and novel finding of this research is the substantial work done by the hip in the frontal and transverse planes, accounting for up to 46% of the total work at the hip (Fig. 9). We hypothesized that the frontal work would account for at least 30% of the total hip work, and we observed an average of 32% for the three decline angles (37%, 32%, and 27% for −6 degrees, −12 degrees, and −20 degrees, respectively) (Fig. 9). The 46% contribution of the hip in the frontal and transverse planes, coupled with the 21% contribution from the frontal and transverse work at the ankle joint, highlight the significant contributions of these planes to slope walking. We also point out that a higher number of significant changes and larger magnitudes of change were observed in the frontal and transverse planes for decline walking (eight significant changes) relative to incline walking (two significant changes), and most of these changes are negative work (Fig. 7, 8; Table 1). Decline walking placed greater demands on the hip ab/adductors and rotators; increased falls during descent may be related to insufficient strength and/or coordination. Older adults have lower strength and muscle quality (Goodpaster et al., 2006), and 37% lower rate of force development (Häkkinen et al., 1998). Thus, the increased demands of slope walking will be especially problematic with advancing age. Overall, the results suggest that more control is required in the frontal and transverse planes to move and stabilize the body and help prevent a fall during decline walking, which highlight the greater risk of falling during slope descent than ascent (Redfern and DiPasquale, 1997). This greater risk is also evident when descending stairs, where 80% of falls occur in descent (Svanström, 1974; Tinetti et al., 1988). Frontal and transverse work is also important for stair descent, as higher peak moments were observed in these planes for the ankle, knee, and hip (Silverman et al., 2014). Examination of the 3D joint work during slope walking provides critical information for the development of prosthetic devices, exoskeletons, and mobility rehabilitation programs. In particular, the role of the frontal and transverse planes must be considered as substantive work was observed at the three lower limb joints in all three dimensions.

In earlier text, we described how the kinetic changes were related to the inverted-U relationship for stride length and speed (Fig. 3). However, inverted-U relationships have not been observed consistently across all slope walking studies. Changes in these parameters include increases (McIntosh et al., 2006), no change (Lay et al., 2006), decreases (Kimel-Naor et al., 2017; Noble and Prentice, 2008; Redfern and DiPasquale, 1997; Sun et al., 1996), and mixed for incline versus decline (Kawamura et al., 1991). Since spatiotemporal changes associated with slope walking are not robust across research studies, it is likely that these parameters are sensitive to environmental differences across studies, such as treadmill versus overground, slopes examined, length and width of the slope, presence of handrails or harness, surface coefficient of friction, etc. However, we note that the inverted-U patterns observed here are consistent with observations on 2400 urban pedestrians walking on Sydney's Circular Quay (Sun et al., 1996), which increases our confidence that the participants in the current study were acting as they would during everyday activities.

5. Conclusions

Slope walking required substantive changes in positive and negative work, reflecting changes in energy generation and absorption, and these changes were not limited to the sagittal plane. In particular, the hip frontal and transverse powers contributed substantially to decline walking, accounting for up to 46% of the total work at the hip. More significant changes were observed in the frontal and transverse planes for decline walking than incline walking. These results suggest that motion was more tightly controlled on declines to help prevent a fall.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "The Relative Contributions of Sagittal, Frontal, and Transverse Joint Powers to Self-Paced Incline and Decline Slope Walking".

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