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Ground reaction forces during downhill and uphill running

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Abstract

We investigated the normal and parallel ground reaction forces during downhill and uphill running. Our rationale was that these force data would aid in the understanding of hill running injuries and energetics. Based on a simple spring-mass model, we hypothesized that the normal force peaks, both impact and active, would increase during downhill running and decrease during uphill running. We anticipated that the parallel braking force peaks would increase during downhill running and the parallel propulsive force peaks would increase during uphill running. But, we could not predict the magnitude of these changes. Five male and five female subjects ran at 3 m/s on a force treadmill mounted on the level and on 3°, 6°, and 9° wedges. During downhill running, normal impact force peaks and parallel braking force peaks were larger compared to the level. At −9°, the normal impact force peaks increased by 54%, and the parallel braking force peaks increased by 73%. During uphill running, normal impact force peaks were smaller and parallel propulsive force peaks were larger compared to the level. At +9°, normal impact force peaks were absent, and parallel propulsive peaks increased by 75%. Neither downhill nor uphill running affected normal active force peaks. Combined with previous biomechanics studies, our normal impact force data suggest that downhill running substantially increases the probability of overuse running injury. Our parallel force data provide insight into past energetic studies, which show that the metabolic cost increases during downhill running at steep angles.

Keywords: Biomechanics; Locomotion; Grade; Decline; Incline

1. Introduction

Ground reaction force (GRF) data have been essential to our understanding of level locomotion biomechanics for over 70 years (Fenn, 1930). Today, we use GRF data to quantify impacts, understand propulsion and braking, compute muscle forces, and calculate mechanical energy fluctuations. In most geographic locales, runners encounter hills, yet there are scant published GRF data for running on declines or inclines and as a result, our understanding of hill running is limited.

Many researchers have quantified GRF values and patterns for running on the level (e.g., Cavanagh and Lafortune, 1980; Fenn, 1930; Munro et al., 1987). At a moderate pace of 3 m/s, for runners who land on their rear-foot, the vertical component of the GRF quickly rises and falls, forming the impact peak (≈1.6 BW). The vertical component of the GRF then more slowly increases to a second peak at mid-stance, termed the active peak (≈2.5 BW), before decreasing prior to toe-off (Fig. 1a). At foot strike, the horizontal component of the GRF is negative as a braking force is applied reaching a nadir (≈−0.3 BW) at about one-quarter of stance time before decreasing in magnitude and crossing zero at mid-stance. The horizontal component of the GRF is then positive as a propulsive force is applied reaching a zenith (≈0.3 BW) at about three-quarters of stance time before decreasing in magnitude prior to toe-off (Fig. 1b).

The dearth of GRF data for hill running is likely due to the difficulty of constructing a force platform runway on an angle or rigidly tilting a force treadmill. Given that challenge, Hamill et al. (Hamill et al., 1984) used tibia mounted accelerometers to measure leg shock. They found that leg shock increased by 30% during −5°

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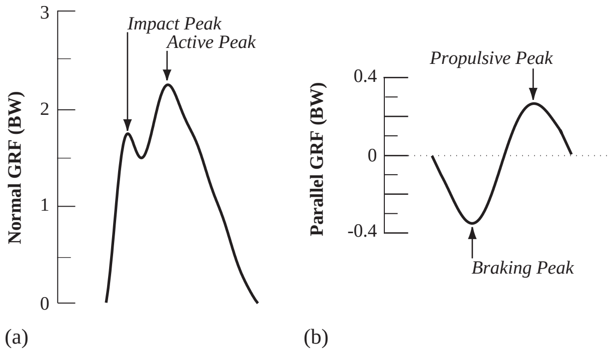

Fig. 1. Typical traces of the normal (a) and parallel (b) ground reaction force data for level running at 3 m/s.

downhill running and decreased by 24% during $+3^\circ$ uphill running. Dick and Cavanagh (1987) secured a force platform to a ramp, at -5° to compare downhill and level vertical force peaks. They demonstrated that during downhill running, vertical impact force peak increased by 14%, horizontal braking impulses increased by almost 200% and vertical active force peaks did not change compared to level running. Miller et al. (1988) used a heel insole transducer to examine the relationship between impact force peaks during distance running at a decline of -3° and an incline of $+3^\circ$. They concluded that there was not a significant difference between impact force values during downhill and uphill running. Thus, they disagreed with Dick and Cavanagh (1987). Iversen and McMahon (1992) utilized a force platform embedded into a motorized treadmill to collect the normal GRF while subjects ran downhill and uphill. However, their device could not measure parallel forces. They reported that the normal active force peak was 2% larger during downhill running at -10° and 11% smaller during uphill running at $+10^\circ$ compared to level running. Thus, their active force peak data during downhill running contradicted the results of Dick and Cavanagh (1987). While these studies have advanced our knowledge of hill running, none quantified both the normal and parallel components of GRF for a range of downhill and uphill angles. Further, the data are inconsistent between studies.

Although there are few published GRF data, past research has answered numerous questions regarding hill running energetics, muscle actions, and mechanics. Margaria (1976) showed that during moderate downhill running, metabolic energy cost decreased and reached a minimum at approximately -8°, beyond which the energy cost curve inflected and began to increase curvilinearly. In contrast, during uphill running, energy cost increased linearly with the angle of the incline. Uphill running required an increase in the activity of leg muscles, particularly the vastus medialis, biceps femoris, and gastrocnemius (Sloniger et al., 1997; Swanson and Caldwell, 2000), that corresponded with the increase in external work rate during uphill locomotion. Buczek and Cavanagh (1990) quantified how much more negative work was absorbed at both the knee and ankle joints during downhill running. Klein et al. (1997) concluded that step length, contact time, and swing time did not significantly change during hill running at a fixed speed.

Questions remain unanswered that can only be addressed and clarified by collecting GRF data on a range of angles during both downhill and uphill running. For example, do impact forces change during downhill and uphill running so as to increase or decrease the probability of injury (Hreljac et al., 2000)? Do normal active force peaks increase during downhill running (Iversen and McMahon, 1992) or remain unchanged (Dick and Cavanagh, 1987)? Can the parallel propulsive force patterns explain the pattern of metabolic energy cost for hill running (Margaria, 1976)?

Our goal was to quantify the ground reaction forces during downhill and uphill running. We measured the forces both normal and parallel to the surface of the treadmill, analogous to the vertical and horizontal forces of level running. To do so, we mounted a force treadmill on wedges at several fixed angles. We tested three hypotheses: compared to level running, (1) normal impact force peaks would be larger during downhill running and smaller during uphill running, (2) normal active force peaks would be larger during downhill running and smaller during uphill running, (3) parallel braking force peaks would be greater during downhill running and parallel propulsive force peaks would be greater during uphill running. We predicted that these changes in parallel forces would be symmetrically opposite for downhill and uphill running at each angle.

2. Methods

Five men and five women volunteered (age = 30.35 ± 5.09 yr, height = 1.72 ± 0.06 m, mass = 62.56 ± 7.59 kg, mean ± standard deviation). These healthy, recreational runners gave written informed consent following the guidelines of the University of Colorado Human Research Committee.

We constructed three sets of aluminum wedges to tilt our force treadmill (Kram et al., 1998) at 3°, 6°, and 9° (5.2%, 10.5%, and 15.8%). The base of each wedge was bolted to the mounting plate. Then, we bolted the force transducer box at each corner of the force platform to the corresponding wedge. Lastly, the treadmill was bolted to the force platform (Fig. 2).

Before collecting running data, we rapped the treadmill to determine that the unloaded natural frequencies of the force treadmill in the normal and parallel directions were adequate (Kram et al., 1998). The lowest natural frequencies on the level were 176 Hz normal and

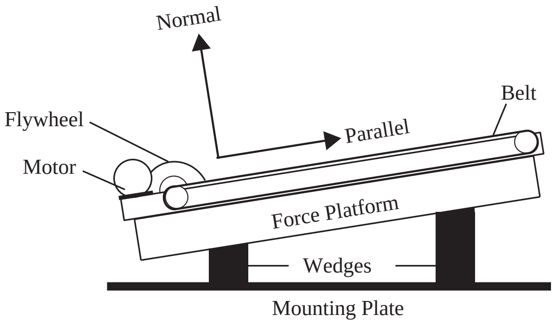

Fig. 2. Force measuring treadmill mounted at 9°.

86 Hz parallel. On the 9° tilt, the values were only slightly decreased, 172 Hz normal and 81 Hz parallel.

Subjects ran at 3 m/s (5.6 min/km, 8.9 min/mi) on the force treadmill mounted on the level and on downhill and uphill angles. Due to the lengthy process of changing the angle, each subject completed experimental sessions on four different days. The order of the sessions was randomized for each subject. During each session, the subjects completed a warm-up run at 3 m/s for 10 min on a level Quinton 18–60 treadmill. Next, they ran on the force treadmill on the level or both downhill and uphill at the established angle of that session, for one minute. We collected data during the last 10 s of each trial (LabView 4.0, National Instruments).

We carefully determined the optimal filtering and processing protocol for the GRF data. With no subject on the treadmill, we operated the motor at a belt speed of 3 m/s and collected force data. A fast Fourier analysis established that the vibration noise primarily had a frequency range of 40–50 Hz and above 70 Hz. Therefore, we filtered the GRF data using a fourth-order recursive, zero phase-shift, Butterworth low-pass filter with a cutoff frequency of 70 Hz, followed by a notch filter, with a band stop range of 40–50 Hz. To validate this filtering procedure, we compared a filtered level force treadmill trial at 3 m/s to a raw over ground runway trial at the same velocity (Fig. 3). Next, filtered GRF data were adjusted so that the mean values for each component during the aerial phases were equal to zero. Lastly, we determined foot strike by a positive change in the normal ground reaction force greater than 1000 N/s, occurring while the force was below a threshold of 100 N. Foot strike pattern, rear-foot versus mid-foot was determined by the analysis of the normal GRF data and visual observation.

For each condition, we calculated normal force peaks, impulses, and loading rates in addition to parallel force peaks and impulses averaging 20 steps per subject. Our algorithm determined the normal impact force peak magnitude by starting from foot strike and finding the value when the positive slope became negative. We determined the normal active force peak by starting from toe-off and working backwards in time towards

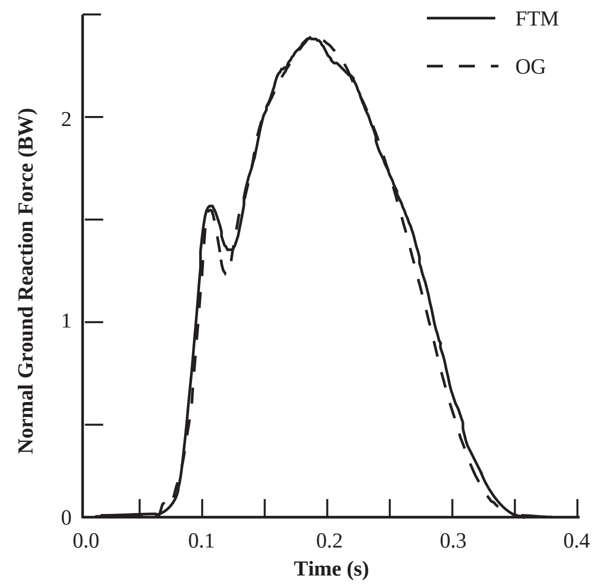

Fig. 3. Comparison of the normal ground reaction force signal obtained from the force treadmill (filtered data, solid line) and an over ground runway (raw data, dashed line) for a subject (54 kg) running at 3 m/s. Treadmill data were low pass filtered at 70 Hz and notch filtered at 40–50 Hz.

foot strike. Both parallel braking and propulsive force peaks were calculated in a similar manner. We obtained normal and parallel impulse data by integrating all the positive (normal and parallel propulsive) or negative (parallel braking) values of the GRF during each ground contact, yielding average impulse per step. Average impact loading rate equals the impact force peak magnitude divided by the time between foot strike to the impact force peak. We calculated the maximum impact loading rate from the instantaneous derivative of the normal GRF with respect to time.

We compared GRF and kinematic data across all conditions using a repeated measures analysis of variance design (ANOVA). In addition, we performed Newman–Keuls post hoc tests to analyze the differences between each condition. Significance was defined as $p < 0.05$.

We calculated the coefficient of variation to determine intrasubject variability and completed a paired t-test to determine bilateral differences. The coefficient of variation during each condition for the peak force values averaged 4% and did not exceed 10%. Paired t-tests revealed no significant difference between the right and left foot forces during any condition.

3. Results

Compared to level running, the normal impact force peaks were dramatically larger for downhill running and smaller for uphill running (Fig. 4a). These results were partly due to subjects progressively altering their foot strike technique during uphill running. All ten subjects intiated foot strike with their rear-foot during the $-9°$, $-6°$, and $-3°$ downhill, level, and $+3°$ uphill conditions. However, at $+6°$ uphill, three subjects switched to a mid-foot strike pattern and at $+9°$ uphill, all subjects landed on their mid-foot. Therefore, we evaluated normal impact data for all ten subjects during downhill running at $-9°$, $-6°$, and $-3°$, level running, and uphill running at $+3°$ and the seven subjects that maintained a normal impact peak during uphill running at $+6°$. Compared to level running, at $-9°$ the normal impact peak increased by 54%, at $-6°$ by 32%, and at $-3°$ by 18% ($p<0.0001$, $p=0.005$, $p=0.06$, respectively). At an uphill angle of $+3°$, the normal impact peak decreased by a non-significant 13% ($p=0.18$, Table 1, Fig. 5a). However, for the seven subjects with a rear-foot strike pattern, at $+6°$ the normal impact peak decreased by 22% ($p=0.04$, Table 2, Fig. 5a).

The normal impact loading rates were also greater for downhill running and reduced for uphill running (Table 1). During level running, for the seven subjects who maintained a rear-foot strike pattern at $+6°$, the average and maximum impact loading rates were 36.3 and 66.1 kN/s, respectively. At a downhill angle of $-6°$, the average impact loading rate increased by 23% ($p=0.01$) while the maximum loading rate increased by 20% ($p=0.03$). At an uphill angle of $+6°$, the average impact loading rate decreased by 23% ($p=0.01$) while the maximum loading rate decreased by 22% ($p=0.02$).

The normal active force peaks did not significantly change during downhill or uphill running (Fig. 4a). The mean normal active peaks were all within 4% of the mean level running value (Fig. 5a).

The parallel braking force peaks were larger for downhill running and smaller for uphill running (Fig. 4b). During downhill running at $-9°$, the parallel braking force peaks increased by 73%, while at $-6°$ and $-3°$, the parallel braking peaks increased by 46% and 27%, respectively. During uphill running at $+3°$, the parallel braking force peaks decreased by 19%, at $+6°$ by 38%, and at $+9°$ by 54%. Each of these values statistically differed from level running ($p<0.0001$, Table 2, Fig. 5b).

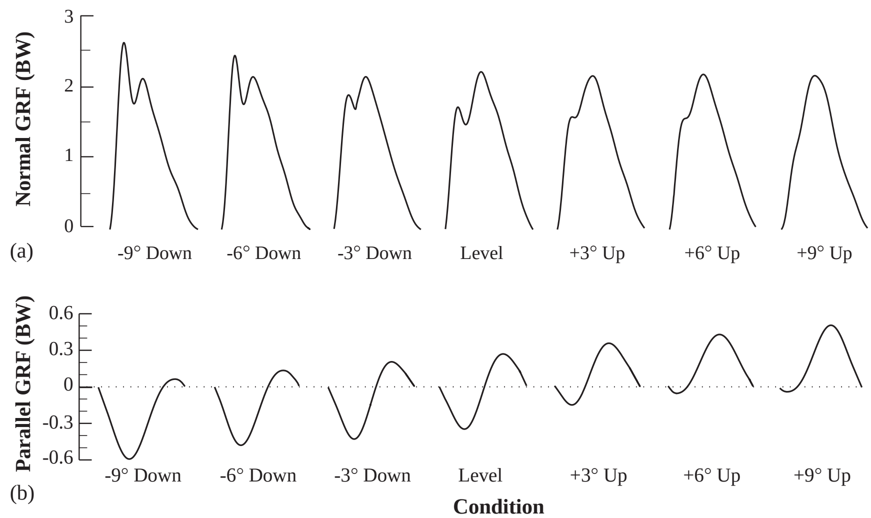

Fig. 4. Normal (a) and parallel (b) ground reaction force versus time traces for a typical subject (73 kg) running at 3 m/s.

Table 1
Effects of downhill and uphill angle on running normal impact force peaks and loading rates

Condition (deg)	Normal impact force peak (N), $n=10$	Normal impact force peak (N), $n=7$	Ave impact loading rate (kN/s), $n=10$	Ave impact loading rate (kN/s), $n=7$	Max impact loading rate (kN/s), $n=10$	Max impact loading rate (kN/s), $n=7$	Normal active force peak (N) $n=10$
−9 Down	1504 ± 273†	1504 ± 362†	47.7 ± 9.3*	49.1 ± 12.6*	94.6 ± 29.8	83.8 ± 24.8*	1341 ± 177
−6 Down	1283 ± 255*	1305 ± 322*	44.8 ± 8.9*	44.8 ± 11.5*	88.2 ± 28.5	79.2 ± 23.2*	1325 ± 205
−3 Down	1149 ± 263*	1174 ± 375*	41.3 ± 9.4	42.6 ± 10.8	78.0 ± 25.9	73.0 ± 12.1	1375 ± 198
Level	974 ± 193	988 ± 252	34.9 ± 6.2	36.3 ± 6.7	71.2 ± 20.8	66.1 ± 13.0	1373 ± 199
+ 3 Up	848 ± 176	840 ± 222	27.8 ± 8.4	32.5 ± 7.8	57.5 ± 20.0	53.5 ± 13.5	1384 ± 168
+ 6 Up	—	767 ± 184*	—	29.4 ± 5.7*	—	48.9 ± 15.8*	1362 ± 174
+ 9 Up	—	—	—	—	—	—	1334 ± 182

Values represent means for all 10 subjects ± standard deviation and 7 subjects that initiated foot strike on their rear-foot.
Conditions that differ from level running are denoted with an '*', $p<0.05$ or with an '†', $p<0.01$.

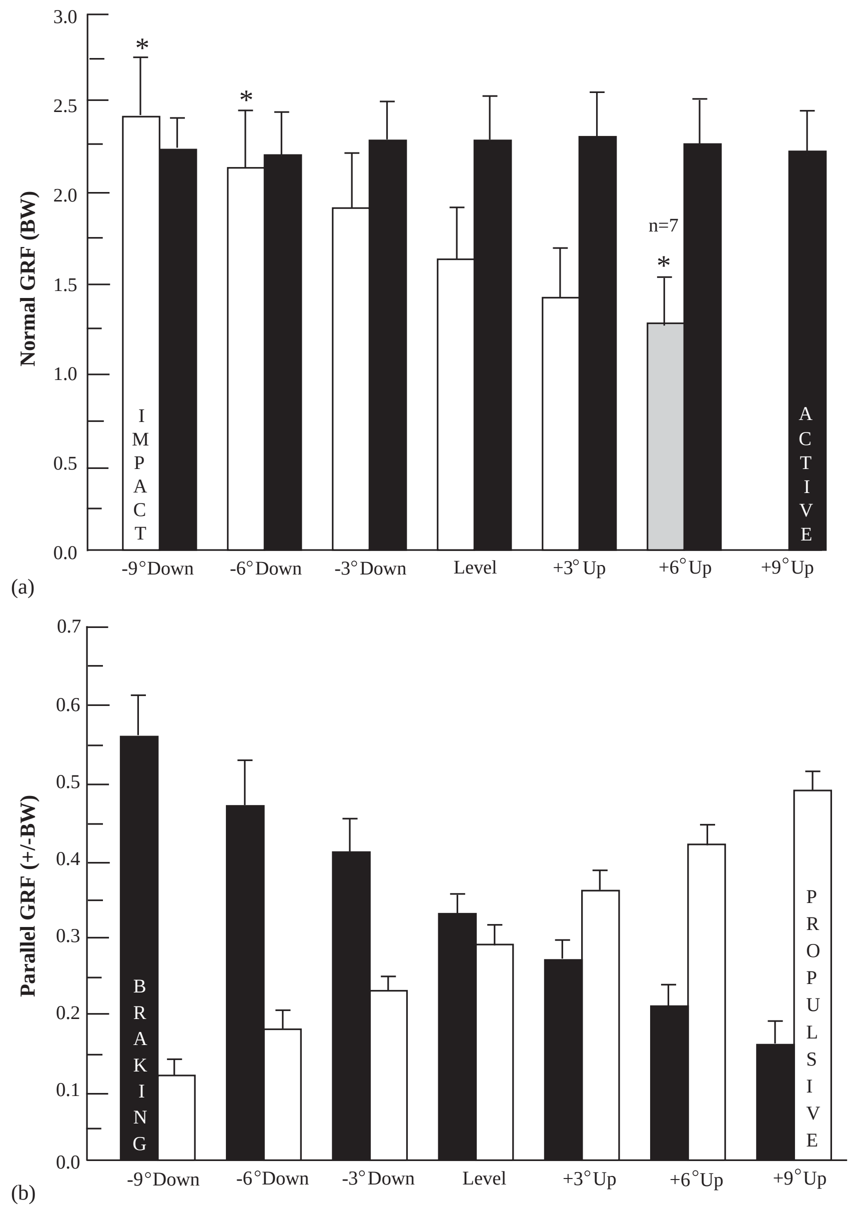

Fig. 5. Mean normal impact (a, white bars) and active (a, black bars) force peaks. All subjects intiated foot strike with their rear-foot during each –9°, −6°, and −3° downhill, level, and +3° uphill condition. However, at +6° uphill, three subjects initiated foot strike on their mid-foot and at +9° uphill, all subjects landed on their mid-foot. Conditions that differ from level running are denoted with an '*', $p<0.05$. Mean parallel braking (b, black bars) and propulsive (b, white bars) force peaks. Mean for 10 subjects ± standard deviation. Note the mean parallel braking force peaks are presented as the absolute value. All conditions differed from level running, $p<0.0001$.

Table 2
Effects of downhill and uphill angle on braking and propulsive peaks and impulses

Condition (deg)	Braking peak (N)	Propulsive peak (N)	Braking impulse (N s)	Propulsive impulse (N s)
−9 Down	−337 ± 102	66 ± 13	−34.7 ± 6.7	7.1 ± 2.4
−6 Down	−284 ± 77	102 ± 24	−28.9 ± 5.1	9.5 ± 2.1
−3 Down	−248 ± 56	132 ± 22	−22.3 ± 3.5	12.5 ± 1.2
Level	−195 ± 21	169 ± 12	−16.7 ± 3.7	16.5 ± 2.9
+ 3 Up	−157 ± 47	216 ± 26	−11.4 ± 3.2	21.4 ± 3.2
+ 6 Up	−122 ± 78	253 ± 32	−9.2 ± 2.7	23.7 ± 3.2
+ 9 Up	−89 ± 106	296 ± 29	−5.8 ± 2.9	27.7 ± 3.8

Values represent means for 10 subjects ± standard deviation.
All conditions differed from level running, $p<.0001$.

Table 3
Effects of downhill and uphill angle on running kinematics

Condition (deg)	Stride freq (Hz)	Stride length (m)	Contact time (s)	Swing time (s)	Duty factor
−9 Down	1.42±0.10	2.12±0.16	0.22±0.02	0.47±0.03	0.32±0.02
−6 Down	1.42±0.08	2.12±0.14	0.22±0.02	0.47±0.03	0.32±0.02
−3 Down	1.43±0.07	2.10±0.11	0.23±0.01	0.47±0.04	0.32±0.01
Level	1.45±0.06	2.07±0.10	0.23±0.02	0.47±0.02	0.33±0.01
+3 Up	1.46±0.06	2.07±0.09	0.23±0.01	0.47±0.04	0.33±0.01
+6 Up	1.49±0.07	2.02±0.10	0.23±0.01	0.45±0.03	0.34±0.01
+9 Up	1.51±0.07*	1.99±0.10*	0.23±0.01	0.45±0.03	0.35±0.01*

Duty factor is the fraction of the stride period that one foot spends in contact with the ground.
Values represent means for 10 subjects ± standard deviation.
Conditions that differ from level running are denoted with an '*', $p<0.05$.

Conversely, the mean parallel propulsive force peaks were smaller for downhill running and larger for uphill running (Fig. 4b). During downhill running at −9°, the parallel propulsive force peaks decreased by 61%, while at −6° and −3°, the parallel propulsive peaks decreased by 40% and 22%, respectively. During uphill running at +3°, the parallel propulsive force peaks increased by 28%, at +6° by 50%, and at +9° by 75%. Each of these values statistically differed from level running ($p<0.0001$, Table 2, Fig. 5b).

The parallel impulse data mimicked the trends in the peak parallel forces (Table 2). When running on the level, subjects had an average braking impulse of −16.7 N s and an essentially equal and opposite average propulsive impulse of +16.5 N s. At a downhill angle of −9°, the braking impulse increased by 108% ($p<0.0001$) while the propulsive impulse decreased by 57% ($p<0.0001$). At an uphill angle of +9°, the braking impulse decreased by 65% ($p<0.0001$) while the propulsive impulse increased by 68% ($p<0.0001$).

Stride kinematics were remarkably consistent during downhill and uphill running (Table 3). Except for the steepest uphill angle, kinematics were not significantly different from level. For uphill running at +9°, stride frequency increased by 4% ($p = 0.04$), and duty factor increased by 5% ($p = 0.05$).

4. Discussion

The normal impact force peaks are larger during downhill running and smaller during uphill running. However, neither downhill nor uphill running affect normal active force peaks. Parallel braking force peaks are greater during downhill running whereas propulsive force peaks are greater for uphill running. Overall, our level running force data, for both normal and parallel components, are quite similar to comprehensive studies of the past (Cavanagh and Lafortune, 1980; Munro et al., 1987).

First, we accept our hypothesis that normal impact force peaks would be greater in downhill running and reduced for uphill running. These impact force changes during hill running are accentuated since the subjects altered their method of foot strike. During downhill and level running, all subjects initially contacted the ground with their rear-foot, but as the uphill angle increases, subjects progressively landed on their mid-foot.

The normal impact force peak data suggest that the probability for musculoskeletal injury increases during downhill running and decreases during uphill running. Hreljac et al. (2000) found that the primary biomechanical variable that distinguishes injured from never injured runners is impact peak force magnitude. The magnitude of the vertical impact peak for the injury group was 13% larger than the non-injury group, a difference equivalent to downhill running at −3°. Our data combined with those of Hreljac et al. allow us to conclude that persons trying to recover from impact injuries would benefit by avoiding downhill running and possibly incorporating purely uphill treadmill running. Other authors also state that high impact forces are associated with an increase in the occurrence of injury (Clement and Taunton, 1981; Grimston et al., 1994). Impact forces can be moderated by increasing the knee flexion angle at foot strike and decreasing stride length during downhill and level running, but such modifications are metabolically expensive (Derrick et al., 1998; McMahon et al., 1987). Athletic footwear is another option purported to reduce high impact peaks. However, numerous studies have surmised counterintuitively that leg shock is not attenuated by shoe cushioning (Nigg et al., 1987, 1988, 1998).

Second, we reject our hypothesis that normal active force peaks would be greater during downhill running and reduced during uphill running. Because we find no significant change in the normal active force peaks, our findings differ from those of Iversen and McMahon (1992) while confirming and extending those of Dick and Cavanagh (1987). The average normal force over a complete stride during hill locomotion must equal the product of mass, gravity, and the cosine of the angle. The cosine of 9° is 0.988, so the average normal forces are almost indistinguishable from level running. The normal active force peaks in level running are typically directly related to the average normal force and inversely related to duty factor (McMahon et al., 1987). The present study and that of Iversen and McMahon (1992) are similar in terms of running speed (3 m/s) and ranges of hill angles (4° and 10° versus 3°, 6°, and 9°). However, Iversen and McMahon instructed subjects to perform each trial, both downhill and uphill, with a fore-foot strike style of running. We did not direct our subjects to use a certain foot strike style, but all subjects preferred to land on their rear-foot during downhill and level running. This difference in foot strike style may have influenced duty factor. Iversen and McMahon did not detect any changes in duty factor, while we identified a slight decrease in duty factor during downhill running and a significant increase during uphill running.

Multiple researchers have formulated versions of spring-mass models that reproduce the impact and active force peaks during running (Alexander, 1995; McMahon and Cheng, 1990; McMahon and Greene, 1979; Nigg and Anton, 1995). These models consist of a large mass representing body mass and a smaller mass representing a foot. The large mass is connected to the foot by a leg spring. The shoe cushioning properties comprise a second shoe spring that interfaces the foot and the ground. The body mass and the leg spring produce the smooth active force curve while the foot mass and shoe spring produce the abrupt impact peak. The impact force is determined by the effective mass of the foot, landing velocity and the passive shoe stiffness. Of these variables, only landing velocity changes. Therefore, the model correctly predicts that impact force peaks would increase during downhill running and decrease during uphill running. According to the model, the peak active force is determined by mass, landing velocity and leg stiffness. Landing velocity increases during downhill running and decreases during uphill running. There is an inverse relationship between landing velocity and duty factor (McMahon and Cheng, 1990). Thus, to maintain the same peak active force, leg stiffness must decrease during downhill running and increase during uphill running.

Third, we reject our hypotheses that changes in parallel forces would be symmetrically opposite for downhill and uphill running at each angle. As expected, parallel braking force peaks increase during downhill running and parallel propulsive force peaks increase during uphill running. But, both the parallel force peak and impulse values illustrate somewhat puzzling trends. During level running at a constant speed, the braking and propulsive impulses must be equal and opposite. During downhill running, the magnitude of increase for the braking impulse is much greater than the magnitude of decrease for the propulsive impulse. For instance, at a downhill angle of −9°, the braking impulse increases over 108% compared to level running while the propulsive impulse decreases by just 57%. This asymmetry does not exist during uphill running. At an uphill angle of +9°, the braking and propulsive impulses both decrease and increase by approximately 65% compared to level running, respectively. It appears that during downhill running, subjects apply larger than needed braking force and thus could not reduce propulsive force proportionately. During uphill running, subjects symmetrically modify both parallel braking and propulsive impulses to sustain the treadmill speed. The reason for this discrepancy cannot be resolved with only GRF data, but it is clear that the strategy chosen by runners during downhill running is not force minimization.

These trends of the parallel force peaks correspond to some aspects of the metabolic cost of hill running (Margaria, 1976). The metabolic cost associated with various types of muscle contractions remains a feasible explanation for the high cost of uphill running where propulsive forces dominate (Minetti et al., 1994). But it is more challenging to explain the low cost of downhill running where braking forces dominate. Concentric muscle contractions during propulsion are more metabolically expensive than eccentric muscle contractions during braking (Abbott et al., 1952). During downhill running, the muscles lengthen while exerting tension, performing less expensive negative work (Gabaldon et al., 2004). During uphill running, the muscles likely shorten while exerting tension (Roberts et al., 1997), performing more expensive positive work (Heglund and Cavagna, 1987). The changes we find in the parallel GRF data partially explain the positive inflection of metabolic cost during downhill running at steep angles. At progressively steeper declines, the parallel propulsive impulse does not decrease linearly but the parallel braking impulse increases linearly. Thus, these asymmetrical parallel propulsive impulse values result in an increase in metabolic cost due to concentric muscle contractions.

In summary, during running, as the angle of the hill changes from a steep downhill to a steep uphill: normal impact force peaks decrease, normal active force peaks do not change, parallel braking force peaks decrease, and parallel propulsive force peaks increase. These data can explain the pattern of metabolic energy consumption during downhill running and they suggest that downhill running increases the risk of injury.

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