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Erin Heald

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Erin L. Heald

College of William and Mary

Honors Committee:

Dr. Raymond McCoy (advisor)

Dr. Michael Deschenes

Dr. Catherine Forestell

Abstract

The purpose of this study was to analyze the effect of cross-sloped surfaces on the kinematics of recreational female runners. Eleven recreational female runners (20.2 ± 1.2 years, 59.8 ± 8.6 kg, 1.65 ± 0.04 m) volunteered to run on a treadmill at a moderate pace of 3.35 m/s in three conditions: level (L), 5^0 lateral elevation (LE), and 5^0 medial elevation (ME). Each participant ran in the same model of neutral shoes with a window cut out of the heel to allow for two calcaneal markers to be placed directly on the skin. Joint angles were recorded for two strides in each condition from the rear and the side view using two Sentech cameras (100 frames/second) and then digitized manually. A repeated measures ANOVA ($p<0.05$) was performed to analyze lower extremity kinematics in the sagittal and frontal planes of the pelvis, hip, knee, and ankle joints. In the frontal plane, the peak medial angle of the rearfoot with respect to the surface of the treadmill (RF/TM) was greater during LE than ME. At foot strike, the RF/TM angle was greater for LE than ME, and greater for L than ME. Rearfoot eversion with respect to the tibia (RF/TB) at foot strike, peak hip adduction, and peak dorsiflexion were all significantly greater for LE than ME. Knee valgus, pelvic tilt, and sagittal plane kinematics were not significantly different between conditions. These results help us understand how the body reacts to cross-sloped surfaces, and the implications for potential injuries.

The Effect of Cross-Sloped Surfaces on Running Kinematics

Recreational running is one of the most accessible forms of exercise, given that the only equipment necessary is a good pair of shoes. Whether a person is running on a sidewalk, road, or trail, the surface is likely to have a slight medial elevation (ME) or lateral elevation (LE) (*Figure 1*). In contrast to uphill-downhill tilt, medio-lateral tilt in the horizontal plane is referred to as "cross-slope." On roads, the cross-slope built for water drainage and banking is referred to as "camber." Sidewalks in the US should not exceed 1.1^0 of cross-slope according to the US Department of Transportation (2001), and it is recommended by the Virginia Department of Transportation (2017) that roads in subdivisions have 1.8^0 camber. Researchers have hypothesized that biomechanics of locomotion on cross-sloped surfaces would exhibit significant changes in joint angles and forces in the lower extremities (Dixon & Pearsall, 2010) (Willwacher, Fischer, Benker, Dill, & Brüggemann, 2013) (Dixon, Tisseyre, Damavandi & Pearsall, 2011) (Damavandi, Dixon, & Pearsall, 2010) (O'Connor & Hamill, 2002).

Early research of the effect of medio-lateral elevation of the foot during running was performed using shoes that had sloped soles. A pair of shoes with 10^0 of lateral elevation, and a second pair with 10^0 of medial elevation were compared to neutral shoes. Maximum values for pronation were greatest for the laterally elevated shoes, followed by the neutral shoes, and least for the medially elevated shoes. Pronation in this study was defined as calcaneal valgus, or the movement of the bottom of the calcaneus away from the body. This was measured by comparing the angle between the calcaneus and the tibia. Each condition had approximately 10^0 difference in pronation, reflecting the elevation of the shoes. Laterally elevated shoes caused 10^0 more pronation than neutral shoes, which caused 10^0 more pronation than medially elevated shoes

(Van Woensel & Cavanagh, 1992). While this research did not study cross-slopes specifically, the results indicate that mediolateral elevation of the foot during landing is associated with changes in pronation. It is important to note the difference between pronation and eversion, as eversion is a uniplanar movement, and pronation is a tri-planar movement that includes rearfoot eversion in addition to movement of the foot up and away from the ankle, also known as abduction (Pronation, n.d.). In the study by Van Woensel & Cavanagh (1992), pronation is synonymous with rearfoot eversion, but pronation may reflect a different angle in other studies.

Kinetics of Cross-Slope Walking

Research of walking on cross-slopes demonstrated changes in mediolateral force when compared to walking on level surfaces. Medially elevated slopes were associated with medially directed ground reaction force (GRF), and laterally elevated slopes were associated with laterally directed GRF (Damavandi, Dixon, & Pearsall, 2012) (Dixon & Pearsall, 2010). Essentially, the force of the ground opposing the force of the runner was directed uphill as the participants worked to stay upright. In the study by Dixon & Pearsall (2010), 10 young adult male participants walked barefoot at a self-selected pace on a wooden walkway. The 6.91-meter long walkway could be inclined to 6^0 for the cross-slope condition, and it contained two consecutive force plates, to capture one step from each foot during walking. In the study by Damavandi et al. (2012), 9 young adult male participants walked barefoot at a self-selected pace on a 7-meter long walkway that could be inclined to 10^0. Only one force plate was used in this study, but participants walked both directions on the platform to record data for both feet. The main difference between these two studies was the degree of cross-slope. Walking on ME cross-slopes was shown to increase medially directed GRF by 300% when compared to level (Dixon &

Pearsall, 2010). For the larger cross-slope of 10^0, the magnitude of this force was 390% greater than level walking (Damavandi et al., 2012), indicating that greater slope created greater medially directed GRF.

Kinematics of Cross-Slope Walking

In addition to studies of cross-slope walking kinetics, other research has emphasized kinematic adaptations for walking on cross-slopes. Kinematic measurements describe movement, velocity, and time, while kinetic measurements describe the forces that cause or result from motion. Damavandi et al. (2010) studied the kinematic adaptations of intra-foot segments for participants walking barefoot on a 10^0 cross-slope. The methods were the same as for the previously mentioned study by Damavandi, et al. (2012), but included foot markers to differentiate between hindfoot, forefoot, and hallux (first toe) kinematics. GRF data were used to locate events of the stance phase where joint angles were recorded. Researchers measured angles for the hindfoot with respect to the tibia (HF/TB), forefoot with respect to the hindfoot (FF/HF), and hallux with respect to the forefoot (HX/FF). For ME at foot strike, the HF/TB was everted, then transitioned to inversion in mid-stance. At the same time, the FF/HF was also inverted in mid-stance and everted at toe-off. The opposite movement sequence was reported for LE. At foot-strike, HF/TB was inverted, transitioning to eversion in early stance. The FF/HF angle was also everted at mid-stance and inverted at toe-off. In simpler terms, weight shifts from the inside, to the outside, to the inside of the foot for ME, and outside, to inside, to outside for LE. It was hypothesized that the rearfoot eversion or inversion at foot strike could be the body's anticipatory method of countering the cross-slope since the elevated side of the foot was the first part of the foot to make contact. After the initial foot strike, the foot rolled to conform to the

slope. If the foot were to land with a midfoot center of pressure rather than with mediolateral

shift, the ankle could roll down-slope and potentially cause falls (Damavandi et al., 2010).

Kinematics of Cross-Slope Running

Studies of walking on cross-slopes could be used to predict outcomes for running, but the

increased vertical ground reaction forces, added flight phase (Farley & Ferris, 1998), and narrow

step width of running (O'Connor & Hamill, 2002) cause differing results in the sagittal plane.

Previous research has suggested that walking on cross-slopes creates a functional leg-length

discrepancy (Dixon & Pearsall, 2010) due to the way one foot lands up higher on the slope than

the other. A functional leg-length discrepancy would manifest as greater flexion of joints on the

LE side to try to make the upper body level. In contrast, functional leg-length difference during

running on cross-slopes was not significant (O'Connor & Hamill, 2002) (Unfried, Aguinaldo &

Cipriani, 2013) (Dixon et al., 2011). One contributing factor to the lack of leg-length discrepancy

was a smaller step width for cross-slope running than level running (Dixon & Pearsall, 2010). A

smaller step width for cross-slope running implies that both feet are landing near the same height

on the slope. Therefore, it is not necessary for the uphill leg to functionally shorten by joint

flexion in the sagittal plane. In a multi-segment foot model for running, the only significant

sagittal plane difference between level and LE conditions was extension of the hallux at foot-

strike (Dixon et al., 2011). It is unlikely that lifting the big toe would decrease the functional

length of the LE leg to adapt to the cross-slope. In another study of cross-slope running, Unfried

et al. (2013) studied the effect of cross-slopes on lower extremity muscle activity and the implied

differences in sagittal plane joint movements. Fifteen male and female recreational runners ran

on an outdoor road with camber between 5^0 and 7^0. Surface electrodes were used to collect EMG

data from muscles in the right leg: tibialis anterior, lateral gastrocnemius, vastus medialis oblique, biceps femoris, and gluteus medius. Participants ran on the level part of the middle of the road and both directions at the edge of the road where cross-slope was greatest. The researchers reported no significant differences in EMG between LE and ME of the right leg during the swing phase. This confirmed that muscles that would cause greater flexion did not have to be more active on the LE side in order to clear the higher side of the road (Unfried et al., 2013).

Kinetics of cross-slope running

Changes in kinetics during cross-slope running can be used to predict changes in kinematics in studies where ground reaction force (GRF) data is not available. Similarly to walking, running on cross-slopes has been shown to shift the medio-lateral force up-slope (Damavandi et al., 2012). One of the most recent studies of cross-sloped running examined kinetics to better understand the effect of cross-slope on trauma and overuse injuries in runners (Willwacher et al., 2013). Nineteen young male participants ran on an inclinable runway that could be adjusted to a 3^0 or 6^0 cross-slope. All the participants were heel or midfoot-strikers, meaning the first part of their foot to contact the runway was either the heel or midfoot. They all wore the same type of neutral racing flat with window holes cut in the heel of the shoe. This window allowed researchers to directly view movement of the rearfoot rather than the movement of the shoe over the heel. Running pace was set by barriers moving at 3.5 m/s in front of and behind the participant. This speed was within the average training speed of each participant, and was similar to speeds used by previous studies. The researchers measured contact time, peak GRFs, mean point of force application (PFA), peak external joint moments, and GRF lever arms.

Results showed that the PFA for the laterally elevated foot shifted laterally while the PFA for the

medially elevated foot shifted medially (Willwacher et al., 2013). This could be reflected in

kinematic data as greater eversion or inversion at the foot or ankle as the PFA shifts. Compared

to the level condition, a smaller first peak of the vertical GRF data was reported for cross-slopes.

This could be explained by a shift from a heel strike to a mid or forefoot strike on cross-slopes

(Willwacher et al., 2013). Without kinetic data, this change in foot strike due to cross-slope may

be characterized kinematically by visual assessment or measurement of the foot strike angle. In

addition to changes in the direction of force, the magnitude of peak mediolateral GRF increased

by 530% for cross-slope running compared to level (*Figure 2*). This peak GRF occurred earlier

in stance for LE than other conditions (Damavandi et al., 2012). Based on these changes in GRF,

range of motion and velocity would be expected to increase in the mediolateral direction for

cross-sloped running if kinetic data were not available.

Rearfoot Eversion in Cross-Slope Running

Excessive pronation excursion that occurs later in stance has been linked to exercise-

related lower leg pain (Willems, Witvrouw, De Cock, & De Clercq, 2007). This study measured

pronation by summing the vectors for eversion, abduction, and dorsiflexion at the ankle. Other

research has reported no significant association between rearfoot eversion and patellofemoral

pain, a specific type of lower leg pain (Noehren, Hamill & Davis, 2013). Whether or not

excessive eversion is a risk factor for injury, it is important to measure in a gait study because the

amount of eversion changes significantly on cross-slopes in comparison to level surfaces

(O'Connor & Hamill, 2002) (Dixon et al., 2011). O'Connor & Hamill (2002) conducted a study

to determine if running on cross-sloped roads could increase injury risk. Twelve male

participants, wearing the same shoe model, ran on a treadmill for about 2 minutes in each

condition at 3.8 m/s. Although the trial time was short, it was long enough to indicate gait

patterns that if repeated during a longer run, could put extra stress on the body. The treadmill

was elevated on the left side to create a 3^0 cross-slope. Rearfoot kinematics were analyzed to

assess mediolateral control on cross-slopes in comparison to level surfaces. Researchers reported

the greatest eversion occurred on the LE side, and the least eversion during level running. Total

rearfoot motion and maximum eversion velocity was similarly greatest for the LE side

(O'Connor & Hamill, 2002) (Dixon et al., 2011). Dixon et al. (2011) also focused their study on

the effect of cross-slope running on foot kinematics, but they additionally measured intra-foot

kinematic adaptations. Like Damavandi et al. (2012), this study included angles for hindfoot,

forefoot, and hallux: HF/TB, FF/HF, and HX/FF, respectively. Other gait models could only

detect rearfoot eversion, but this model could separate forefoot eversion from the rest of the

foot's movement. Forefoot eversion was reported as greater at the time of maximum vertical

GRF for ME than the level condition. Their results also showed greater hindfoot inversion at foot

strike for LE than ME, but O'Connor & Hamill (2002) reported the opposite—greater inversion

at foot strike for ME than LE. This could be due to differences in cross-slope angle: Dixon et al.

(2011) used 10°, while O'Connor & Hamill (2002) used 3° of cross-slope. Additionally, Dixon et

al. (2011) used a multi-segment model of the foot, while O'Connor & Hamill (2002) used three

markers on the rearfoot to measure 3-dimensional movement. The model used by Dixon et al.

(2011) would allow for separate analysis of inversion at the rearfoot and the forefoot, potentially

creating more accurate results than the results from O'Connor and Hamill (2002).

Although the eversion angle is often used to determine risk of overuse injuries, some

research suggests it is not well correlated with external eversion moment, which directly

measures forces on the joint that could predict injury (Tsujimoto, Nunome, & Ikegami, 2016). Studies that used joint moments to understand how forces change for cross-slope running have reported greater joint moment changes associated with the LE condition than the ME condition (Willwacher et al., 2013) (O'Connor & Hamill, 2002). The external ankle eversion moment for a 6^0 cross-slope increased by 35% for LE compared to level. For ME, the external ankle eversion moment decreased by 16% when compared to level (Willwacher at el., 2013).

Biomechanics of Female Runners

Previous research of running on cross-slopes lacks data on female participants (Willwacher et al., 2013) (Dixon et al., 2011) (Damavandi et al., 2012) (O'Connor & Hamill, 2002) even though women made up 57% of running race finishers in the U.S. in 2015 (Running USA, 2016). Female biomechanics during running are impacted by a larger hip width to femur length ratio when compared to men. As a result of the wider pelvis and femoral internal rotation, the Q-angle (*Figure 3*), or quadriceps angle of force direction on the patella, is 4.6^0 larger for females than males (Horton & Hall, 1989). A later study by Guerra, Arnold, & Gajdosik (1994) investigated gender differences in Q-angle using four different measuring strategies. The participant was either standing or supine, with or without an isometric quadriceps contraction. This study also reported a greater Q-angle for women than men across all four conditions. To understand the effect of these biometrics in women, researchers analyzed the differences between males and females while walking and running on a treadmill at various paces and grades of inclination (Chumanov, Wall-Scheffler & Heiderscheit, 2008). Half of the 34 participants were male, and half were female. Forty reflective markers were placed on anatomical landmarks of the body to collect kinematic data, and EMG surface electrodes were used to measure activity

of the hip adductors, gluteus medius, gluteus maximus, and vastus lateralis muscles on the right

side of the body. Researchers reported greater lateral pelvic tilt excursion in females during

walking. Additionally, they reported greater peak hip adduction and hip internal rotation for

females than males during walking and running (Chumanov et al., 2008). Ferber, Davis &

Williams (2003) reported the same results for gender differences in hip adduction and hip

internal rotation. The population for this study was specifically recreational runners, 20 men and

20 women, who were all rearfoot-strikers. This study focused on hip and knee kinematics rather

than differences across the whole body. The participants ran on a 25-meter platform with a force

plate at an average speed of 3.65 m/s, a moderate speed, although it may not be equally

challenging for men and women. In addition to greater hip adduction and hip internal rotation,

they reported that female runners had greater knee valgus, and more negative work was

performed by the hip abductors in the frontal and transverse planes (Ferber, Davis & Williams,

2003). This is supported by evidence of greater activity of the gluteus maximus, a hip external

rotator, during the stride of females during running (Chumanov, Wall-Scheffler & Heiderscheit,

2008).

Risk of Injury in Female Runners

These differences in female gait patterns have been linked to higher risk of certain

injuries such as tibial stress fracture (TSF), iliotibial band syndrome (ITBS), and patellofemoral

pain (PFP) (Pohl, Mullineax, Milner, Hamill, & Davis, 2008) (Noehren, Davis, & Hamill, 2007)

(Taunton, Ryan, Clement, McKenzie, Lloyd-Smith, & Zumbo, 2002) (Foch, Reinbolt, Zhang,

Fitzhugh, & Milner, 2015) (Noehren, Hamill, & Davis, 2013). In a retrospective study of 30

female runners that had a history of TSF and 30 age and mileage-matched controls, researchers

analyzed biomechanical factors that were associated with TSF. Greater hip adduction and

rearfoot eversion were strongly associated with a history of tibial stress fracture, correctly

predicting a prior TSF 83% of the time (Pohl et al., 2008). Another study by Noehren et al.

(2007) collected kinematic and kinetic data from 400 currently healthy female participants who

ran at least 20 miles per week and had no previous knee or hip injuries. Eighteen women from

the original group developed ITBS over a 2-year follow-up period. The data from the beginning

of the study were analyzed for differences between the women who developed ITBS and their

age and mileage-matched healthy controls. Excess hip adduction and knee internal rotation were

strongly associated with development of ITBS and were identified as risk factors for ITBS.

Rearfoot eversion was not significantly different between the group with ITBS and the group

without (Noehren et al., 2007). In support of the association of ITBS with female gait

characteristics, it was reported that women are twice as likely as men to be affected by ITBS

(Taunton et al., 2002). This study included 2,002 patients with injuries related to running, and

analyzed the strength of associations between factors such as gender, age, height, weight, activity

history, and the type of injuries sustained. Foch et al. (2015) studied 27 female runners who were

divided into categories of past ITBS, current ITBS, and healthy controls. Participants ran on a

17-meter long runway with a force plate for gait analysis. IT band flexibility was measured with

the participant lying on his or her side, the pelvis perpendicular to the exam table. A gravity

goniometer was placed at the knee, and the examiner stabilized the pelvis while the participant

raised the top leg away from the stationary leg. Hip abductor strength was measured with a hand-

held dynamometer during isometric contraction. In women with current ITBS, hip abductor

strength was low, and IT band flexibility was also low (Foch et al., 2015). Although these

observations could be a result of the ITBS, they could also be contributing factors to the cause of

ITBS. If women have greater adduction during running and the hip abductors are too weak to control it, the IT band could become excessively tight, creating pain and altered biomechanics. Since retrospective studies do not establish causal relationships as well as prospective studies, the study by Noehren et al. (2013) was important for linking gait characteristics to future injury risk. In a group of 400 healthy female runners, gait was analyzed at the beginning of the study, and researchers tracked the incidence of patellofemoral pain (PFP) in the participants over 2 years of follow-up. Females that developed PFP within the follow-up period had significantly greater hip adduction at the beginning of the prospective study than their age-matched controls who had no PFP. There was no significant association of PFP with peak hip internal rotation or rearfoot eversion (Noehren et al., 2013). In female runners, it is important to identify running environments that could increase hip adduction, knee internal rotation, and rearfoot eversion beyond biomechanical norms because of the increased risk of injury. Cross-sloped surfaces could augment these risks, putting additional stress on the joints.

Predictions

The purpose of the current study was to analyze the effect of cross-sloped surfaces on the kinematics of recreational female runners. Based on previous literature, it was hypothesized that there would be no sagittal plane differences between cross-sloped and level surfaces. Foot strike was expected to shift from heel-strike to midfoot or forefoot on cross-slopes. Although there was no previous data on stride rate or length, due to a predicted lack of sagittal plane differences, it was hypothesized that stride length and stride rate would not change on cross-slopes. In the frontal plane for the LE condition, it was expected that left lateral pelvic tilt, peak hip adduction, knee valgus, and rearfoot eversion would all be greater than that of the ME and level conditions.

Additionally, the rearfoot was hypothesized to be more inverted at foot strike for LE when compared to ME and level conditions. Finally, step width was predicted to decrease on cross-slopes in comparison to level surfaces.

Methods

Participants

A total of 11 volunteers were recruited from the College of William and Mary campus (59.8 ± 8.6 kgs, 1.65 ± 0.04 m, BMI 21.9 ± 3.2, 20.2 ± 1.2 years). Participants were females between the ages of 18-24 years who ran an average weekly mileage between 10 and 25 miles. Collegiate and elite runners were excluded due to their advanced training experience. Participants reported having no lower extremity injuries in the previous 6 months, did not wear orthotics in their running shoes, and had no leg length discrepancies greater than two cm. Participants had shoe sizes ranging from 7.5-10.5, limited by the shoe sizes provided for this study.

Experimental set-up

During the trials, participants wore Asics Cumulus 17 running shoes (a neutral cushioned shoe) with a window cut out in the heel of the right shoe (the primary leg of interest). A sharp knife was used to cut the heel window with a large enough diameter to see two markers directly on the calcaneus (*Figure 4*). This method provides more accurate rearfoot data than markers placed on the shoe (Stacoff, Reinschmidt, Stussi, 1992). A combination of 3D ball markers and 2D markers drawn on the participant's skin were used to track movement of the right lower extremity in the video recordings. Two Sentech cameras recorded video of the runners at 100 frames per second: one for the side view of the right side of the body (1.5:1 aspect ratio) and one

for the rearview (1.4:1 aspect ratio). Both cameras were perpendicular to the participant on the

treadmill at a height of 1 meter from the floor. The side view camera was 3.5 meters from the

treadmill, and the rearview camera was 4.25 meters from the treadmill. Three 300-Watt lamps

illuminated the participant from the side and rear (*Figure 5*). The TRUE700 treadmill could be

manually elevated laterally with wooden blocks to create five degrees of cross-slope. This degree

of camber was determined based on angles of cross-slope in previous research and data for

average camber collected from suburban roads around the Williamsburg, Virginia area. An

inclinometer was used to measure camber approximately one foot from the edge of roads that are

commonly used for running in Williamsburg, Virginia. Twenty total readings were taken in five

neighborhoods with paved roads, and they averaged to 5.3^0. The computer programs MaxTRAQ

and MaxMATE (Innovision Systems, Inc.) were used to record, digitize, and analyze the video

files.

Recording Procedures

Participants came to the lab for an initial visit to fill out an informed consent form,

exercise screening questionnaires, and an eligibility questionnaire. The eligibility questionnaire

contained questions about the participant's injury and running background. The participant's leg

length was measured from greater trochanter to lateral malleolus to verify that there was no more

than a two-cm difference between right and left legs. Each qualifying participant ran on the

treadmill in the lab shoes and barefoot before the recorded trial day to allow them to become

accustomed to the trial conditions: barefoot (BF), level (L), 5° LE, and 5° ME. Data were

collected for only the right leg on the recording day, so LE indicated that the right foot was

higher, and ME indicated that the right foot was lower when standing on the treadmill. The

acclimation trials lasted three minutes per condition with rest between trials.

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The trial recording day occurred at least 24 hours after acclimation, but within a week of acclimation. Markers for the side view on the right leg were placed at the following locations: 5th metatarsal head, lateral calcaneus, lateral malleolus, lateral femoral epicondyle, superior aspect of the greater trochanter, and the middle of the neck (*Figure 6*). Markers for the rearview were placed at the following locations: superior aspect of left and right posterior superior iliac spines, two points in a vertical line on the shank, two points in a vertical line on the right calcaneus viewed through shoe window, and the base of the left and right shoes (*Figure 7*).

Each subject ran in each condition in a randomized order. After a static initial capture to be used as a baseline for marker alignment, each participant ran in each condition for approximately three minutes in each of the 4 trials (BF, LE, ME, L). Cavanaugh (1990) determined that 3.8 m/s was a "typical distance running speed" (p. 69) for a young adult male, so the pace equivalent of 3.35 m/s for a female of the same age was used in this study (Fitness calculators, n.d.). The participant's heart rate was monitored using a Polar A300 heart monitor to ensure that the heart rate was within the range for low to moderate exercise (57-76% of maximum heart rate) based on the age-predicted maximum heart rate (Pescatello, Arena, Riebe, Thompson, 2014). Participants ran for approximately one minute before two, 2-second recordings were taken to capture at least two strides per condition. In order to synchronize the recordings from side and rearview cameras, one researcher silently cued two others to manually start the video recordings from two separate computers. Rest between trials lasted three minutes to allow the participant's heart rate to decrease and the treadmill to be set up for the next trial condition.

Data processing and analysis

Manual digitization of each of the markers using MaxTRAQ (Innovision Systems) was performed by 6 researchers, and then edited for consistency. Data were smoothed in MaxMATE using a Butterworth Digital Filter with a cut-off frequency of 8 Hz to control for digitizing error. The digitized points were then used to calculate maximum joint angles during stance phase as well as joint angles at foot strike. The stance phase was defined as the time from foot strike to one frame before toe-off. From the side view recording, angles were analyzed for the hip, knee, ankle, and foot relative to the treadmill (*Figure 8*). Stride rate and stride length were also calculated. From the rearview recording, angles were analyzed for lateral pelvic tilt (*Figure 9*), hip adduction (*Figure 10*), knee valgus (*Figure 11*), rearfoot relative to the tibia (RF/TB) (*Figure 12*), rearfoot relative to the treadmill (RF/TM) (*Figure 13*), and step width. Peak lateral pelvic tilt in each direction was subtracted from the baseline pelvic angle from the standing initial capture to correct for baseline pelvic tilt (which was near 180°). Eversion for the RF/TB angle was defined as any angle greater than 180° and inversion as any angle less than or equal to 180°. For the RF/TM angle, eversion was defined as any angle less than or equal to 90° and inversion as any angle greater than 90°. Angle analysis focused on the stance phase when the right foot was in contact with the ground. Peak values and angles at foot strike were recorded, and data from Stride 1 and Stride 2 for each category within each condition were averaged together before statistical analysis. Using the program IBM SPSS Statistics, a repeated measures ANOVA was performed to determine significant differences. A Bonferroni post hoc test showed where the significant differences occurred between BF, ME, L, and LE conditions. This study focused on the results between cross-sloped and level surfaces. Barefoot data were not included in these

results. Following the data collection and analysis, participants were offered a debriefing and opportunity to watch their recordings.

Results

Running on cross-sloped surfaces led participants to adopt novel movement patterns differing from the biomechanics of running on level surfaces. ANOVA analysis revealed significant differences between lateral elevation (LE), medial elevation (ME), and level (L) conditions in both planes of motion analyzed. In the sagittal plane, peak ankle dorsiflexion was greater for LE (67.2°) than the level condition (69.0°) ($p = 0.001$), and greater than ME (69.8°) ($p = 0.000$) (*Figure 14*). All the other sagittal plane angles were not significantly different. Stride rate and stride length were unchanged across conditions. Foot strike angle did not significantly change on cross-slopes (Table 2).

In the frontal plane, step width, pelvic tilt, and knee valgus did not have significantly different peak angles between conditions. Peak hip adduction, in contrast, was significantly greater for LE (287.3°) than ME (285.6°) ($p = 0.010$) (Table 3) (*Figure 15*).

At foot strike, the rearfoot angle relative to the tibia (RF/TB) showed greater inversion for ME (177.1°) than LE (179.6°) ($p = 0.001$) (*Figure 16*). Peak RF/TB eversion was not significantly different between conditions. When measuring the rearfoot angle relative to the treadmill (RF/TM), angles at foot strike indicated that the rearfoot was more inverted for LE (101.7°) than ME (96.0°) ($p = 0.000$) or the level condition (98.3°) ($p = 0.002$) (*Figure 17*). Peak RF/TM eversion was greatest for ME (86.6°) in comparison to LE (92.7°) ($p = 0.000$) (Table 2) (*Figure 18*).

Discussion

This study revealed information about a population not previously studied in cross-slope running research. Recreational female runners may be at a higher risk of injury than elite male runners due to a larger Q-angle and a lower level of running experience. Changes in the mediolateral elevation of the treadmill were expected to create changes in joint angles in the mediolateral plane. Contrary to the study predictions, there were few significant changes in running gait to indicate a biomechanical reaction to the cross-sloped surface.

Rearfoot movement in the frontal plane during stance phase was measured by two different angles, RF/TB and RF/TM. Our results for running kinematics showed that greater RF/TB eversion occurred at foot strike for LE than ME, which contradicted the results of Damavandi et al. (2010) for walking. The alternative measurement of RF/TM in our study showed more inversion for LE than ME or level at foot strike, corresponding with the results of Damavandi et al. (2010). Greatest peak eversion for RF/TM occurred for ME in comparison to LE in this study, but greatest peak eversion in previous research was identified for LE. This opposing data shows that cross-slope affects running gait differently than walking gait, which could be due to increased vertical ground reaction forces, added flight phase (Farley & Ferris, 1998), and narrow step width of running.

When the data from this study were compared to previous studies of running, rather than walking, there were more similarities. Greater rearfoot inversion at foot strike for LE than ME reported by Dixon (2011) was reflected in our results for RF/TM angles. O'Connor & Hamill (2002) reported the opposite--that there was more inversion at foot strike for ME--and this was

supported by our reported RF/TB angles. The RF/TB angle more accurately corresponds to the way previous studies measured rearfoot eversion. The RF/TM angle depicts what is happening to the rearfoot relative to the treadmill, but does not account for movement of the leg above the ankle. As a result, peak RF/TM eversion caused by LE contradicts what was reported by O'Connor (2002) and Dixon (2011) because these studies measured a different angle for eversion. If RF/TM eversion measured the same changes in kinematics as previous studies of eversion, we could predict that the leg on the LE side of a cross-slope would be more susceptible to injury due to greater eversion. RF/TM angles were not measured in previous studies, so it was an exploratory measure. It is likely that measures of RF/TB eversion explain the full picture of gait adaptations better than RF/TM eversion.

Although previous research led to the hypothesis that there would be no sagittal plane changes between conditions (Dixon et al., 2011) (Unfried et al., 2013), the increased dorsiflexion for LE in this study is a relatively small movement in comparison to knee or hip flexion. This could be explained by functional leg-shortening to adapt to the higher side of the cross-slope (Dixon & Pearsall, 2010).

Willwacher et al. (2013) suggested that the foot strike on cross-slopes was likely to transition to mid or forefoot striking based on GRF data. Angles for foot strike relative to the treadmill were expected to decrease on cross-slopes as the foot strike pattern changed, but there was no significant difference between conditions. Unlike Willwacher et al., our study did not seek participants with heel or midfoot strike patterns, so for participants with a natural toe-strike, shifting of the foot strike forward would be less evident.

Step width was expected to decrease on cross-slopes when compared to the level condition (Dixon & Pearsall, 2010), but our results showed no significant difference for step

width. This could be due to the small number of steps analyzed for step width. Each trial recording consisted of only two strides averaged together, and step width is highly variable. This measurement would be more accurate if a greater number of strides were analyzed and averaged.

Since the angle for lateral pelvic tilt was measured relative to the horizontal and not relative to other parts of the body, the use of baseline pelvic tilt was expected to increase the accuracy of pelvic tilt measurements during running. Though the values in this study were not significantly different between conditions, this technique is recommended for future studies to allow for comparison between subjects by controlling for discrepancies in marker placement and pelvic alignment.

Although knee valgus was expected to change on cross-slopes, it was not significantly different between conditions. This could be due to adaptations in other joints, such as the ankle or the hip, allowing the knee to maintain the same movement pattern despite a cross-sloped surface.

The increased hip adduction for LE in comparison to ME is particularly important to note, given that the participants were all female. If the femur was exactly perpendicular to the pelvis, the hip adduction angle would be 270 degrees. The hip adduction angle of 287.3 degrees for LE indicates that the femur is adducted 17.3 degrees past vertical, and could alter the direction of forces on lower extremity joints. When weight-bearing on the laterally elevated leg, the body is likely to shift up-slope to counterbalance against the slope. This movement could contribute to the increased hip adduction as the pelvis shifts up-slope and the foot remains at the same location on the treadmill. Greater hip adduction puts female runners at higher risk of developing TSF, ITBS, and PFP (Pohl et al., 2008) (Noehren et al., 2013) (Noehren et al., 2007).

Limitations to the Study

This study was limited by the technology available for recording running biomechanics. In contrast to a two-camera, two-dimensional set-up, an 8-camera Vicon three-dimensional recording system including a force plate would allow for kinematic and kinetic data to be captured and synchronized (Dixon et al., 2011). This type of system would help us more precisely locate foot strike and toe-off using kinetic data, and it would also allow for faster processing. This would make it feasible to collect more data from a greater number of participants and would eliminate the need for multiple digitizers. Even though all digitized recordings were assessed for consistency, multiple people digitized the recordings, so there may have been some inter-digitizer error. When markers were obscured, digitizers had to approximate the location of the marker. This could also be improved by an 8-camera Vicon system and mathematical processing system that could calculate the path of a marker based on previous strides.

Future Research in Cross-Sloped Running

Future research should be conducted to explore adaptations at the hip during cross-sloped running. Placing ball markers on the skin over the pelvis may not be the best way to measure pelvic biomechanics, but previous research has not compared pelvis marking systems for cross-slope running. Data from the participants' injury history could be studied for associations between previous injuries and the change in hip adduction on cross-slopes. Additionally, gluteus maximus and gluteus medius strength could be studied to analyze how isometric hip strength is reflected in dynamic hip strength during running on cross-slopes. Females continue to be a critical population of study for running as most of the running research has historically focused on male participants.

Conclusion

A surface with 5° of cross-slope created changes in kinematics for female recreational runners who naturally adapted to the mediolateral challenge. RF/TB inversion at foot strike was greatest for ME, while RF/TM inversion at foot strike was greatest for LE. Peak RF/TM eversion was greatest for ME, but this angle may not be a true reflection of eversion because it does not account for movement of the tibia. Ankle dorsiflexion and hip adduction were both greater for LE. The majority of angle values that changed significantly between conditions were greatest for LE, affecting the right leg when a runner is moving against traffic on the left side of a road. In female runners who have a higher risk of certain injuries due to greater hip adduction, cross-slope-induced hip adduction increases injury risk further. Based on the results of this study, it is recommended that female recreational runners should limit the amount of time they spend running on cross-sloped surfaces to decrease their risk of lower extremity injury.

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Table 1

Descriptive Data on Participants

Participant #	Height (m)	Weight (kg)	BMI (kg/m^2)	Age (yr)
1	1.62	54.4	20.6	21
2	1.60	53.1	20.7	19
3	1.63	59.0	22.3	20
4	1.62	52.2	19.7	20
5	1.74	50.8	16.8	23
6	1.65	59.4	21.8	20
7	1.65	77.1	28.3	20
8	1.65	72.6	26.6	19
9	1.68	65.8	23.3	21
10	1.65	58.1	21.3	20
11	1.68	54.9	19.5	19
Mean ± SD:	**1.65 ± 0.04**	**59.8 ± 8.6**	**21.9 ± 3.2**	**20.2 ± 1.2**

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Table 2

Side View Joint Angles

Angle (degrees)	Medial Elevation (ME)	Level (L)	Lateral Elevation (LE)	*p* value LE - L	*p* value ME - L	*p* value ME - LE	F-value
Hip flexion (P)	147.4 ± 5.22	147.5 ± 5.40	148.3 ± 5.50	1.000	1.000	0.306	15.4
Knee flexion (P)	130.4 ± 4.12	130.9 ± 4.47	130.6 ± 4.15	1.000	1.000	1.000	11.0
Ankle dorsiflexion (P)	69.8 ± 2.33	69.0 ± 1.92	67.2 ± 2.32	0.001 *	0.158	0.000 *	6.8
Foot strike relative to horizontal (FS)	7.7 ± 6.8	8.1 ± 6.17	8.9 ± 6.47	0.600	1.000	0.615	14.1

Note. Peak angles labelled (P) and angles at foot strike (FS). Mean angles ± S.D. and *p* values for each pairwise comparison are presented.
* Indicates significant difference.

Table 3.

Rearview Joint Angles

Angle (degrees)	Medial Elevation (ME)	Level (L)	Lateral Elevation (LE)	*p* value LE-L	*p* value ME-L	*p* value ME-LE	F-value
Rearfoot relative to treadmill (FS)	96.0 ± 4.13	98.3 ± 4.77	101.7 ± 4.16	0.002 *	0.052	0.000 *	18.8
Rearfoot relative to treadmill (P)	86.6 ± 3.91	89.4 ± 4.67	92.7 ± 2.99	0.066	0.116	0.000 *	15.0
Rearfoot relative to tibia (FS)	177.1 ± 1.29	179.1 ± 1.44	179.6 ± 1.17	1.000	0.110	0.001 *	6.9
Rearfoot relative to tibia (P)	190.0 ± 5.08	192.0 ± 4.41	192.9 ± 3.64	1.000	0.759	0.011	3.0
Knee valgus (P)	182.5 ± 4.70	182.7 ± 4.59	183.8 ± 4.46	0.390	1.000	0.954	2.8
Hip adduction (P)	285.6 ± 2.41	286.3 ± 2.24	287.3 ± 2.52	0.460	0.826	0.010 *	6.8
Lateral pelvic tilt left (P)	-4.6 ± 0.64	-4.8 ± 0.69	-4.9 ± 0.61	1.000	1.000	1.000	0.3
Lateral pelvic tilt right (P)	3.8 ± 0.47	3.7 ± 0.50	3.8 ± 0.58	1.000	1.000	1.000	2.8
Step width	2.13 ± 4.56	2.20 ± 4.87	3.25 ± 4.91	0.362	1.000	0.341	1.4

Note. Peak angles labelled (P) and angles at foot strike (FS). Mean angles ± S.D. and *p* values for each pairwise comparison are included.
* Indicates significant difference.

Table 4

Stride rate and length

	Medial Elevation (ME)	Level (L)	Lateral Elevation (LE)	LE - L	ME - L	ME - LE	F-value
Stride rate (strides/s)	1.49 ± 0.7	1.49 ± 0.07	1.50 ±0.07	0.401	1.000	1.000	23.7
Stride length (m/stride)	2.25 ± 0.10	2.25 ± 0.12	2.24 ± 0.11	0.628	1.000	0.934	24.2

*Note.* Mean values ± S.D. and *p* values for each pairwise comparison are presented.

Figure 1. Medial elevation (ME) was created by raising the left side of the treadmill by 5°, (photo on left) and lateral elevation (LE) was created by raising the right side of the treadmill by 5° (photo on right).
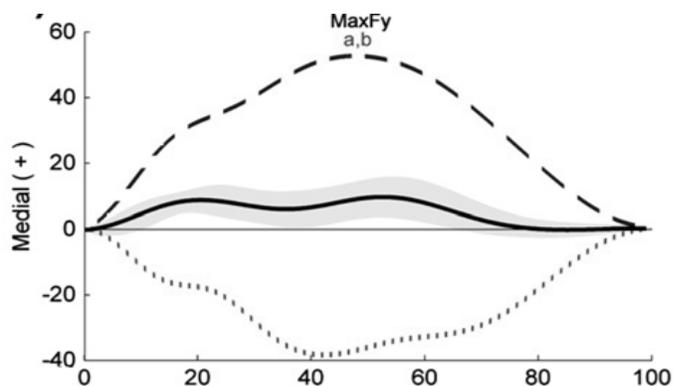
Figure 2. Peak mediolateral GRF increased by 530% for cross-slope running compared to level running. The y-axis for GRF has units of % of body weight, while the x-axis is for percent of stance phase. Solid line = level running, dotted line = LE, dashed line = ME (Damavandi et al., 2012).
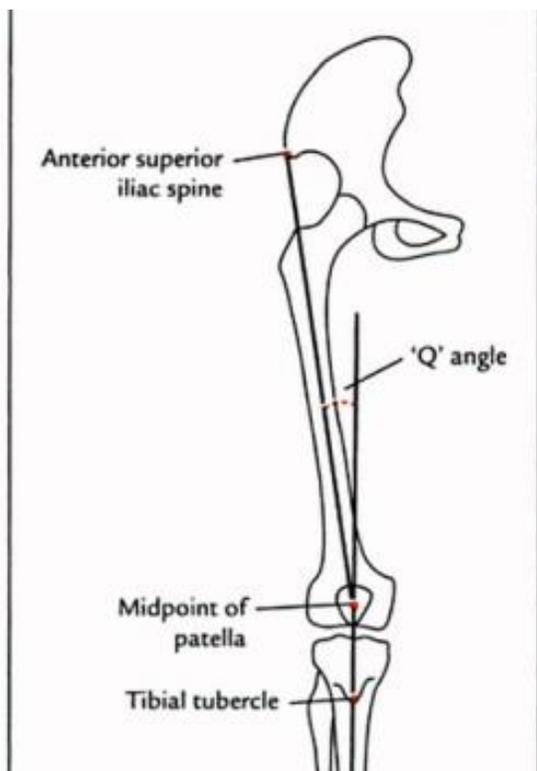
Figure 3. Quadriceps angle of force on the patella measured relative to a vertical line through the patella (Pagare, n.d.).

Figure 4. Heel window in right shoe with vertical calcaneus markers.
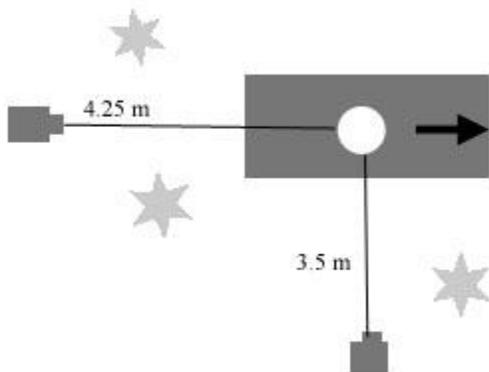
Figure 5. Diagram of the lab setup: the treadmill is the rectangle, the runner is the circle running in the direction of the arrow, the stars are lamps, and the cameras are shown at the distances they were placed from the treadmill (side view = 3.5 m away from runner, rearview = 4.25 m away from runner).

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Figure 6. Markers captured by the side view camera.

Figure 7. Markers captured by the rearview camera during initial capture.
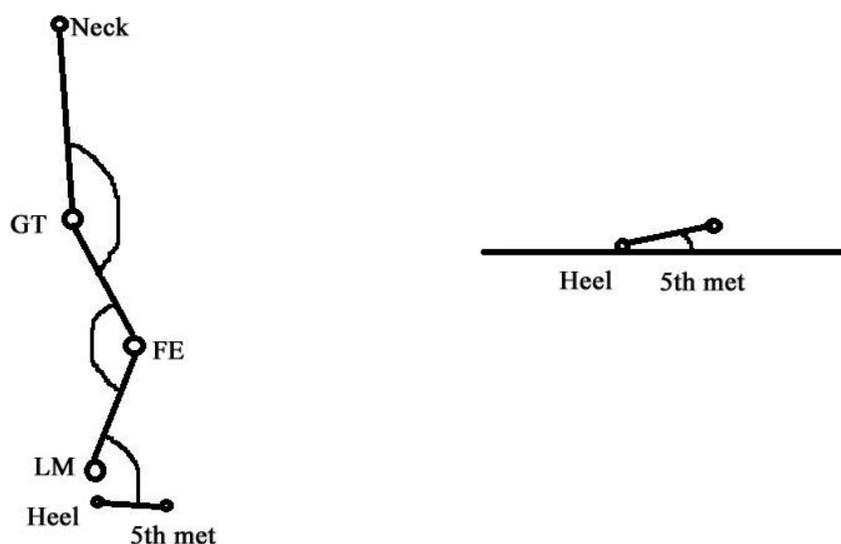
Figure 8. Side view angles (on the left): hip flexion, knee flexion, and ankle dorsiflexion
On the right: foot strike angle relative to the horizontal. Markers on neck, greater trochanter
(GT), femoral epicondyle (FE), lateral malleolus (LM), heel, and 5th metatarsal.

Figure 9. Lateral pelvic tilt left (on the left) (angle greater than 180 degrees), lateral pelvic tilt
right (on the right) (angle less than 180 degrees). Markers on the left PSIS (LPSIS) and the right
PSIS (RPSIS).
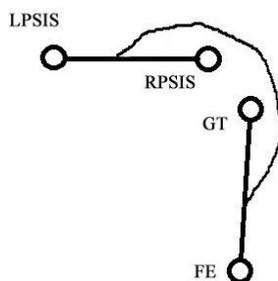
Figure 10. Hip adduction angle, markers on left PSIS and right PSIS, greater trochanter (GT), and femoral epicondyle (FE), a larger value indicates greater hip adduction.
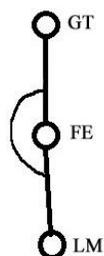
Figure 11. Knee valgus, markers on greater trochanter (GT), femoral epicondyle (FE), and lateral malleolus (LM), a larger value indicates greater knee valgus.
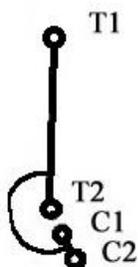
Figure 12. Rearfoot with respect to tibia, two markers on the center of the tibia (T1 and T2), and two on the calcaneus (C1 and C2), a larger value indicates greater eversion.

Figure 13. Rearfoot with respect to treadmill, two markers on the calcaneus (C1 and C2), and two markers on the left (LT) and right (RT) sides of the treadmill, a smaller value indicates greater eversion.
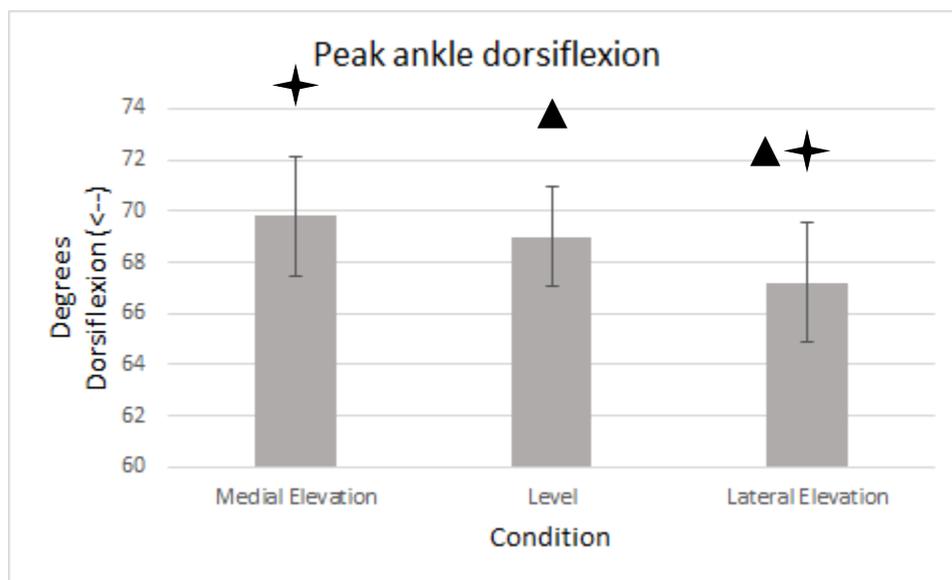
Figure 14. Peak ankle dorsiflexion, mean angles ± S.D. presented. LE = greatest peak dorsiflexion, ME = least peak dorsiflexion. ✦ and ▲ indicate significance.
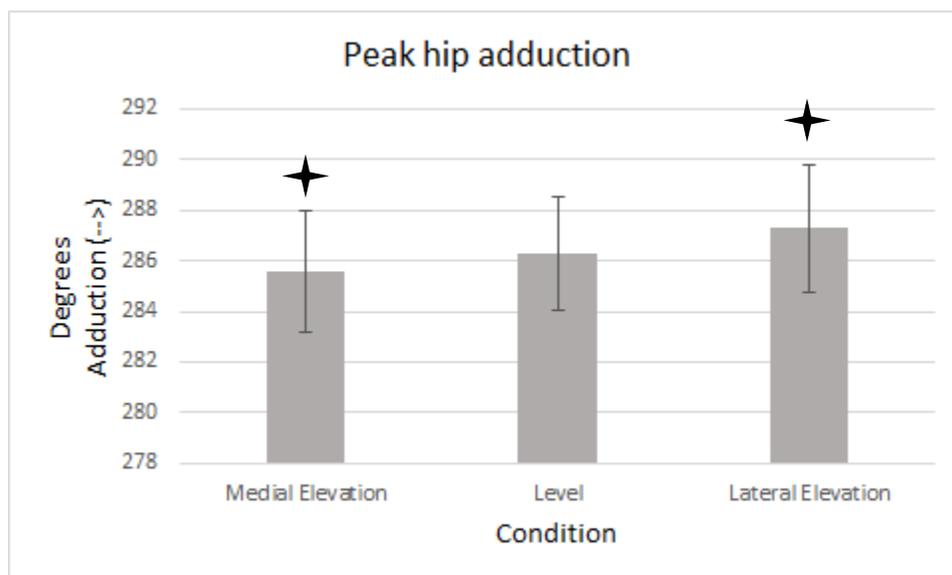
Figure 15. Peak hip adduction, mean angles ± S.D. presented. LE = greatest peak adduction, ME = least peak adduction. ✦Indicates significance.
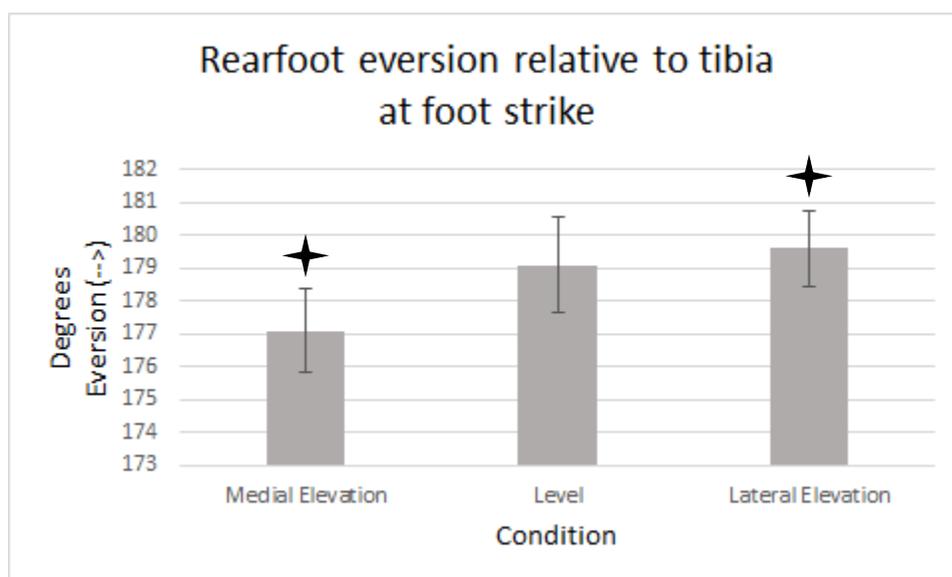

Figure 16. Rearfoot eversion relative to tibia at foot strike, mean angles ± S.D. presented. LE = least inverted at foot strike, ME = most inverted at foot strike. ✦ Indicates significance.

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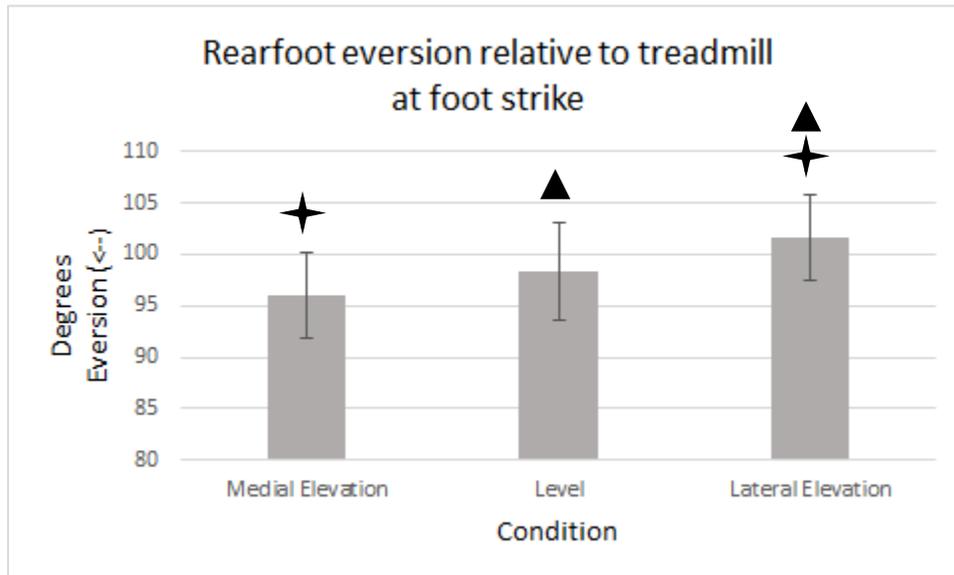*Figure 17.* Rearfoot eversion relative to treadmill at foot strike, mean angles ± S.D. presented, ME = least inverted at foot strike, LE = most inverted at foot strike.
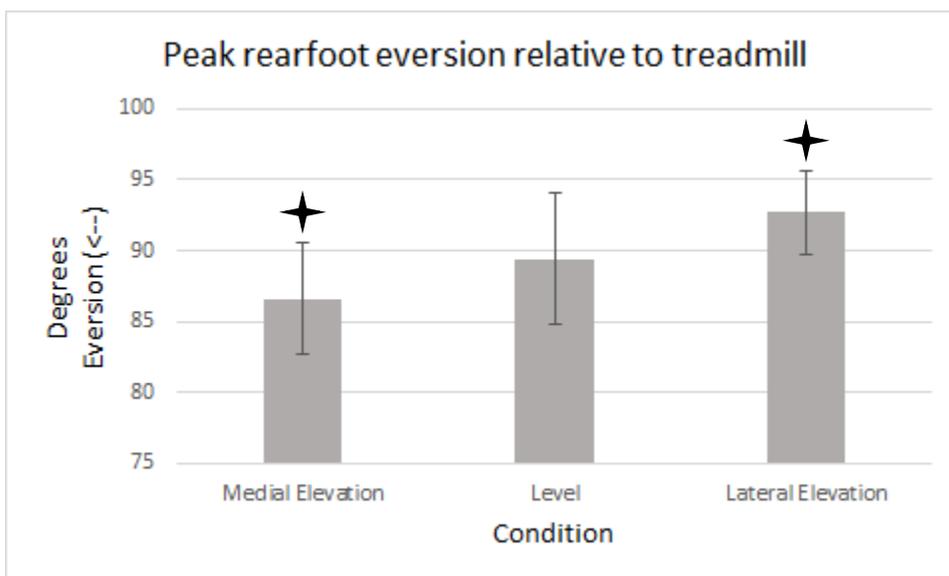✦ and ▲ indicate significance.

Figure 18. Peak rearfoot eversion relative to treadmill, mean angles ± S.D. presented. ME = greatest peak eversion, LE = greatest peak inversion. ✦ Indicates significance.