THE EFFECT OF SPEED ON LOWER EXTREMITY JOINT STIFFNESS DURING GRADED RUNNING

by

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Joint stiffness is defined as a given joint's resistance to angular displacement under mechanical loading expressed as a moment of force.[1] Increased joint stiffness is associated with the inability to adequately attenuate shock throughout the body, which is a mechanism associated with an increased risk of running related injuries.[2] Understanding the factors that influence stiffness has potential application in injury prevention and rehabilitation with respect to running related overuse injuries.[3] Across the literature, increases in running speed have been correlated with increased joint stiffness.[4] However, this relationship has only been examined during level ground running; the effect of speed on joint stiffness during uphill and downhill running is relatively unexplored.[1] The purpose of this study is to examine the effect of speed on joint stiffness and quantify differences in stiffness between the hip, knee, and ankle, and examine the relationship between foot strike patterns and joint stiffness during graded running.

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Introduction

Literature Review

Running is one of the most common forms of exercise; requiring almost no equipment, its accessibility has made it a popular activity for people of all ages and fitness backgrounds.[20] However, as more people engage in this activity, there is an increased incidence of running related injuries, particularly running-related overuse injuries.[1,20] Running-related over-use injuries result from chronic stress to the muscles, bones, and joints of the lower limbs in response to repeated bouts of mechanical loading.[2,4] Commonly reported running overuse injuries include plantar fasciitis, medial tibial stress syndrome, patellofemoral pain syndrome, Achilles tendinopathy, sprains and ligament injuries.[20] These types of injuries are reported by runners from a broad range of demographics, including both novice and trained athletes.[1,3] In a systematic review performed by Kakouris, et.al., it was reported that approximately 50% of runners experience an injury that prevents them from engaging in activity for any period of time, and that 70%-80% of these occurrences are due to running-related overuse injuries. Factors that are correlated with higher injury incidence include history of previous injury, changes in training volume and load, and increased age.[1,20] Typical sites of overuse injuries include the thigh and shank segments and their associated muscles, as well as the hip, knee, and ankle joints.[2,20] The consequences of over use running-related injuries are detrimental to physical health and wellness, can present financial stress, and can prevent further participation in running activity and exercise.[2,4,20]

When examining running related injuries, joint stiffness has been identified as a factor of interest because it has been associated with both enhanced performance, as well as increased incidence of running-related overuse injuries.[1,2,3,4,5] Joint stiffness is defined as a given joint's resistance to angular displacement under mechanical load, expressed as a moment of force.[10,12] It can be quantified by dividing a joint's moment of force in the sagittal plane, by its angular displacement.[12,14] This is represented by the equation:

$$K_{joint} = \frac{\Delta M_{joint}}{\Delta \theta_{joint}}$$

where ΔM_{joint} describes the change in sagittal plane joint moment, and $\Delta\theta_{joint}$ describes the change in the given joint's angular displacement from initial contact to midstance.

Joint stiffness provides a quantitative measure of the elastic properties of the lower extremity and characterizes its ability to store elastic energy.[5] Elastic energy is a form of potential energy, which describes the amount of energy returned to a system by a given material, in response to mechanical deformation. Increasing elastic energy return is biomechanically advantageous, as it can reduce the metabolic energy needed to move the joints and generate propulsive energy through muscle contractions. This suggests that by increasing utilization of potential elastic energy, leg stiffness plays a role in running efficiency by decreasing metabolic costs. However, the 'optimal' range of leg stiffness for enhanced running performance, in terms of increased efficiency, has not yet been defined.[5]

Conversely, joint stiffness has also been identified as a factor that has been associated with increases in incidence of running related overuse injuries.[1,2,3,4] Joint stiffness has been associated with a decrease shock attenuation,[6,10] which is defined as the ability to disperse the forces of impact throughout the body.[4,5] During running, the lower limbs must attenuate the impact forces associated with each foot strike, known as ground reaction forces, (GRFs).[5,7,13] This force of impact is proportional to the amount of force the runner is exerting on the ground, and in turn, the amount of force the ground is exerting on the runner. Factors that influence

GRFs include: the foot and center of mass acceleration at initial contact, effective mass of the body at contact, the area of contact, as well as the material properties of damping elements such as cushioned shoes or orthopedic insoles.[7, 17] Failure to attenuate these forces adequately can lead to excessive stress placed on the muscles, tendons, and ligaments of the lower extremity, which may lead to the development of running overuse injuries.[1,2,3,4,6,10]

The dispersion of these forces is primarily achieved by a combination of passive and active mechanisms.[7] Passive mechanisms include the deformation of the ligaments, bones, and muscles of the lower limb, as well as non-anatomical elements, such as deformation of damping materials found in running shoes.[5,7,17] Active mechanisms include eccentric muscle contractions of the plantar flexors, hip and knee extensors, as well as changes in joint stiffness through changes in angular displacement of lower extremity segments.[7]

Another possible active mechanism for modulating joint stiffness may be through the modification of foot strike patterns. Foot strike angle, defined as the angle of the foot relative to the ground at initial contact, is typically described by three distinct patterns: forefoot strike (FFS), midfoot strike (MFS), and rearfoot strike (RFS).[15,18,19] These patterns are characterized by the part of the foot that comes into contact with the ground first; FFS is characterized by the ball of the foot making initial contact, MFS is characterized by a flat foot landing (equal distribution of weight across the foot), and RFS is characterized by the heel striking the ground first.[15,18] In a study conducted by Gruber, et.al., it was found that RFS patterns resulted in higher impact loads in comparison to FFS running.[7] This suggests foot strike patterns may alter shock attenuation ability, thus, modifying foot strike patterns may play a role in running related overuse injuries.

Foot strike patterns have been observed to change in response to speed and grade. In a study conducted by Vernillo, et.al., it was found that foot strike patterns differ during uphill running and downhill running.[15] While on an incline, runners tend to adopt an MFS or FFS pattern, whereas runners tend to adopt a RFS pattern during decline running.[15] Foot strike patterns have also been reported to change in response to speed. In a study conducted by Forrester and Townend, it was reported that as running velocities increased, FSA decreased. This suggests that as speed increases, runners tend to adopt either FFS or MFS over RFS patterns.[23]

Significance

While the effect of speed on joint stiffness has been described for level ground running, it has not yet been thoroughly examined across different gradations of running. However, in the real world, graded running is a common condition that runners will encounter (i.e., trail running). Due to the influence of joint stiffness on running-related injuries, an investigation into the combined effects of speed and grade on joint stiffness is warranted. Additionally, while the effects of speed and grade on foot strike patterns have been analyzed separately, the effect of speed during graded running on foot strike angles has not yet been explored but may provide insight into gait modifications that can be utilized to modulate joint stiffness.

Hypotheses

It was hypothesized that as speed increases, stiffness of the hip, knee and ankle will also increase for all grade conditions. However, across all speeds, it was hypothesized that joint stiffness of the hip, knee, and ankle will be greatest during the incline grade condition, followed by the level ground, and decline condition.

It was also hypothesized that as speed increases, foot strike pattern will shift from a RFS to a FFS pattern, across level ground and incline grades. However, during decline running, RFS patterns will be maintained regardless of increases in speed. Lastly, it was hypothesized that as FSA increases, stiffness of the hip, knee and ankle joints will decrease.

Methods

This study was divided into three phases: data collection, processing, and statistical analysis. Data were collected from participants prior to the beginning of this study, thanks to the BSSC team.

Phase 1: Data Collection

Approval from the IRB was obtained, and all participants provided written informed consent prior to data collection. Twelve healthy recreational runners (7 female, age: 24 years, height: 162 cm, mass: 72 kg) performed three 30 second running trials at three different speeds, across three different grade conditions, for a total of nine trials. Speeds were selected based on each participant's self-reported 5k pace:

Speed Category	5k pace
Speed 1	1:30 min/mile slower than 5k pace
Speed 2	1:00 min/mile slower than 5k pace
Speed 3	0:30 min/mile slower than 5k pace

Table 1: Assigned Speed Categories. Categories based on self-reported 5k pace.

Trials were conducted on an instrumented treadmill on three different grade conditions: level ground (LG), 7.5° incline (INC) and 7.5° decline (DEC). Ground reaction forces (GRF) were measured by the instrumented treadmill at a sampling frequency of 1000 Hz (Bertec, Columbus, OH). Prior to data collection, participants were outfitted with 35 reflective markers placed at key lower extremity landmarks, and kinematic data from these markers were collected via an 8-camera motion capture system (Motion Analysis, Rohnert Park, CA) at 200 Hz during each trial.

Marker	Location
VSAC	Sacrum
ASIS	Anterior superior iliac spine
PSIS	Posterior superior iliac spine
TTL	Top of thigh, lateral
TTM	Top of the thigh, medial
TBL	Bottom of thigh, lateral
TBM	Bottom of thigh, medial
STL	Top of shank, lateral
STM	Top of shank, medial
SBL	Bottom of shank, lateral
SBM	Bottom of shank, medial
TOE	Toe
IMU	Inertial motion unit
MH1	Metatarsal head 1
MH5	Metatarsal head 5
HEP	Heel, proximal
HED	Heel, distal
HEL	Heel, lateral

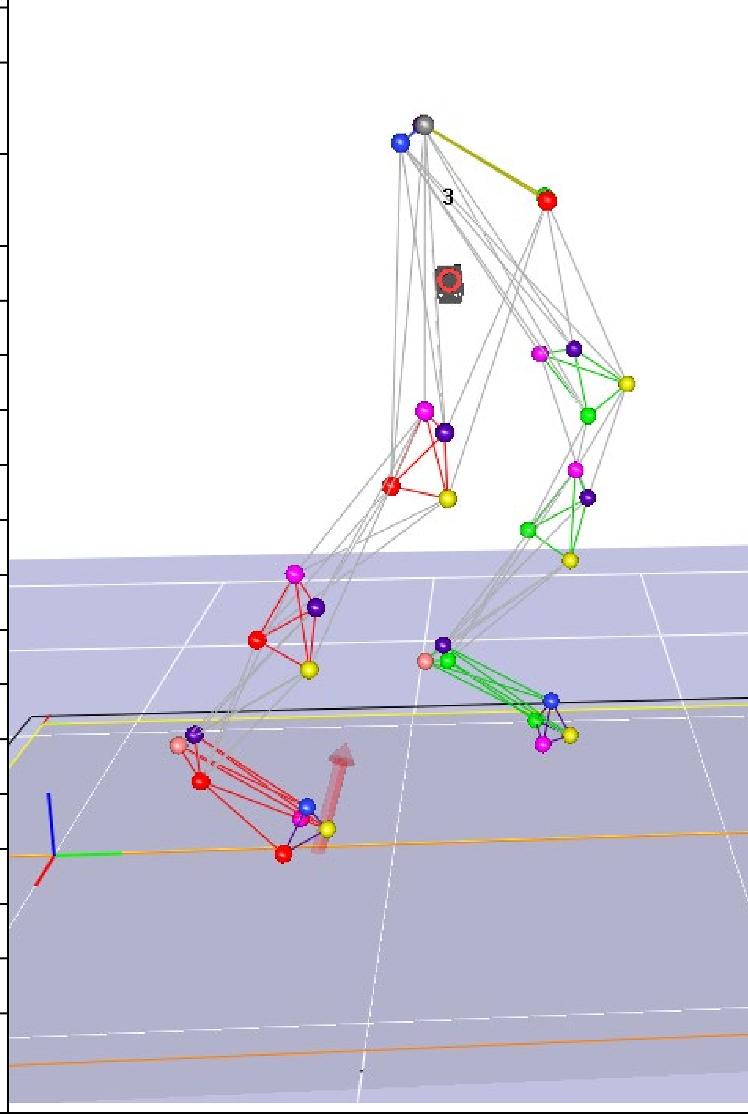

Table 2: Motion capture markers and description of corresponding anatomical locations, markers were placed on both right and left extremities.

Phase 2: Data Processing

Markers were labeled using Cortex motion capture software (Motion Analysis, Rohnert Park, CA). Gaps in marker trajectories were filled using a cubic spline function. Sagittal plane joint angles and internal moments of the hip, knee, and ankle were calculated using a custom pipeline in Visual 3D software (C-motion, Inc., Germantown, MD). Joint stiffness of the lower extremity joints was quantified using the equation:

$$K_{joint} = \frac{\Delta M_{joint}}{\theta_{joint}}$$

where ΔM_{joint} is the change in joint moment in the sagittal plane, and $\Delta \Theta_{joint}$ is the change in angular displacement over the first half of stance phase. Initial contact was identified as the first instance of vertical GRF greater than 50N for each step. Midstance was identified by identifying the transition between braking GRF and propulsive GRF. Stiffness of the hip, knee, and ankle joints was calculated for the right leg of all twelve participants, across each speed and grade. Foot strike angles (FSA) were defined as the sagittal plane angle between the foot and the ground at initial contact, and categorized as forefoot (FFS), midfoot (MFS) or rearfoot (RFS) using the ranges defined by Altman and Davis.

Foot Strike Categorization	**Angle Range**
Forefoot	<-1.6°
Midfoot	-1.6°≤x≤8.0°
Rearfoot	>8.0°

Table 3: Foot strike pattern categorization based off foot strike angle range set by Altman and Davis.[18,19]

Phase 3: Statistical Analysis

A two-way repeated measures ANOVA (3 speeds x 3 joints) was performed for each grade condition using Excel (Microsoft, Redmond, WA) to determine the effect of speed and joint type on joint stiffness. Post hoc pairwise t-tests were run in the case of a significant main effect (alpha = 0.05). A linear regression model was applied to compare FSA and joint stiffness of the ankle, as well as FSA and joint stiffness of the knee and hip, to determine the relationship between FSA and stiffness at each joint. Confidence intervals (95%) were calculated for FSA and joint stiffness, also using Excel (Microsoft, Redmond, WA).

Results

The average velocities for speed categories 1, 2 and 3 were 3.23 m/s, 3.44 m/s, and 3.68 m/s, respectively. For all grades, a significant main effect was detected for joint type ($p<0.001$), but not for speed. No significant interaction effects were detected.

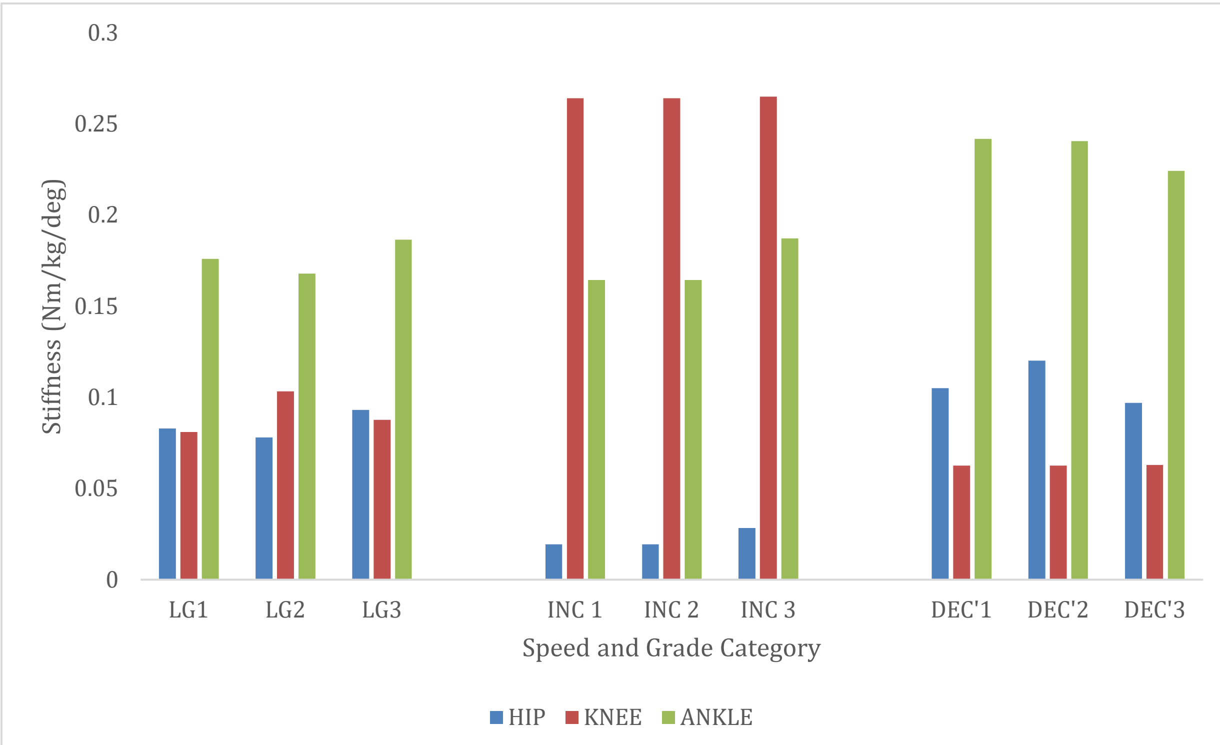

Figure 1: Average Joint stiffness (Nm/kg/deg) across all speed categories (1, 2, 3) and grade conditions (Level ground, Incline, and Decline).

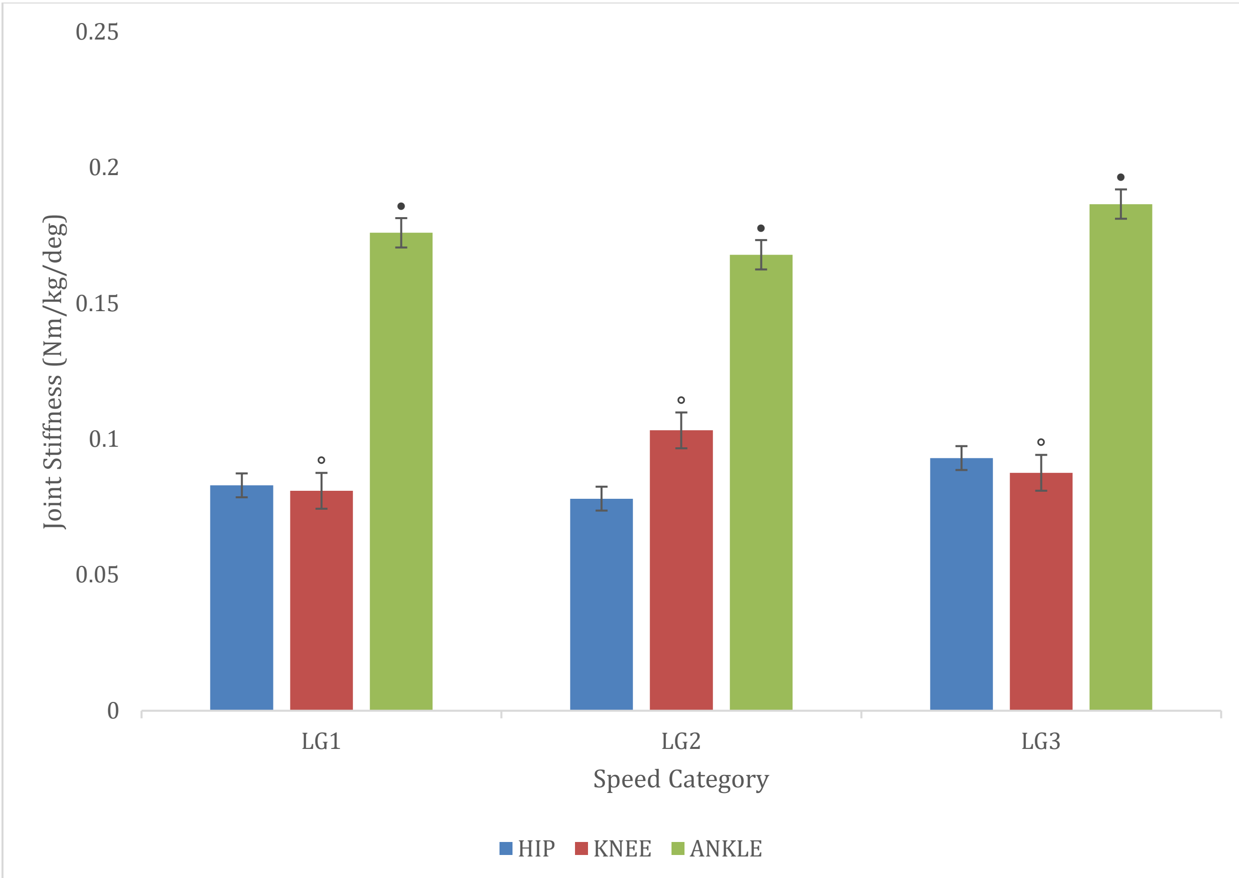

Figure 2: Average Joint Stiffness (Nm/kg/deg) across speed categories (1,2,3) during level ground running. Significant difference ($p < 0.05$) between hip/knee denoted as *, knee/ankle°, ankle/hip•

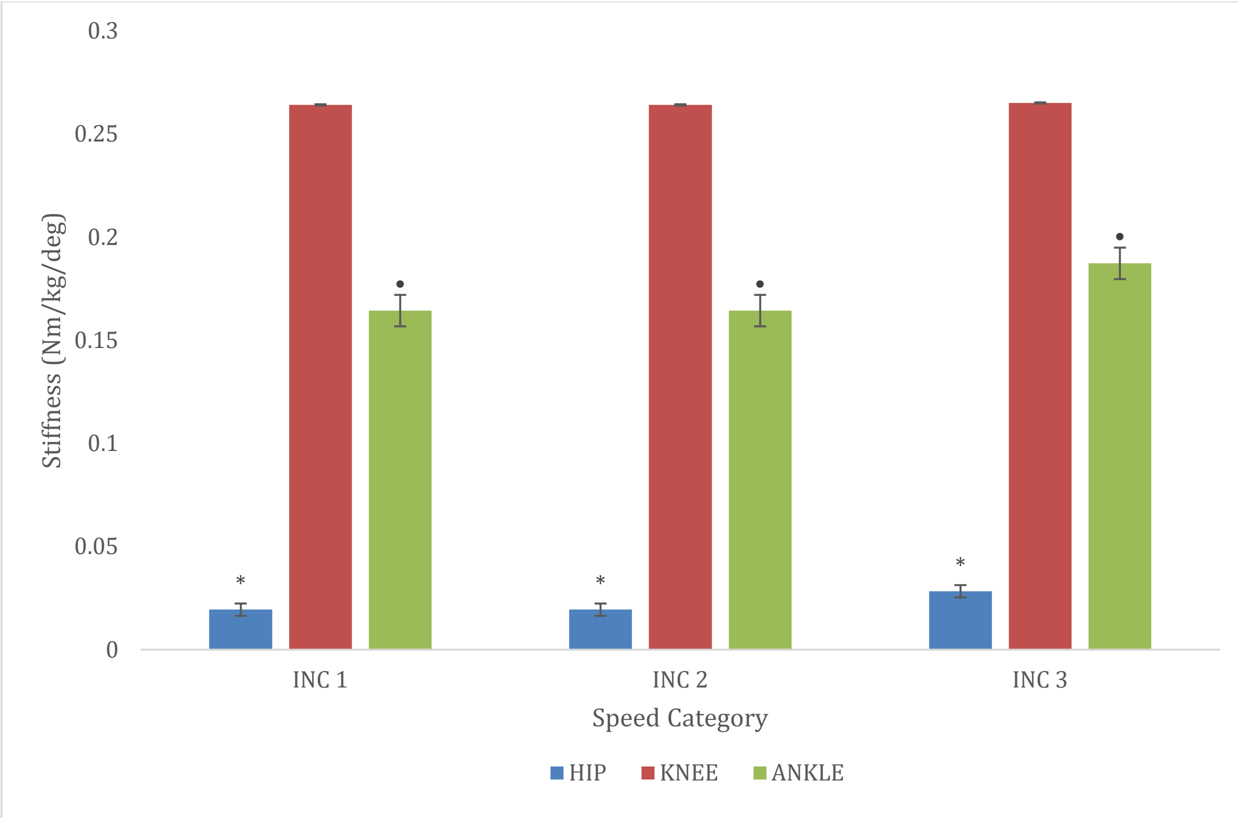

Figure 3: Average Joint Stiffness (Nm/kg/deg) across speed categories (1,2,3) during incline running. Significant difference ($p < 0.05$) between hip/knee denoted as *, knee/ankle°, ankle/hip•

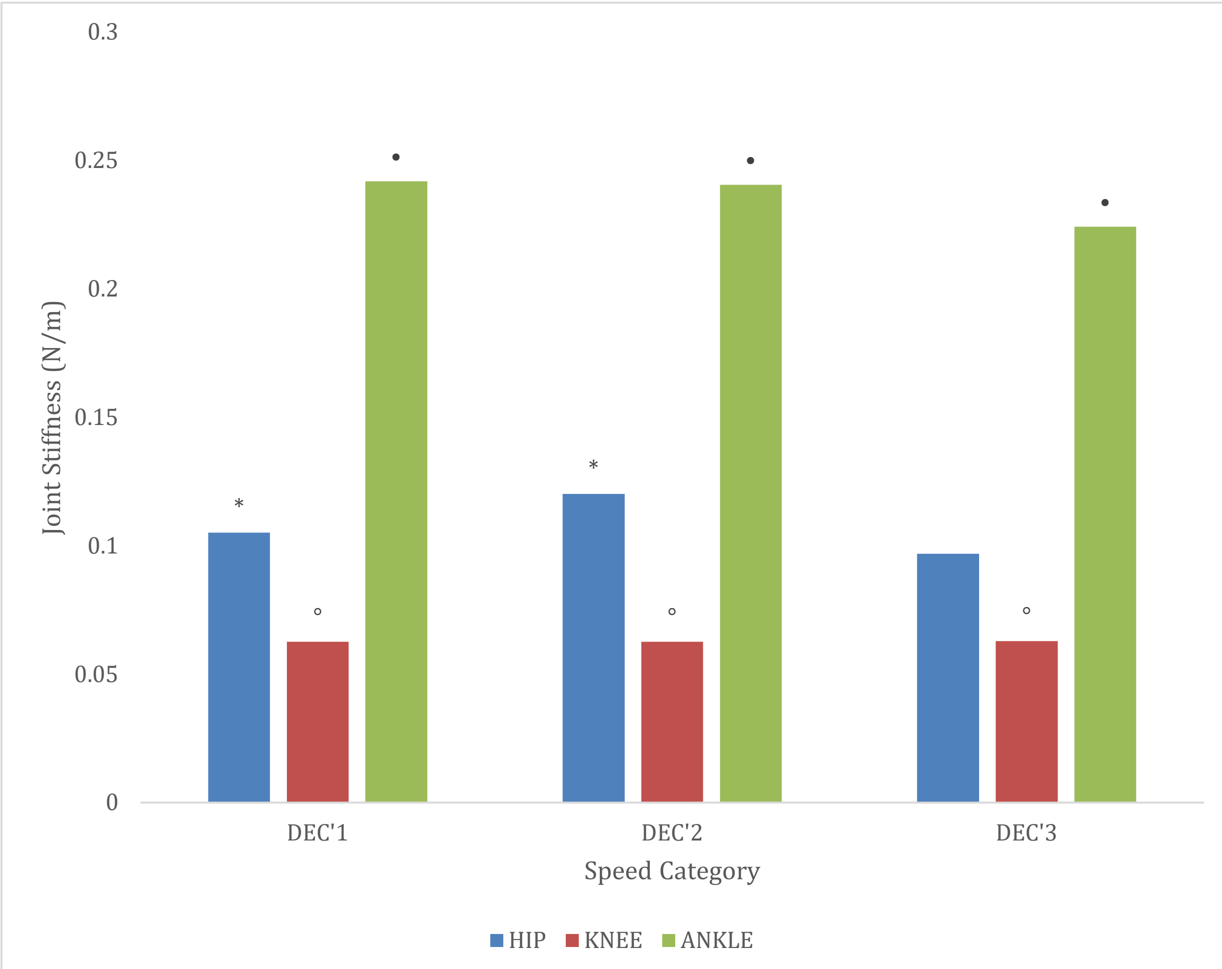

Figure 4: Average Joint Stiffness (Nm/kg/deg) across speed categories (1,2,3) during decline running. Joint stiffness across grades and speeds. Significant difference ($p < 0.05$) between hip/knee denoted as *, knee/ankle°, ankle/hip•

	LG1	LG2	LG3	INC1	INC2	INC3	DEC1	DEC2	DEC3
HIP	0.08± 0.04	0.08± 0.05	0.09± 0.05	0.02± 0.01*	0.04± 0.05*	0.03± 0.05*	0.11± 0.05*	0.12± 0.06*	0.10± 0.06
KNEE	0.08± 0.02°	0.10± 0.07°	0.09± 0.02°	0.30± 0.21	0.28± 0.26	0.27± 0.20	0.06± 0.02°	0.06± 0.02°	0.06± 0.02°
ANKLE	0.17± 0.0•	0.17± 0.0•	0.19± 0.0•	0.16± 0.0•	0.16± 0.0•	0.19± 0.1•	0.24± 0.1•	0.24± 0.0•	0.22± 0.12•

Table 4: Joint stiffness (average ± standard deviation) across grades and speeds. Significant difference ($p < 0.05$) between hip/knee denoted as *, knee/ankle°, ankle/hip•

In the LG condition, ankle stiffness (0.17 Nm/kg/deg) was significantly greater than hip (0.08 Nm/kg/deg) and knee (0.08 Nm/kg/deg) stiffness across all speeds (Figure 4). During the INC condition, ankle and knee stiffness were significantly greater than hip stiffness across all speeds. During the DEC condition, ankle stiffness was significantly greater than hip and knee stiffness across all speeds. In both the LG and DEC running, stiffness was greatest at the ankle, but during INC running across all speeds, stiffness was greatest at the knee.

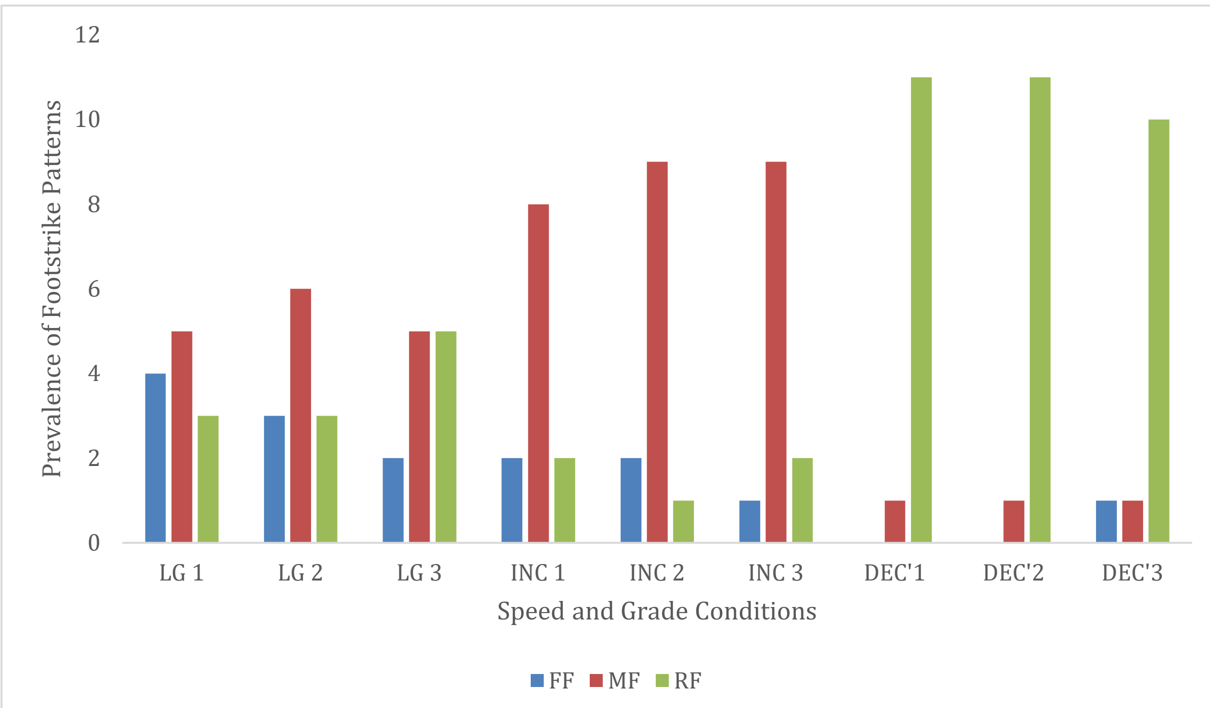

Figure 5: Prevalence of foot strike patterns across speed categories during level ground, incline and decline running.

During level ground running, the midfoot strike (MFS) pattern was favored across the first two speed categories, however in the fastest speed category, both the MFS and the rearfoot strike (RFS) pattern were equally favored. During incline running, MFS patterns were favored across all speeds, as compared to the FFS and RFS patterns. During decline running, the RFS was favored over both the FFS and MFS patterns across all speeds.

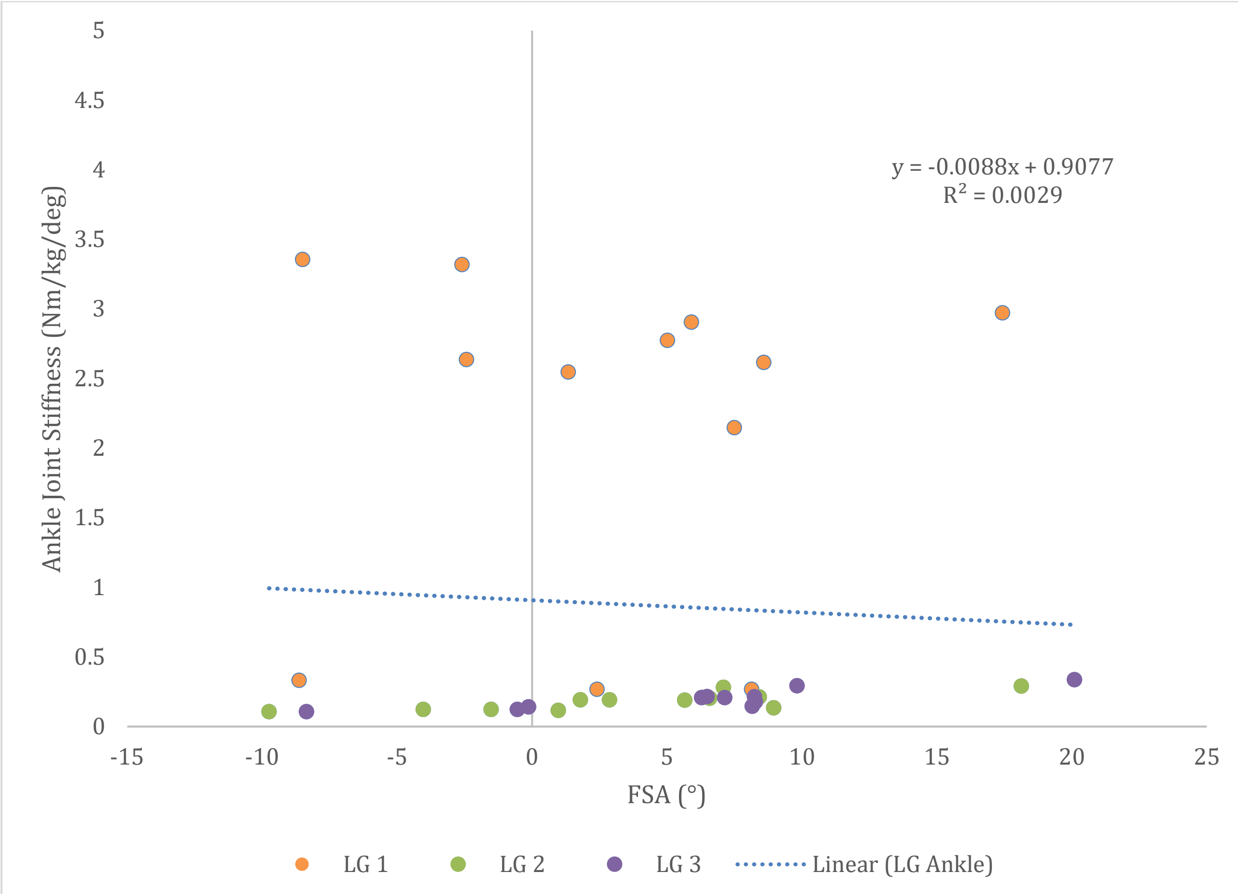

Figure 7: FSA (°) as a predictor of ankle joint stiffness (Nm/kg/deg) across speeds during level ground running. Coefficient of determination reported as 0.0035.

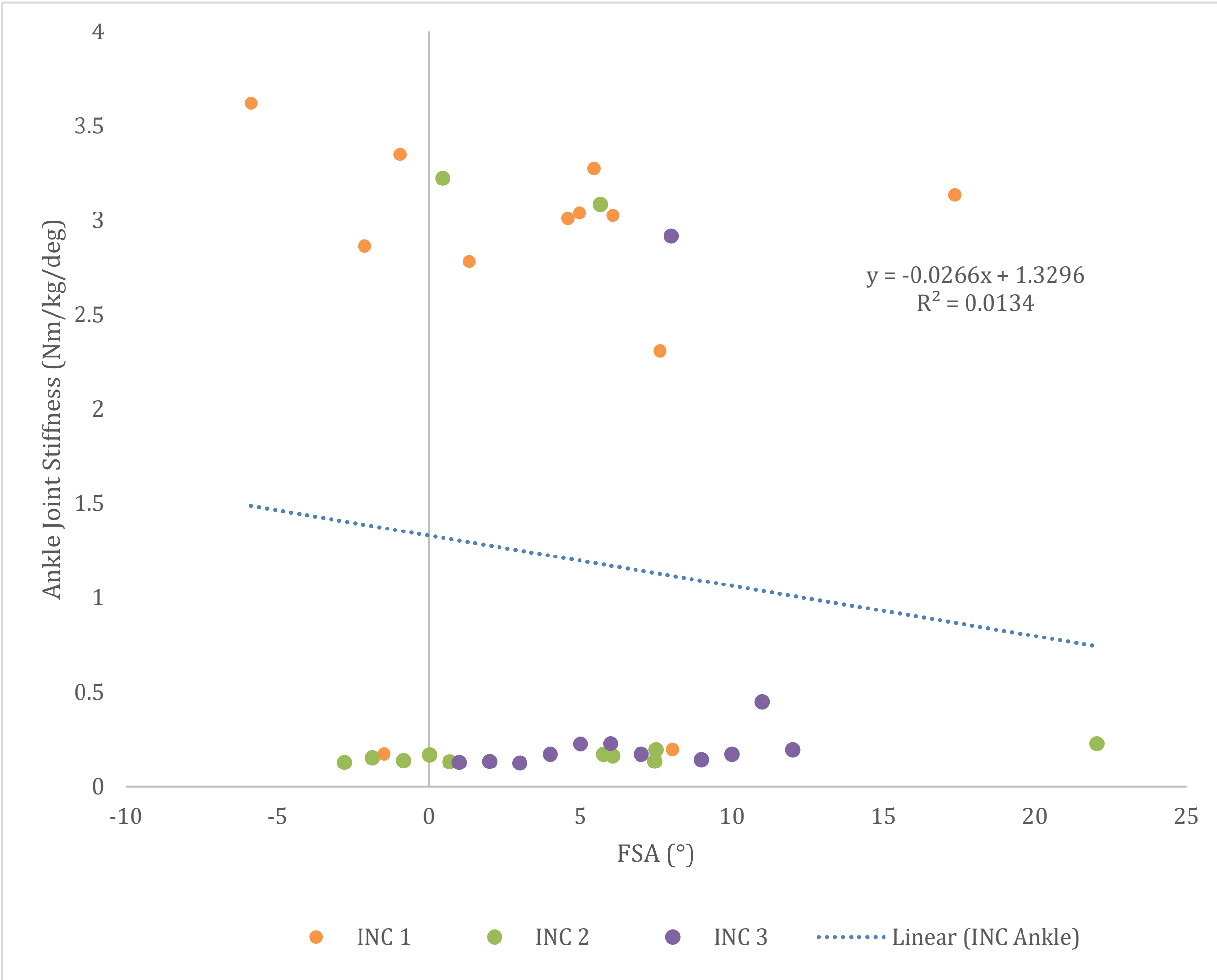

Figure 8: FSA (°) as a predictor of ankle joint stiffness (Nm/kg/deg) across speeds during incline ground running. Coefficient of determination reported as 0.0134.

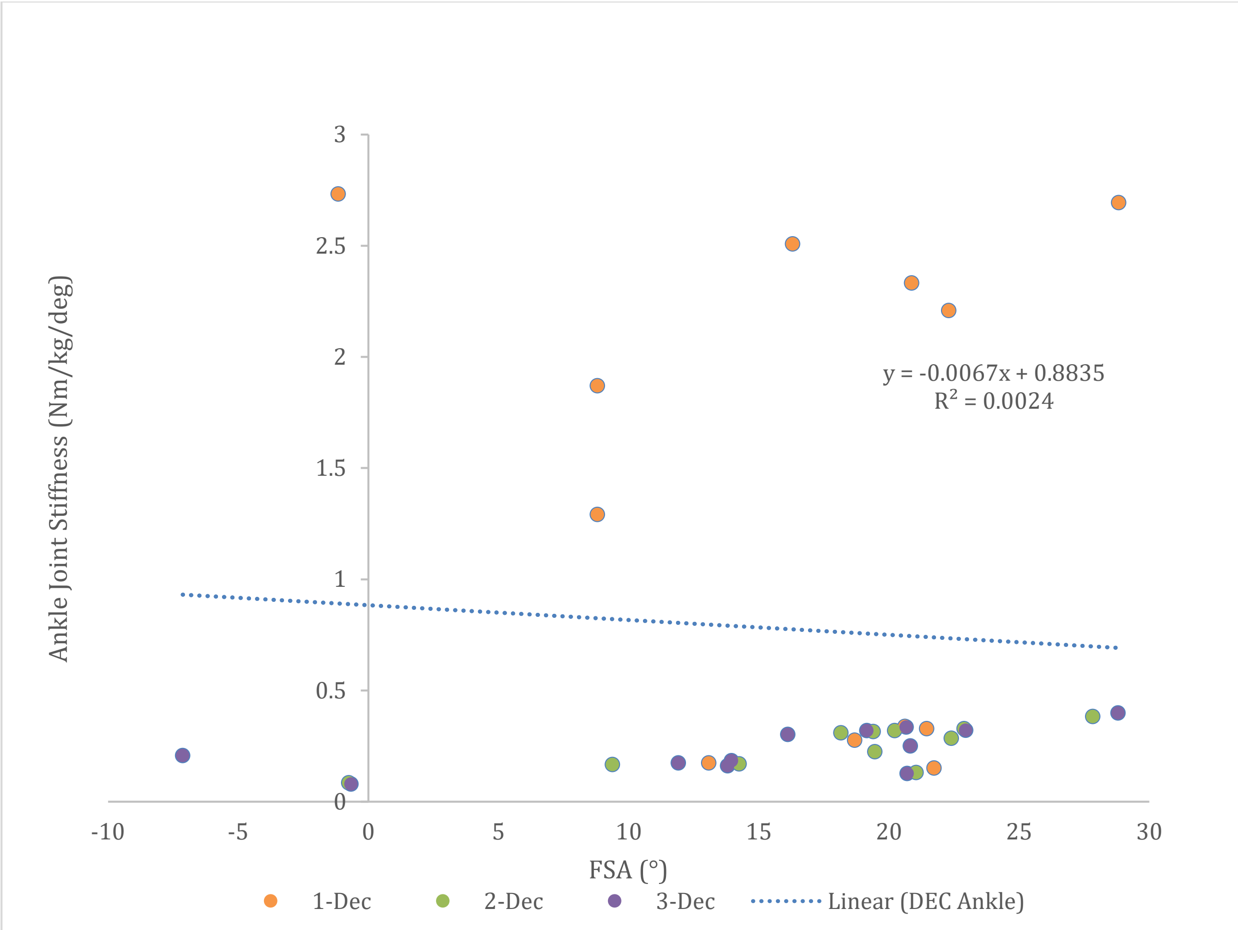

Figure 9: FSA (°) as a predictor of ankle joint stiffness (Nm/kg/deg) across speeds during decline ground running. Coefficient of determination reported as 0.0024.

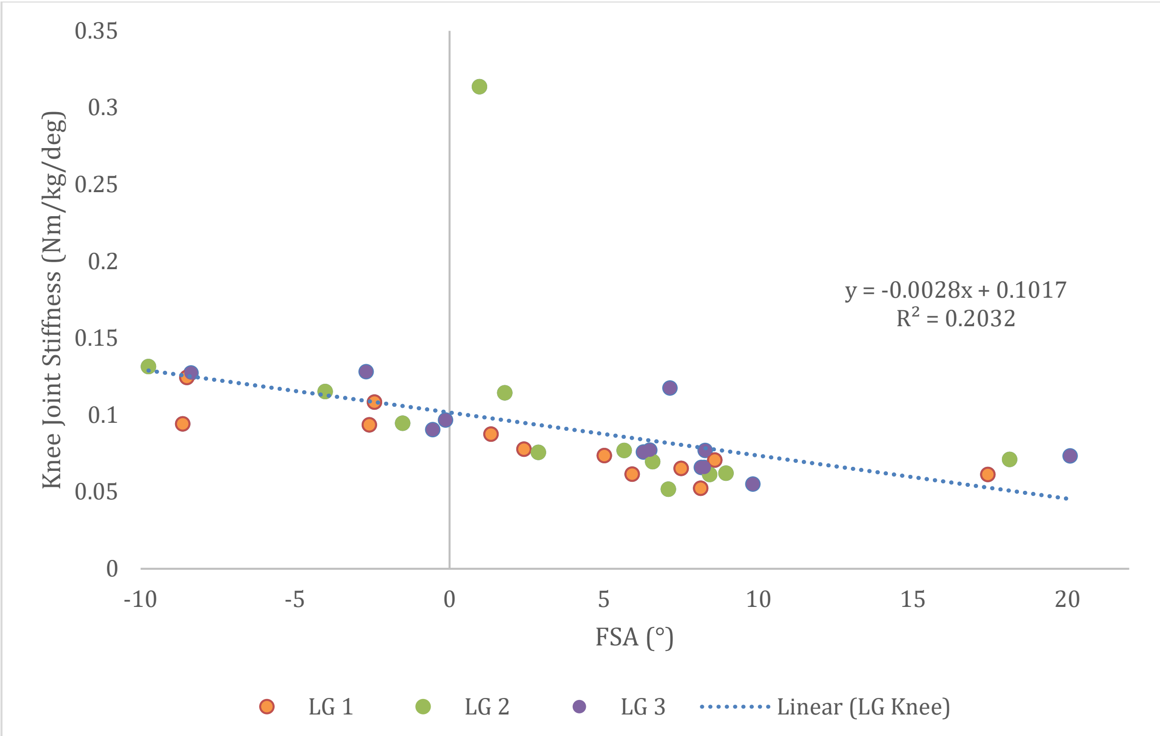

Figure 10: FSA (°) as a predictor of knee joint stiffness (Nm/kg/deg) across speeds during level ground running. Coefficient of determination reported as 0.2221.

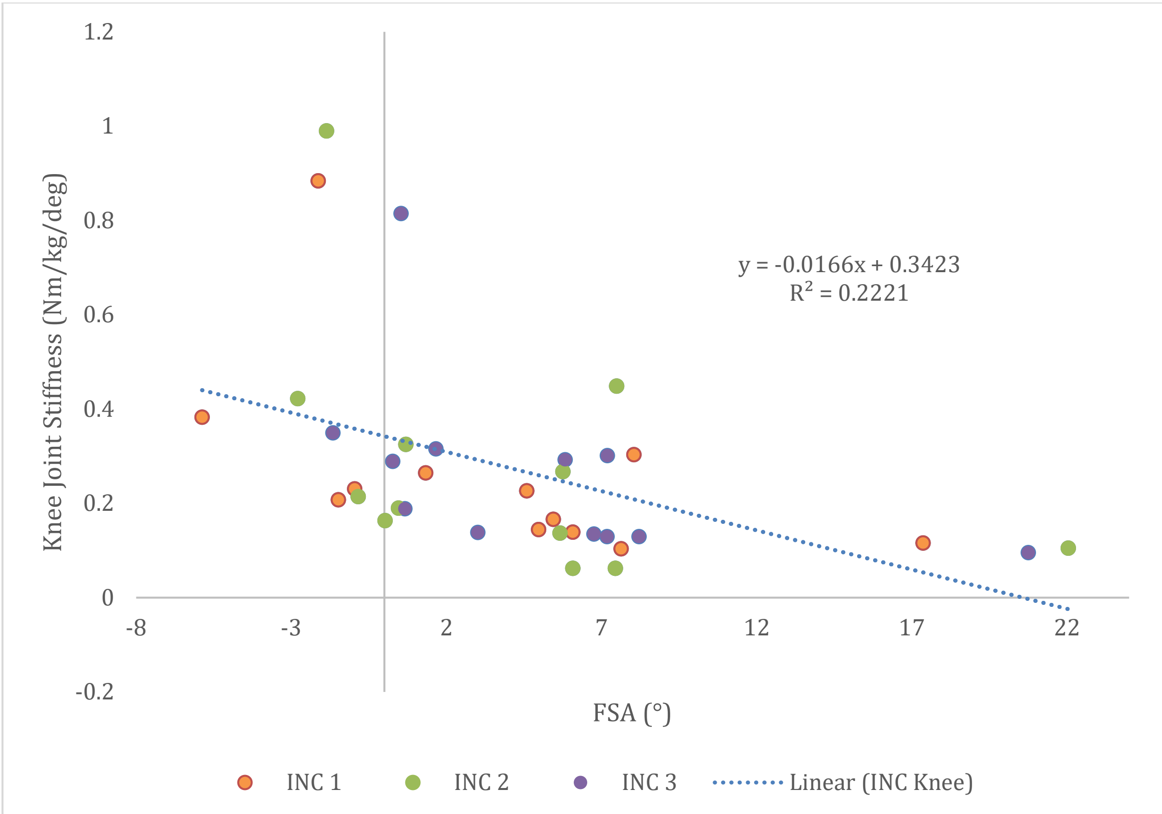

Figure 11: FSA (°) as a predictor of knee joint stiffness (Nm/kg/deg) across speeds during incline running. Coefficient of determination reported as 0.2221.

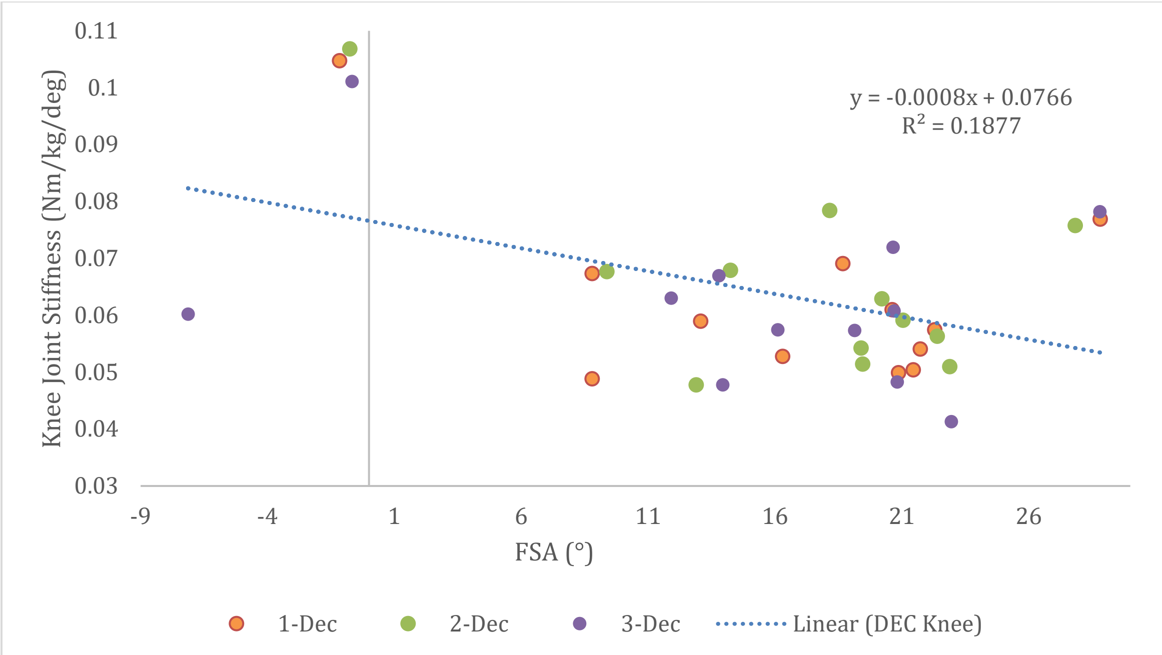

Figure 12: FSA (°) as a predictor of knee joint stiffness (Nm/kg/deg) across speeds during decline running. Coefficient of determination reported as 0.1877.

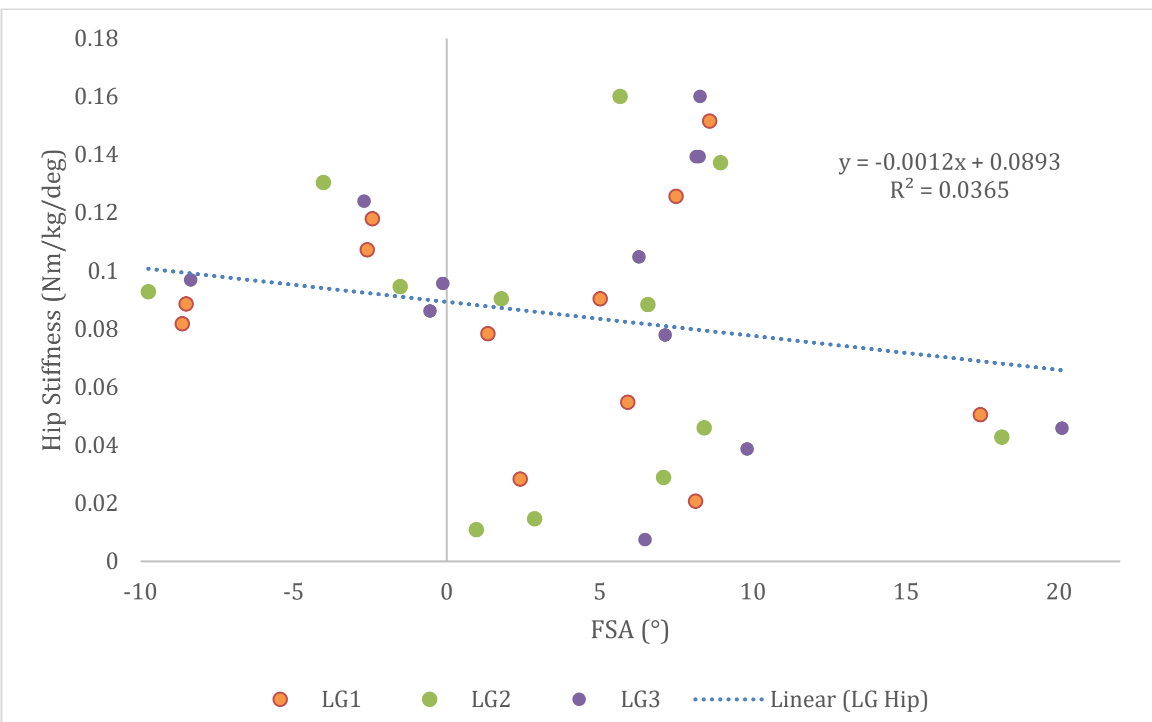

Figure 13: FSA (°) as a predictor of hip joint stiffness (Nm/kg/deg) across speeds during level ground running. Coefficient of determination reported as 0.0365.

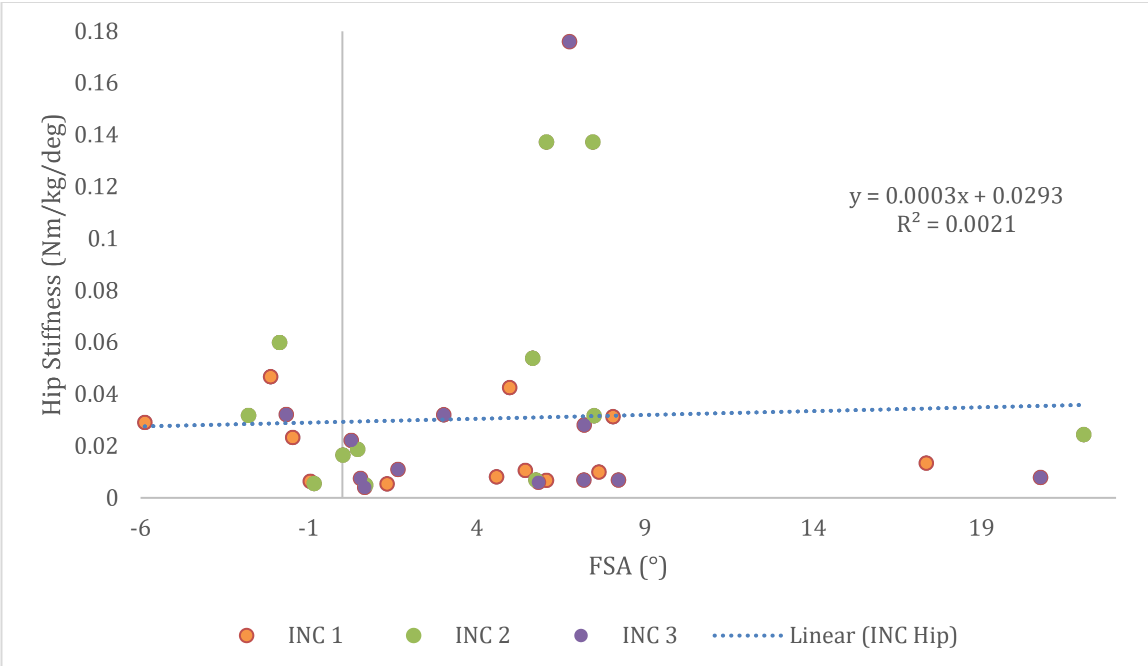

Figure 14: FSA (°) as a predictor of hip joint stiffness (Nm/kg/deg) across speeds during incline running. Coefficient of determination reported as 0.0021.

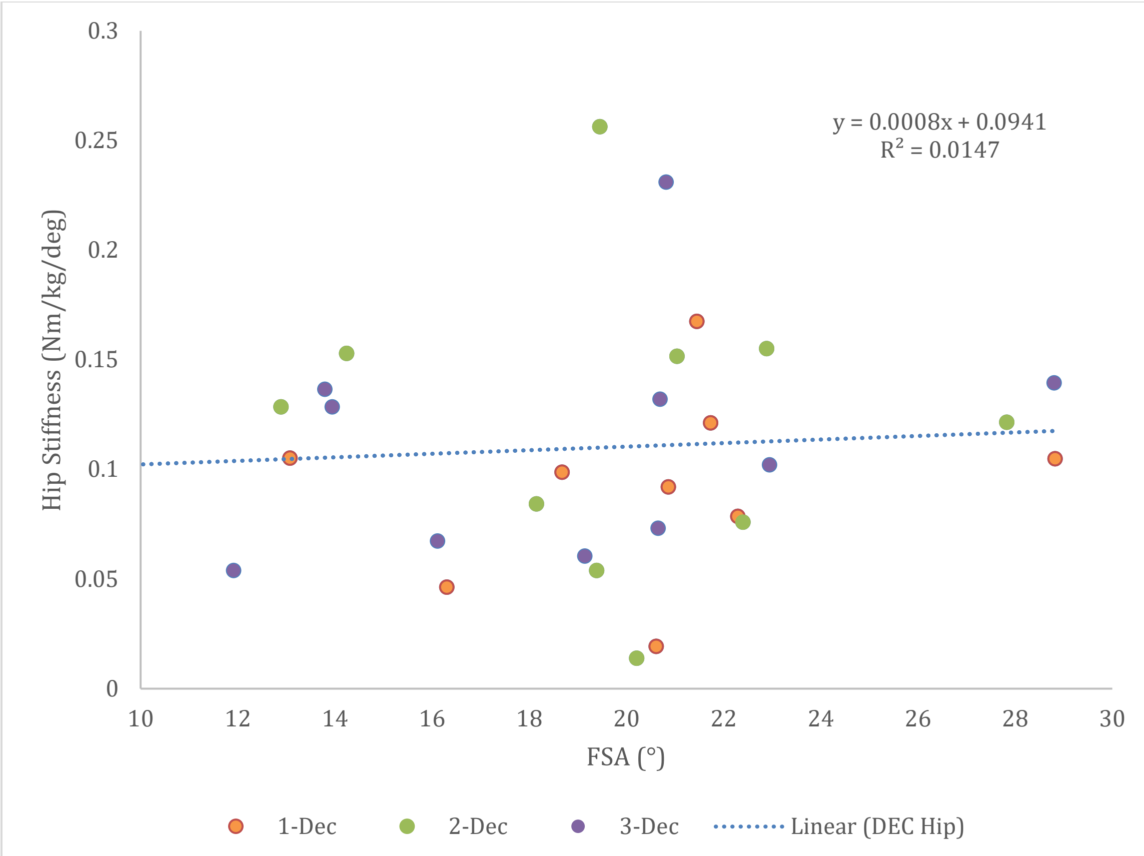

Figure 15: FSA (°) as a predictor of hip joint stiffness (Nm/kg/deg) across speeds during decline running. Coefficient of determination reported as 0.0147.

Speed/Grade Condition	Average FSA (°)	Average Ankle Joint Stiffness (Nm/kg/deg)
LG1	4.3	0.18
LG2	3.8	0.17
LG3	4.9	0.19
INC1	3.7	0.16
INC2	4.0	0.16
INC3	5.0	0.19
DEC1	16	0.24
DEC2	17	0.24
DEC3	17	0.22

Table 5: Average FSA (Upper CI: 13.3°, Lower CI: 3.6°) and Knee Joint Stiffness (Upper CI: 0.22 Nm/kg/deg, Lower CI: 0.07 Nm/kg/deg)

Speed/Grade Condition	Average FSA (°)	Average Knee Joint Stiffness (Nm/kg/deg)
LG1	4.3	0.08
LG2	3.8	0.10
LG3	4.9	0.09
INC1	3.7	0.26
INC2	4.0	0.28
INC3	5.0	0.27
DEC1	16	0.06
DEC2	17	0.07
DEC3	17	0.06

Table 6: Average FSA (Upper CI: 13.3°, Lower CI: 3.6°) and Knee Joint Stiffness (Upper CI: 0.22 Nm/kg/deg, Lower CI: 0.07 Nm/kg/deg)

Speed/Grade Condition	FSA (°)	Hip Joint Stiffness (Nm/kg/deg)
LG1	4.3	0.08
LG2	3.8	0.08
LG3	4.9	0.09
INC1	3.7	0.02
INC2	4.0	0.04
INC3	5.0	0.03
DEC1	16	0.10
DEC2	17	0.12
DEC3	17	0.10

Table 6: Average FSA (Upper CI: 13.3°, Lower CI: 3.6°) and Hip Joint Stiffness (Upper CI: 0.10 Nm/kg/deg, Lower CI: 0.05 Nm/kg/deg)

A positive correlation was observed between FSA and hip joint across increasing speeds during incline (0.0003) and decline conditions (0.0008). A negative correlation was observed between FSA and joint stiffness for the hip (-0.0012) during the level ground condition. Negative correlations between FSA and both the ankle and knee joints across speed categories were observed for all grade conditions (Ankle LG: -0.0088, INC: -0.0266, DEC: -0.0067) (Knee LG: -0.0028, INC: -0.0166, DEC: -0.0008). The coefficient of determination (r^2) for ankle joint stiffness and foot strike angle was 0.0029 during level ground, 0.0134 during incline, and 0.0024 during decline conditions. The coefficient of determination (r^2) for knee joint stiffness and foot strike angle was 0.221 during level ground and incline, and 0.1877 during decline conditions. The coefficient of determination (r^2) for hip joint stiffness was 0.0365 during level ground, 0.0021 during incline, and 0.0147 during decline conditions.

Discussion

It was hypothesized that as speed increases, stiffness of the hip knee and ankle joints will also increase for all grade conditions. However, this hypothesis was not supported by the findings in this study, as it was observed that not every joint increased in stiffness across speeds across all grade conditions. While a main effect for speed was not detected for stiffness of the hip joint, hip stiffness tended to increase with faster speeds during level ground running. It was also hypothesized that across all speeds, stiffness of the hip, knee, and ankle joints will be greatest during incline running, followed by level ground, and decline running. During level ground and decline running, stiffness was greatest at the ankle joint. However, during incline running, stiffness was greatest at the knee joint.

The increase in knee stiffness during incline running suggests that when running uphill, the role of the knee shifts from a more deformable shock absorber to a stiffer and more stable joint. This shift during incline running is not wholly unexpected; compared to decline and level ground running, more propulsive energy is needed to maintain the same speeds during inclined grade conditions. Additionally, this shift in knee stiffness may be biomechanically more advantageous as a stiffer knee joint may allow for improved transmission of propulsive energy generated by the hip and ankle joints, and their associated muscles such as the hip extensors, gastrocnemius, and soleus.[20] Additionally, increasing elastic energy return by modulating joint stiffness may be advantageous when running on inclined surfaces, as it reduces the metabolic costs associated with moving the lower extremities through skeletal muscle contractions.[5,7] However, though increased joint stiffness may improve energy transmission and a reduce metabolic costs, these benefits may come at the cost of an increased risk for running related overuse injuries, particularly at the knee joint. Reducing the amount of deformation of the knee joint may increase stability but reduce the ability to absorb shock, which may lead to increased joint reaction forces experienced at the knee and the hip.

While a previous study reported increases in hip, knee and ankle joint stiffness with faster running speeds, a significant speed effect was not observed in the current study.[12,14] This may be attributed to the smaller margins between speed categories in the current study compared to previous studies. Previous studies examined stiffness with six different speed categories ranging from 1.8 m/s to 3.8 m/s, separated by 0.4 m/s intervals.[12] However, this study examined stiffness across three speed categories, which were determined based on participants' self-reported 5k pace and were separated by 0.2 m/s intervals.

It was also hypothesized that as speed increases, foot strike patterns will shift from a RFS to a FFS pattern across level ground and incline grades, but during decline running, RFS patterns will be maintained regardless of increases in speed. This hypothesis was partially supported as during decline running, RFS was predominant across all speeds. However, during level ground and incline running, MFS was predominant across all speeds, instead of the hypothesized FFS. These foot strike patterns observed across speed categories and across grade conditions were consistent with previous studies. Previous studies have reported that during level ground and incline running, FFS and MFS patterns were most common, and that during decline running RFS was most common.[17,22] The current study was consistent with previous findings, as the MFS pattern was predominant across all speeds on level ground and incline, and the RFS pattern was predominant across all speeds during decline running. A possible explanation for the shift in foot strike patterns in response to grade could be attributed to modulation of joint stiffness to either increase running efficiency, or better attenuate GRFs.

Lastly, it was hypothesized that as FSA increases, stiffness of the hip, knee and ankle joints will also decrease. Though the observed foot strike patterns were consistent with previous findings, based on what was observed from the linear regression analysis, FSA may not be a strong predictor for all lower extremity joint stiffness across speeds during graded running. However, FSA may be a better predictor for stiffness in some joints, as compared to others. The coefficients for determination for the knee were reported as 0.221 during level ground and incline conditions, and 0.1877 and during decline conditions. This suggests that approximately 20% of the variance in knee joint stiffness across speeds during graded running can be explained by foot strike angle. The observed coefficients of determination for the hip were 0.0365 during level ground, 0.0021 during incline, and 0.0147 during decline conditions, which suggests that less of the variance in joint stiffness in the hip can be explained by FSA. The coefficients of determination reported for the ankle were 0.0029 for level ground, and 0.00024 for the decline condition, however during the incline condition, the coefficient of determination was reported as 0.0134; suggesting that more the variance in ankle joint stiffness can be explained by FSA. This suggests that within joints, FSA may be a better at explaining the variance in joint stiffness during some grade conditions over others. From what was observed from the linear regression analysis, though it does not appear to explain a high amount of variance in joint stiffness, FSA may be a better predictor for joint stiffness of the knee, as compared to the ankle and hip.

Limitations

One limitation to this study may be related to the method used to identify midstance for stiffness calculations. Per methodology used in previous studies, midstance was identified as the transition from braking GRF to propulsive GRF. Knee flexion was identified at this frame and was used to calculate the change in angular displacement from initial contact to midstance. In most cases, peak knee flexion occurred at this time point. However, for some steps, peak knee flexion occurred before midstance, and the knee had already begun extending at midstance. In these cases, angular displacement values would not represent the true displacement experienced by the knee in the first half of stance. This then led to overly high stiffness values for the affected steps. Steps in which peak knee flexion did not occur at midstance (occurring in two trials: INC 1 and one INC 3) were removed from the analysis. Future studies examining joint stiffness should consider calculating the change in angular displacement by determining the difference in position from initial contact to peak flexion, rather than the braking-to-propulsive GRF transition.

Another limitation for this study lies in the duration of each trial. Given that participants performed each trial for only 30 seconds, there may not have been adequate time for runners to habituate to the treadmill. As a result, the running gait analyzed may not provide the best representation of how the participant runs in real world, overground conditions. In a study conducted by Play, et.al., it was determined that when running on a treadmill, there should be a two-minute minimum habituation period before measuring sagittal joint kinematics, and an eight-minute minimum habituation period before measuring GRFs.[24] Since the current study only analyzed gait after 30 treadmill second running trials, future studies conducted on treadmills should consider analyzing sagittal joint kinematics and running GRFs after a longer habituation period, to ensure that running gait is normalized.

Conclusions

The purpose of this study is to highlight how the role of each lower extremity joint changes to adapt to sloped terrain. While joint stiffness differs between the hip, knee, and ankle when running on graded surfaces, stiffness does not appear to change in response to speed. Additionally, foot strike angle does not appear to be a strong predictor for joint stiffness, but may be better at explaining the variance in joint stiffness in the knee, as compared to the ankle and hip. To characterize the role of each joint more thoroughly during uphill and downhill running, future studies should analyze the interaction effects of speed and grade on joint stiffness, as well as how foot strike patterns are influenced by speed.

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