ABSTRACT

Title of Thesis:	SHOE MIDSOLE DROP AFFECTS JOINT-LEVEL KINETICS AND ENERGETICS DURING JUMP-LANDING
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Traditional athletic footwear is designed with an elevated heel, causing ankle plantarflexion (positive drop). Conversely, research suggests an elevated forefoot (negative drop) could take advantage of calf musculature and improve jump height. It is unknown, though, if a negative drop simultaneously benefits landing mechanics related to lower extremity injury risk, and how individual lower extremity joints are affected, which contribute to whole-body jump-landing performance. Maximum vertical countermovement jumps were performed by 16 females in shoes with negative (NEG), neutral (NTRL), and positive (POS) drops. Although jump height was similar, peak concentric joint power was significantly greater in NEG than POS at the ankle, but opposite at the knee during jumping. During landing, eccentric work was greatest in POS. Joint work was greater in NEG than POS at the ankle, but opposite at the knee. These findings suggest shoe drop can affect joint-level jump-landing mechanics without concomitant changes in whole-body performance.

SHOE MIDSOLE DROP AFFECTS JOINT KINETICS AND ENERGETICS DURING JUMP-LANDING

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Arts
2019

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Acknowledgements

I would like to thank several people for their continued support and encouragement throughout my time at UMD. First, I would like to thank my advisor, Dr. Shim, for allowing me to pursue my passions in biomechanics and sports performance with the best tools available. This would not be possible without his patience and guidance as I tried to develop as a graduate student and researcher. I feel very lucky to be a part of the Neuromechanics Research Core.

I would also like to my fellow graduate students Mia and Jessica, who have been instrumental in my survival throughout the treacherous path that is graduate school. Learning from the experience of others and from the mistakes of my own has been both extremely fulfilling and humbling. I look forward to the progress we all make together as students and professionals in biomechanics.

I certainly would not be here if it were not for my family. The unconditional love and support from my parents and brothers has helped me continue to pursue my graduate degree, even in the most stressful times. I will never underestimate the calming power of a phone call home. Lastly, I would like to thank my boyfriend Eric who has also been pursuing his graduate degree along with me. His love and support, with a side of humor, has made the days spent reading, writing, and studying just a little bit easier.

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List of Abbreviations

Anterior cruciate ligament (ACL)

Countermovement jump (CMJ)

Initial contact (IC)

Knee abduction moment (KAM)

Negative shoe (NEG)

Neutral shoe (NTRL)

Patellofemoral pain (PFP)

Positive shoe (POS)

Range of motion (ROM)

Stretch-shortening cycle (SSC)

Vertical ground reaction force (vGRF)

Chapter 1: Introduction

General Introduction

Previous research has demonstrated the significant benefits of specialized sports equipment on athletic performance and injury avoidance. In particular, shoe design has evolved tremendously throughout the years. Arguably, the most important innovations have been changes to the shoe midsole, defined as the material between the insole and outsole of the shoe, as it is responsible for providing cushioning and shock attenuation during impact with the ground (48). Midsole cushioning and stiffness have been extensively researched, with studies supporting that both styles can be beneficial to athletic performance (36, 43). However, one important element of the midsole that has not been extensively studied is the midsole drop. Today the industry standard athletic shoe is cushioned with a ~4-5° drop from heel to forefoot, which puts the ankle in a plantarflexed position (37, 57). Rarely used are shoes that have a forefoot higher than the heel, a negative drop. A negative drop puts the ankle in a dorsiflexed position, and research suggests this change in midsole slope may be beneficial for athletic performance, especially jumping.

Larkins and Snabb tested both countermovement and running jumps and found that a negative 3.5° drop immediately improved jump height by 2.7-7.2 cm compared to traditional athletic shoes (37). Even after including an acclimatization period, shoes with a negative 4° drop significantly increased jump height by up to 4.5 cm (15). However, there is conflicting evidence of the effect of negatively sloped shoes. When Salinero et al. and Lapole et al. (36, 57) compared shoes with 2° of dorsiflexion to neutral or standard athletic shoes, there were no improvements in jump height, while Larkins and Snabb (37) found that jumping off of a wooden platform with a negative 2° drop actually increased jump height. These studies employed different jump protocols and used subjects with varying jump-training levels which may account for difference in results. Notably, lower extremity joint contributions to jump performance were not directly investigated in any of these previous studies, so it is unknown if dorsiflexion shoes change the way joints interact to improve overall jumping performance.

Midsole drop affects the ankle joint angle when standing, which can alter the kinetics and kinematics of joints along the kinetic chain, ultimately affecting whole-body jumping performance. Dorsiflexion shoes may provide a stretch to the musculotendinous structures in the calf, specifically the triceps surae complex which is responsible for producing a majority of the plantarflexion torque needed during jumping. Due to the parabolic relationship between muscle force and length (55), this stretch can move the operating range of the triceps surae complex towards optimal force production (61). This can increase ankle torque production during jumping and improve the use of the stretch-shortening cycle (SSC), resulting in greater power production (35, 42, 56). Previous research (1, 46) has demonstrated a strong relationship between CMJ height and power production. Regression analysis has shown that peak power production during the concentric phase may explain over 80% of the variation in CMJ height (13, 47). Force and velocity are components of power, so these two kinematic variables also have a strong relationship with jump height. Since total power is commonly calculated as the sum of individual lower extremity joint powers (17, 34), it is appropriate to use both total and joint-level power production and its components during the CMJ to demonstrate the effect midsole drop has on jump performance.

However, whether the knee and hip also benefit from increased ankle dorsiflexion is unclear. One study saw no difference in knee extensor torque between ankle dorsiflexion and plantarflexion conditions (10), while another saw significantly greater improvements in knee extensor torque after 3 weeks of training with the ankle fixed in dorsiflexion compared to plantarflexion (32). The combined effort from the ankle, knee, and hip determine overall jumping performance, so it is important to understand if changes to one or more of these joints can result from changes in midsole slope, and if this can ultimately lead to improved jump performance.

Arguably just as important as jump height to a jumping athlete's success is the way in which he/she lands. Remaining injury free allows for optimal performance and playing time. Shoes with a negative drop remove a portion of the available joint range of motion (ROM) an athlete can use to absorb impact when landing. Limiting the available dorsiflexion ROM at the ankle can also affect more proximal joints along the kinetic chain, due in part to the biarticulate nature of the gastrocnemius muscle (59). For example, placing a wedge under the forefoot to increase dorsiflexion and create a negative slope during a squat led to increased frontal plane movement of the knee (41). The effect of a negatively sloped shoe on joint displacement can have a cascading effect on joint stiffness, vertical ground reaction forces (vGRF), and energy absorption during landing (7, 12). Energy absorption is quantified as the negative work done during the eccentric phase of landing (66), and less energy absorption is associated with smaller joint displacements and greater impact forces, which can put considerable strain on the lower extremity (12, 34). Individual joints each contribute to total energy absorption, but it is currently unknown how they are affected by midsole drop during landing to contribute to whole-body energy absorption. Although the effect of landing in a negatively sloped shoe has not been directly investigated, Hagins et al. studied a similar phenomenon of dancers who performed drop jumps onto a negatively sloped stage (3.6°). They found that dancers landed with higher knee valgus, higher posterior GRF, and smaller ankle joint displacements (21). Furthermore, individuals with less passive dorsiflexion ROM land with less knee flexion, greater vGRF, and greater knee valgus during drop jump tasks (18, 59), which can also contribute to greater knee abduction loads and an overall more rigid landing (28).

This is significant because knee valgus, knee abduction loads, smaller joint displacements, and higher vertical GRF are all notable risk factors for both patellofemoral pain (PFP) and acute anterior cruciate ligament (ACL) injury (18, 51, 65). In sports like volleyball and basketball where players may jump hundreds of times each week, the cumulative effect of poor landing mechanics could have serious implications for injury (2). It is critical that the link between midsole drop and landing mechanics be investigated to ensure shoes with negative drops will not expose the athlete to increased risk of injury.

The purpose of this study was to investigate if shoes that vary in midsole drop (negative, neutral, positive) affect joint level kinetics and kinematics that contribute to overall jump performance and landing mechanics related to lower extremity injury risk. It is hypothesized that 1) use of the negatively sloped shoe (NEG) will augment peak ankle joint power production to result in the greatest jump height compared to both neutral (NTRL) and positive (POS) due to increased ankle dorsiflexion and possible stretch of the triceps surae complex, which may optimize their position on the force-length curve and consequently their use of the SSC, and 2) NEG will adversely affect joint-level jump-landing mechanics shown to increase the risk of lower extremity injuries. The increased dorsiflexion experienced in NEG during landing will increase frontal plane motion of the knee, contributing to greater knee valgus, impact forces, and decreased energy absorption.

Chapter 2: Methods

Experimental Approach to the Problem

This study was designed to test if shoes with different degrees of midsole drop affected jump performance and landing mechanics in young, recreationally active females. Participants wore each of three pairs of prototype athletic shoes designed by Under Armour to the specifications of the researcher. The shoes were identical except for changes to the forefoot and heel height. This resulted in midsole drops of -3 mm (NEG; ~-1.5°), 0 mm (NTRL; 0°), and 18 mm (POS; ~8°). A drop of ~-1.5° was chosen to compare the results of the current study with those from Salinero et al. and Lapole et al. who used -2° dorsiflexion shoes and did not find improvements in jump height (36, 57). Some of the only commercially available dorsiflexion shoes (Springboost shoes, Switzerland) also have midsole drops between negative 1-2°, adding ecological validity to the current study. The experiment was a within-subjects repeated measures design. Participants performed jumps in all three shoes, and the order of shoes was randomly assigned for each participant. The maximal effort vertical countermovement jump was used to test jump-landing performance as it reflects the types of loading, magnitudes of loading, joint ranges of motion, and joint angular velocities observed in sport. Subjects were instructed to keep their hands on hips to remove the effect of arm swing on performance. Kinematic and kinetic variables were calculated at both the whole-body level and joint-level.

Subjects

Participants were randomly recruited using flyers and postings on listservs at the University of Maryland-College Park (UMD-CP). Inclusion criteria were (i) females aged 18-35, (ii) approximately US size 7 feet, (iii) no medical conditions that interfere with their ability to jump, (iv) no chronic mobility impairments, and (v) no history of major lower extremity injury that required surgery or medical attention. The UMD-CP Institutional Review board approved the study's protocol. Previous studies on dorsiflexion shoes and jump performance (15, 37) and landing mechanics related to lower extremity injury (12, 21, 34) achieved statistical significance ($p < 0.05$) using 8-21 participants, therefore, sixteen young females (Mean ± SD: age, 21.65 ± 4.7 years; mass, 63.69 ± 14.3 kg, height, 1.60 ± 0.05 m) completed the study.

Procedures

After providing informed consent, height, physical activity status, and injury history were recorded. Participants wore a non-reflective, tight-fitting spandex top and shorts provided by the laboratory. To capture the movement of the lower extremity, reflective markers were placed on the following anatomical sites bilaterally: anterior superior iliac spines, posterior superior iliac spines, sacrum, 4-marker thigh and shank clusters, lateral and medial epicondyle of the femur, lateral and medial malleoli, and 1st and 5th metatarsal heads. Additional markers were placed on the shoe midsole at the location of the heel, 1^{st,} and 5th metatarsal heads. Kinematic data were collected using a 13-camera motion capture system (VICON, Centennial, CO, USA). Ten embedded force plates sampling at 1000 Hz recorded 3-dimensional GRF data (Kistler, Amherst, NY, USA).

Participants wore each of three pairs of prototype athletic shoes, which were identical except for chances to the forefoot and heel height. Forefoot heights were either 12 millimeters (mm) or 15 mm, while heel heights were either 12 mm or 30 mm. Shoes are referred to by their drop, the change in slope from heel to forefoot: Negative (NEG), Neutral (NTRL), and Positive (POS) (Figure 1). A positive drop indicates that the heel is elevated above the forefoot.

Figure 1. A lateral view of the three shoe conditions. From the left; NEG, NTRL, POS. Red lines indicate approximate midsole slopes.

All testing took place in one lab visit lasting approximately two hours for each participant. A static calibration trial was collected by having participants stand still for approximately ten seconds with their feet shoulder-width apart, shoulders abducted to roughly 90°, and palms facing forward. The left and right foot were positioned on one force plate each. The static calibration trial was repeated at the start of each shoe condition. For dynamic trials, markers along the medial side of the body were removed (medial malleoli, 1st metatarsal heads). Two practice CMJ trials with hands on hips were performed at near maximal effort to familiarize the participant with the CMJ movement. The researcher instructed the participant to, in one smooth motion, lower into a self-selected countermovement depth and jump vertically as high as possible. It was imperative that they land with one foot on each force plate so forces from the left and right foot could be identified. Feedback from the researcher was provided so the participant complied with the procedure, but it was important the researcher did not influence the participant's natural jumping pattern. Verbal confirmation from the participant guaranteed the protocol was understood prior to testing.

Three successful jump trials were collected, with approximately one minute of rest between each trial to prevent against the effects of muscular fatigue (62). If there was marker dropout or the participant did not land fully on the force plates, additional jump trials were performed. Approximately a five-minute rest was taken before beginning the next shoe condition. Additional rest was taken at any time at the participant's request.

Data Analysis

A custom Visual3D script (C-Motion, Inc, Germantown, MD, USA) was used for all data analysis. Kinematic data was filtered with a fourth order low-pass Butterworth filter with a frequency cutoff of 10 Hz (54). Residual analysis was used to determine the cutoff frequency of 12 Hz for force plate data (44, 66). Previous studies have demonstrated that this value allows for high reliability of ground reaction force data (19). Force plate and kinematic data was used to calculate forces and moments in the lower extremity using inverse dynamics (66). Both kinematic and kinetic variables were primarily calculated in the sagittal plane with the exception of knee valgus angle and knee abduction moment (KAM). Participant mass was determined from the static calibration trial recorded before each condition. Vertical ground reaction force (vGRF) was used to determine timing of jump events. A threshold of 20 N was used to determine instances of takeoff, initial contact, initiation of the countermovement, and standing. Figure 2 displays how jump events were determined from vGRF with the exception of maximal joint flexion during jumping and landing.

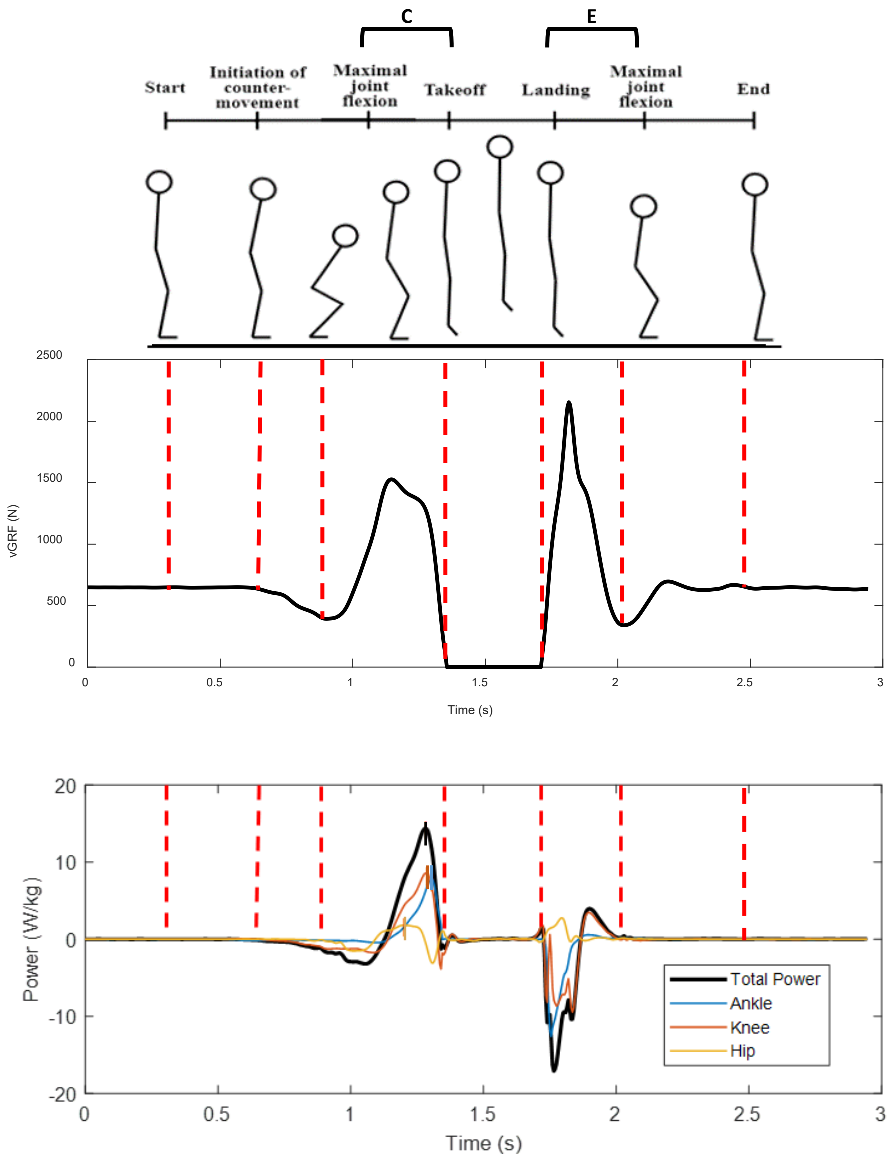

Figure 2. Jump events are labeled above a schematic of the countermovement jump motion. C and E represent concentric and eccentric time periods used for data analysis, respectively. Timing of jump events (red dotted lines) were determined by vertical ground reaction force data with the exception of times of maximal joint flexion. Total power and individual joint power curves are displayed in the bottom panel. Peak concentric powers are indicated by a vertical line in the respective color. Data is from a representative subject.

Peak vGRF before takeoff and after landing was recorded for each trial. The RFD for each trial was calculated as the ratio of change in vGRF over time from the lowest force during the countermovement to peak vGRF produced before takeoff. Maximal vertical countermovement jump height was determined using the impulse-momentum method (40). Average force and contact time from the initiation of the countermovement to takeoff were also calculated as analogues to the impulse-momentum method.

Ankle, knee, and hip joint kinematics were calculated for each trial. By convention, positive values indicate ankle dorsiflexion, knee extension and adduction, and hip flexion. Joint displacements during both the countermovement and landing were recorded. The peak knee valgus angle during landing was determined as the minimal knee joint position along the frontal plane between instances of landing and maximal joint flexion. Larger negative values indicate greater knee valgus. Knee valgus during initial contact was also recorded. Maximal joint flexion during both the countermovement and landing was determined as the timepoint when knee flexion was greatest. The ankle, knee, and hip joints reached their greatest displacement at the same time, so one timepoint was used for time of maximal flexion for all joints.

Joint moments are expressed as internal moments with the exception of knee abduction load, as external valgus load on the knee has been linked to risk of injury (27). Peak external KAM between initial contact and maximal joint flexion, as well at initial contact was recorded for each trial. Joint power during jumping was calculated in Visual3D as the product of joint moment and respective angular velocity, which were recorded for each trial. The positive portion of the power curve before takeoff quantified concentric power production during jumping (Figure 2). Total power production was calculated as the sum of the ankle, knee, and hip joint power curves. The peak total positive value and individual joint powers at the instance of peak total power were recorded. Joint work was calculated as the integral of the joint-power curve for the ankle, knee, and hip. Negative work was recorded for each trial to quantify eccentric energy absorption during landing. Total joint work was calculated as the sum of ankle, knee, and hip joint work. Joint work can also be represented as the product average torque and joint displacement, and these components were recorded for each trial. Both concentric power and eccentric work were normalized to bodyweight.

Statistical Analysis

A customized script in R (R Core Team, 2016) was used for analysis. All outcome variables were averaged over the three trials. A one-way repeated measures ANOVA with correction for sphericity assessed group differences. For variables with a significant main effect of shoe condition, post-hoc Tukey contrasts with a Bonferroni correction for multiple comparisons were calculated. Cohen's *d* effect sizes (ES) were calculated to determine the effect of shoe condition on the dependent variables. Effect sizes less than 0.2 were considered trivial, between 0.2-0.5 were small, between 0.5-0.8 were medium, and greater than 0.8 were large (9). An alpha level of 0.05 was used for all analyses.

Chapter 3: Results

Jumping Performance

Whole-body level

Participants performed relatively similarly in all three shoe conditions. Jump height was similar between shoe conditions ($p = 0.95$), as was average force ($p = 0.66$), takeoff velocity ($p = 0.96$), and contact time ($p = 0.38$). Participants also had similar rates of force development ($p = 0.08$). Main effects of shoe condition existed for both total power production (Figure 3a) and peak vGRF produced before takeoff ($p = 0.004$), which was greater in NEG than both NTRL and POS (1249 ± 170 vs. 1220 ± 179 and 1218 ± 171 N, respectively).

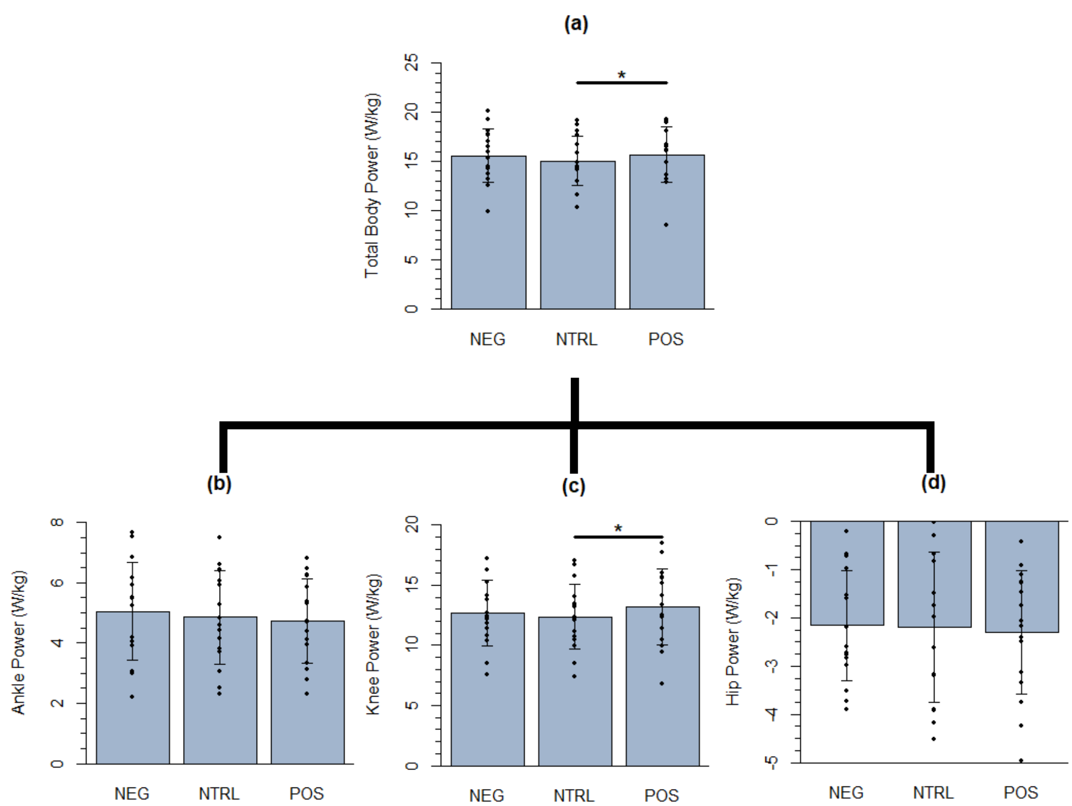

Figure 3. Mean absolute contribution of each joint (b-d) to peak total concentric power production (a). Shoe condition only affected power production at the knee joint in POS.

Joint level

Although shoe condition had minimal effect on whole-body performance, joint-level kinematics and kinetics were significantly affected (Table 1 & 2). At the time of peak total power, shoe condition only affected the knee joint as evidenced by greater power in POS than NTRL (Table 1, Figure 3c). Significant differences were also observed in peak joint power production at both the ankle and knee (Table 2). Pairwise comparisons revealed peak ankle joint power was greater in NEG than POS and greater in NTRL than POS. The opposite pattern existed at the knee, with greater power in POS than NEG, and greater power in POS than NTRL. Hip power was unaffected by shoe condition. Analysis of the components of joint power revealed significantly different ankle angular velocity at peak joint power and torque at both peak total power and peak joint power. At the knee, only angular velocity differed between conditions at peak joint power.

Analysis of the timing of peak joint powers with respect to peak total power revealed that it took significantly longer for peak ankle power to occur in NEG than NTRL (Figure 4). There were no differences in timing of peak power at the knee and hip.

Table 1. Mean ± SD and *p*-value for total power and its components at the instance of peak total power during jumping.

	NEG	**NTRL**	**POS**	***p***
Peak total power (W/kg)	15.58 ± 2.70	15.04 ± 2.52	15.66 ± 2.82	0.044
Joint power (W/kg)				
Ankle	5.05 ± 1.63	4.85 ± 1.55	4.73 ± 1.40	0.108
Knee	12.68 ± 2.73	12.38 ± 2.71	13.22 ± 3.17	0.030[b]
Hip	-2.16 ± 1.15	-2.19 ± 1.55	-2.30 ± 1.29	0.802
Angular velocity (deg/s)				
Ankle	-413.33 ± 80.05	-418.39 ± 78.75	-432.89 ± 75.72	0.187
Knee	549.35 ± 65.62	548.82 ± 66.35	557.17 ± 70.78	0.549
Hip	-392.79 ± 41.90	-389.35 ± 39.37	-389.45 ± 33.63	0.777
Joint Moment (N m)				
Ankle	-43.19 ± 11.95	-41.35 ± 12.83	-38.80 ± 10.81	0.003[a]
Knee	81.01 ± 13.43	79.18 ± 13.83	83.17 ± 15.56	0.067[b]
Hip	19.53 ± 10.04	19.75 ± 12.99	20.59 ± 10.50	0.830

[a] Significant difference between NEG-POS ($p < 0.05$)
[b] Significant difference between NTRL-POS ($p < 0.05$)

Table 2. Mean ± SD and *p*-value for peak joint power and its components at the instance of peak joint power.

	NEG	**NTRL**	**POS**	***p***
Concentric peak joint power (W/kg)				
Ankle	6.21 ± 1.85	5.89 ± 1.76	5.39 ± 1.56	<0.001[ab]
Knee	13.09 ± 2.86	12.80 ± 2.87	13.79 ± 3.22	0.004[ab]
Hip	2.54 ± 0.94	2.57 ± 0.94	2.44 ± 0.76	0.585
Angular velocity (deg/s)				
Ankle	-652.82 ± 82.46	-627.96 ± 98.28	-611.38 ± 95.05	0.002[a]
Knee	613.79 ± 86.50	614.08 ± 87.91	637.34 ± 89.28	0.015[ab]
Hip	-202.83 ± 42.27	-213.26 ± 63.39	-223.39 ± 80.91	0.334
Joint Moment (N m)				
Ankle	-33.49 ± 9.74	-32.94 ± 9.34	31.04 ± 8.04	0.037[a]
Knee	75.41 ± 14.18	73.53 ± 13.08	76.21 ± 13.87	0.158
Hip	-44.50 ± 11.06	-42.97 ± 7.45	-37.27 ±7.34	0.001[ab]

[a] Significant difference between NEG-POS ($p < 0.05$)
[b] Significant difference between NTRL-POS ($p < 0.05$)

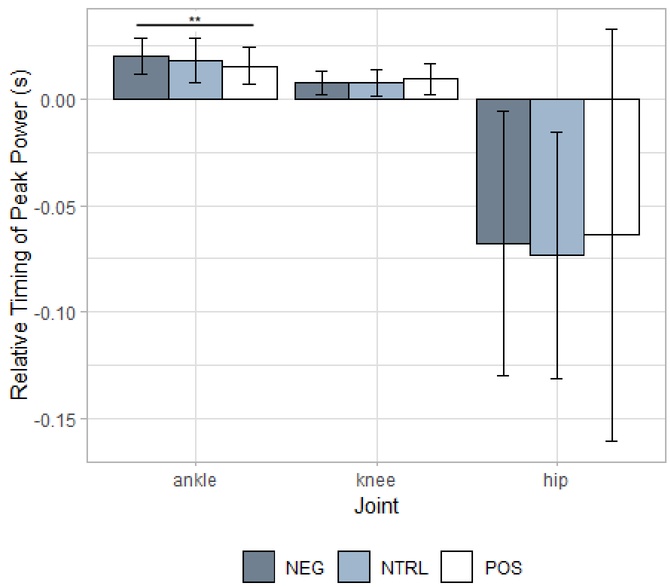

Figure 4. Relative timing of peak joint powers with respect to timing of peak total power. Positive values indicate the joint peak power occurred after peak total power.

Landing Mechanics

Whole-body level

Evaluation of peak impact force revealed it was similar between shoe conditions ($p = 0.06$). However, shoe condition did affect total eccentric work, with a statistical difference between NTRL-POS (Figure 5a).

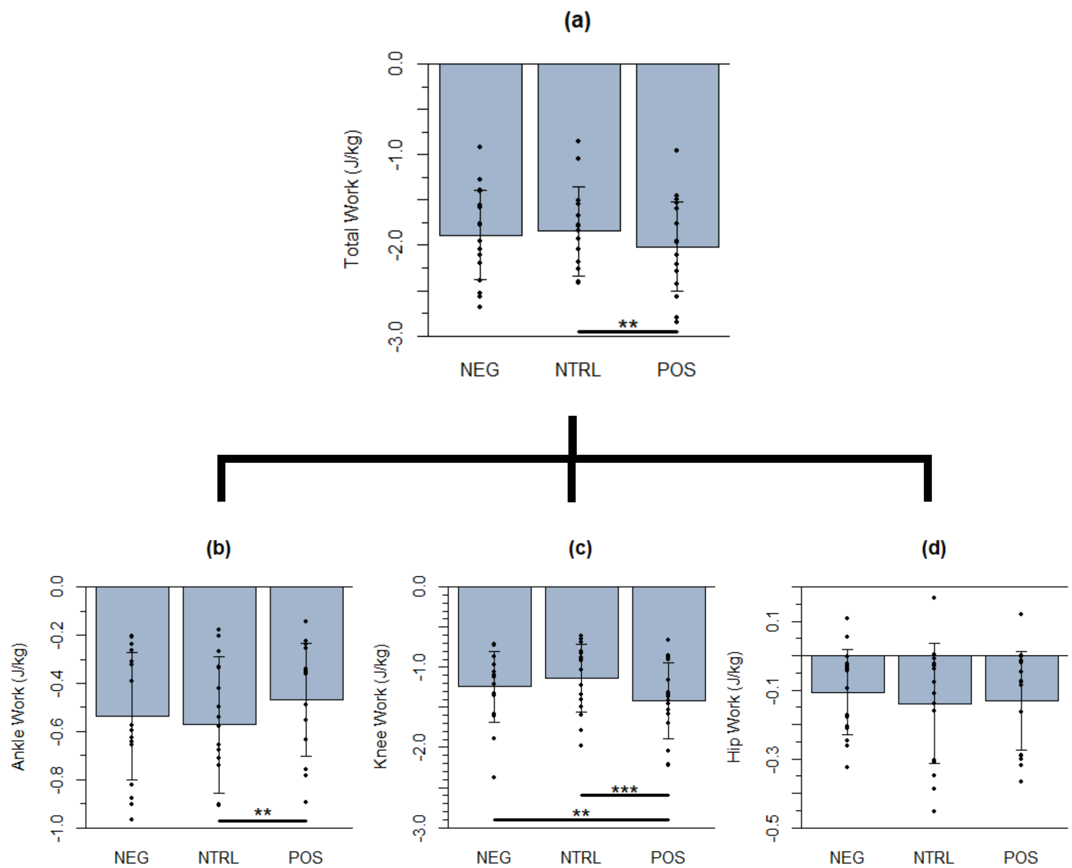

Figure 5. Mean absolute contribution of each joint (b-d) to total eccentric joint work (a). Eccentric work was significantly greater in POS than NTRL.

Joint level

Mean values and statistical significance of the ANOVAs for joint-level landing mechanics variables are detailed in Table 3. There were no effects of shoe condition on KAM and knee valgus at IC and for peak values (all $p > 0.7$). Both eccentric ankle and knee joint work were affected by shoe condition. Pairwise comparisons revealed eccentric ankle work was greater in NTRL than POS and knee work was greater in POS than both NEG and NTRL (Figure 5b-c). Evaluation of the components of joint work revealed significant differences only in average joint moment at the ankle and joint displacement at the knee. Differences in knee joint displacement were due to significantly greater final knee flexion angle in POS than both NEG ($p = 4.9 \times 10^{-4}$) and NTRL ($p = 7.5 \times 10^{-5}$) during landing.

Table 3. Mean ± SD and *p*-value for eccentric work and its components during landing (from IC to maximal joint flexion).

	NEG	**NTRL**	**POS**	***p***
Eccentric Work (J/kg)				
Total	-1.89 ± 0.51	-1.85 ± 0.46	-2.02 ± 0.53	0.029[b]
Ankle	-0.54 ± 0.27	-0.57 ± 0.28	-0.47 ± 0.23	0.005[b]
Knee	-1.24 ± 0.44	-1.14 ± 0.42	-1.42 ± 0.47	<0.001[ab]
Hip	-0.11 ± 0.12	-0.14 ± 0.17	-0.13 ± 0.14	0.27
Average joint moment (N m)				
Ankle	-40.28 ± 16.30	-42.92 ± 15.92	-35.65 ± 15.08	0.006[b]
Knee	80.87 ± 17.11	74.80 ± 23.04	86.21 ± 21.86	0.004[b]
Hip	2.56 ± 19.41	-1.10 ± 21.83	-1.16 ± 23.55	0.220
Joint displacement (deg)				
Ankle	60.39 ± 10.02	58.91 ± 11.31	58.91 ± 9.53	0.486
Knee	-59.57 ± 12.90	-58.94 ± 12.72	-63.54 ± 14.32	0.001[ab]
Hip	35.79 ± 14.48	35.5 ± 14.85	35.49 ± 14.23	0.963

[a] Significant difference between NEG-POS ($p < 0.05$)
[b] Significant difference between NTRL-POS ($p < 0.05$)

Chapter 4: Discussion

Jump Performance

The purpose of the current study was to investigate the effect of varying midsole slope on whole-body and joint-level (1) jump performance, and (2) landing mechanics related to risk of PFP and ACL injury.

At the whole-body level, jump performance was relatively unaffected by the increase in dorsiflexion from NEG. Jump height, RFD, takeoff velocity, average force, and contact time were all similar between conditions. Although peak total power was greatest in POS, and it is well established that peak concentric power is a significant predictor of jump height (13, 47), this did not affect jump height in the current study. It is possible that the greater peak vGRF in NEG, which also correlates well with jump height (13) negated the advantage of increased power in POS to result in similar jump performance. This conflicts with findings from both Larkins & Snabb and Faiss et al. (15, 37) who demonstrated that jump height was improved by wearing dorsiflexion shoes. Larkins & Snabb allowed the use of arm swing during the CMJ and a running start in some trials which are both known to contribute to improved jump height (24, 64). Furthermore, subjects were trained volleyball players who are familiar with jumping, whereas in our study subjects were not specifically jump-trained. Faiss et al. used subjects similar to our own, but the protocol included an acclimatization period before testing, which we did not. Comfort plays a role in performance (25), so it is possible this contributed to greater jump heights. Most significantly, for both studies the degree of dorsiflexion tested was between 3-4°.

Both Salinero et al. and Lapole et al. tested shoes with negative 2° slope and did not find improvements in jump height. This, along with findings from the current study using shoes with a negative ~1.5° drop, suggests slopes greater than -2° maybe needed to augment jump height.

However, joint kinetics and kinematics were significantly affected by a change in midsole slope. Shoe condition affected the contribution of the knee at the instance of peak total power, as evidenced by greater joint power in POS. Joints did not reach peak power at the same time as peak total power (Figure 4), so analysis of the individual peak joint powers provided an indication of how midsole drop could maximally affect each joint without concern for timing of peaks. Peak ankle joint power was greatest in NEG and least in POS, while peak knee joint power was greatest in POS and least in NEG and NTRL. The effects of shoe condition on joint power did not appear to reach the hip joint. Peak total power can be improved when the timing of peak joint powers occurs in a proximal-to-distal sequence (4) and closer to the time of peak total power (29). Subjects in the current study displayed this sequence of peak joint powers (Figure 4), but the timing of peak ankle power was significantly closer to peak total power in POS. This may have contributed overall greater total power in POS as the ankle was closer to its peak at the time of peak total power.

A closer look at the components of joint power reveal that ankle joint torque at peak joint power was significantly greater in NEG than POS, which may have contributed to the difference in peak ankle power. Ankle joint torque was also increased in NEG at the time of peak total power. This finding is supported by work from Sale et al., who tested maximal voluntary contraction (MVC) of the triceps surae complex at varying positions of the ankle joint. As the ankle moved from plantarflexion into dorsiflexion, torque production drastically increased; torque at ankle positions most similar to the current study (5° plantarflexion and 5° dorsiflexion) show a ~26% increase (56). It is important to note that the torque-angle relationship for the ankle is commonly obtained during isolated plantarflexion and that this relationship may not be the same for multi-joint movements. Hahn et al. (22) investigated the torque-angle relationship during multi-joint leg extension for the knee and ankle and found that, in contrast to isolated plantarflexion, torque production decreased after the ankle angle exceeded 5° of dorsiflexion. This represented the average response, but torque-angle profiles for individual subjects varied greatly. As this study was performed only in males, it is possible the relationship between torque and joint angle would differ among females since there are known differences in ankle joint kinematics and strength between genders (20, 30). It is thus possible that the increased dorsiflexion experienced by the ankle joint in NEG contributed to increased joint moment in NEG, which ultimately resulted in greater power at the ankle.

Numerous studies have determined that the force a muscle can produce is linearly related to the amount of myofilament overlap, which in turn dictates a muscle's length (26, 31, 42, 55). There is a parabolic relationship between force production and muscle length, and optimal force production typically occurs at a length slighter greater than a muscle's resting length. It was expected that manipulating shoe midsole slope would change the ankle joint angle, thus affecting the length of the triceps surae complex and torque production. In a traditional athletic shoe, the ankle is slightly plantarflexed which puts the triceps surae complex in a shortened initial length. In this shortened position, these muscles are operating on the ascending limb of the force-length curve, limiting their potential for producing force. Increasing the initial length of these muscles would move their operating range further along the curve, towards optimal length and force production (42, 61).

We also found that knee torque was similar between conditions, although peak knee power was greater in POS than NEG and NTRL. In a study that examined plantarflexion torque during isokinetic knee extension at different ankle positions, there were no differences in peak extensor torque when the ankle was at full plantarflexion (~160°) compared to full dorsiflexion (90°). This study used a taping method to fix the ankle at the extremes of its ROM, which does not correspond to the joint angles elicited by shoes in the current study. Researchers also used electromyography (EMG) to quantify muscular electrical activity of the main knee extensors. They showed no difference in muscle excitation of the vastus lateralis and vastus medialis muscles between plantarflexion and dorsiflexion conditions (10). This suggests the muscles' potential to produce contractile force was not improved with an increase in dorsiflexion (38). This demonstrates that knee torque may be unaffected by ankle joint position. It is possible the lower extremity may pick a different strategy to increase joint power, as in our study where we observed the increased knee joint power was a result of increased angular velocity.

Landing Mechanics

To our knowledge, this is the first study that examined if shoes that elicit dorsiflexion adversely affect both whole-body and joint level kinetics and kinematics related to PFP and ACL injury risk. Knee valgus and KAM are closely related to incidence of both PFP and ACL injury (27, 50), and both were unaffected by increases in dorsiflexion in NEG. This contrasts with findings from Hagins et al. who showed that dancers who landed on a negatively sloped stage (3.6°) landed with significantly greater knee valgus and impact forces compared to a flat stage (21). In the present study, peak impact force tended to be least in POS, however it did not reach significance.

Most notably, though, total eccentric negative work was greatest in POS, indicating that energy absorption was greatest in this condition compared to NEG and NTRL. Several studies have demonstrated that decreased energy absorption during landing, quantified as negative work, coincides with stiffer landings (11, 12, 58). Stiff landings are also commonly identified by decreased knee flexion (39, 52). Furthermore, stiffer landings, decreased knee flexion, and increased vGRF are risk factors for PFP and ACL injury (6, 27, 39, 52, 63, 65). Landing with less sagittal plane ROM, particularly knee flexion, prevents effective absorption of energy and increases the strain on the patellofemoral ligament and ACL and can lead to injury (53, 65). In the present study decreasing the available dorsiflexion at the ankle in NEG led subjects to land with less total eccentric work and less knee flexion compared to POS, which suggests dorsiflexion shoes may put individuals at greater risk of injury of PFP and ACL injury. However, it is less likely that injury, especially

ACL rupture, will occur the absence of increased valgus loads (45). Nevertheless, these results are particularly important considering the small angle of dorsiflexion that was actually induced by NEG. The 3-4° dorsiflexion shoes used in previous studies may have an even greater risk of injury, although future studies must be done to confirm this (15, 37).

The current study demonstrates that both the jump and landing movements must be analyzed when testing new shoe designs. Although a main component of jump performance, jump height, was not affected, joint level contributions to total power were significantly different between shoe conditions. In terms of landing mechanics, athletes can be moderately confident that these negatively sloped shoes do not increase risk of knee injury. However, caution is advised if using shoes with greater degrees of dorsiflexion as they may cause more drastic alterations in knee flexion, ground reaction forces, and possibly knee abduction loads.

Chapter 5: Practical Applications

Improving jump performance is a focus for athletes and their coaches in many sports. Equipment selection is oftentimes crucial to optimal performance, especially determining which type of shoe is best suited for the demands of the sport. Our results suggest that although dorsiflexion shoes with slopes less than 2° likely do not improve jump height, contributions of individual joints to total power are affected. Strength and conditioning or sport coaches can apply these results to target specific joints during training, for example choosing a dorsiflexion shoe to target the ankle and calf musculature.

The current study also demonstrated how restricting dorsiflexion during landing can lead to smaller peak knee flexion angles and less energy absorption. This more rigid landing strategy prevents effective absorption of impact forces, which is especially important in jumping sports. Although these changes were not accompanied by increases in knee valgus or abduction loads, coaches should execute caution before allowing their athletes to wear a shoe designed to improve jump performance before its effects on landing are determined.

Appendices

Literature Review

Jump Performance and Methodology

The design of athletic shoes has evolved tremendously throughout the years. The flat, thin-soled Converse All Star shoes popularized by basketball players in the 1960s were soon replaced by Nike's cushioned 'waffle sole' (37). Then the minimalist and barefoot running trend gained popularity, and shoes with little to no cushioning became the shoe of choice for many athletes. Today the industry standard athletic shoe is cushioned with a 12 millimeter (~5°) drop from heel to forefoot, but still a wide variety of designs exist. However, the one element of shoe design that has remained relatively untouched is the midsole drop. Some shoes have a higher heel, a steeper drop, or have no difference between heel and forefoot height. Next to none, though, have a forefoot that is higher than the heel. This is essentially opposite of the industry standard shoe, putting the ankle in a dorsiflexed position as opposed to typical plantarflexion. As many new shoe designs may seem unusual at first, it is reasonable to question if this particular design has any benefits for athletic performance.

Although researchers have extensively manipulated other shoe characteristics like cushioning and stiffness in recent years, midsole drop has been fairly under-studied. Changing the slope between heel and forefoot will immediately change the ankle angle during static and dynamic tasks, and this change will have an effect on more proximal joints along the closed kinetic chain, specifically the knee and hip. Several studies have investigated this phenomenon in relation to jump performance, and the results provide convincing evidence that wearing negatively sloped shoes can immediately affect jump height.

Larkins and Snabb tested the effect of negative midsole drop on jump performance in three phases. In the first two phases, athletes performed maximal effort countermovement jumps on a wooden platform adjustable from negative 4° to positive 4°, which simulated the drop in standard athletic shoes. An optimal angle of -3.5° of dorsiflexion was determined in the first series of jumps, and this angle was compared to +4°. Mean jump height significantly increased on the negatively inclined platform by 2.8 cm. Phase three tested shoe prototypes with the same inclinations as the wooden platform. On average, participants jumped 4.8 cm higher after two rounds of jumping in the negative drop shoes. These results demonstrate that dorsiflexion can have a significant impact on jump performance. However, it is important to note that this study was conducted with small sample sizes and the countermovement jump protocol allowed the use of arm swing (37). Using a traditional standing countermovement jump protocol with hands on hips would better isolate the effect of negatively sloped shoes on the lower extremity. Furthermore, the order of conditions was not randomized and could influence results.

Building upon these findings, Faiss et al. investigated the effect of dorsiflexion shoes on jump performance after an acclimatization period. In addition to countermovement jumps with hands on hips, participants performed a continuous jumping test, which mimics the repetitive jumping common in sports like volleyball and basketball. Their dorsiflexion shoes had a negative 4° drop and were compared to standard fitness shoes. Participants were randomly assigned to wear one of the shoes for at least 1 hour every day for 10 days prior to testing and this was repeated for the second shoe condition. Dorsiflexion shoes significantly increased jump height in both countermovement jump and continuous jump tests (+2.2 cm and +4.5 cm, respectively). Furthermore, during the acclimatization period participants noted that they did not feel limited by the dorsiflexion shoes, and that they did not induce any discomfort or pain (15). Comfort level is extremely important in the athlete-equipment interaction, so this is promising evidence that dorsiflexion shoes can be worn to improve performance without sacrificing comfort.

Shoes with lesser degrees of dorsiflexion have also been tested. Both Salinero et al. and Lapole et al. compared shoes with 2° of dorsiflexion to neutral or standard athletic shoes and found similar countermovement jump heights between conditions. This is in contrast to Larkins and Snabb's findings that jumping on a platform with a negative 2° drop led to improved jump height (37). One of the only commercially available shoes with a negatively inclined midsole has a slope of 2°, so while these studies possess higher ecological validity, the degree of dorsiflexion may not have been large enough to induce significant changes at the whole body level to affect jump height (36). However, 2° may be enough to elicit changes at the lower extremity joint level. Salinero et al. revealed participants in the dorsiflexion shoes exhibited higher force at the moment of peak power and greater force in the concentric phase. They postulated this could be due to increased torque generated at the ankle from a stretch to the triceps surae complex (57). Since this still resulted in similar jump heights, this is an indication that joints along the kinetic chain may compensate for changes at the ankle joint. It is thus possible that even if shoes with a smaller degree of dorsiflexion do not affect whole-body performance, that joint-level variables that contribute to total performance may be affected.

The maximal effort vertical jump is a movement vital to a successful performance in numerous sports such as basketball and volleyball. These jumps involve a natural countermovement, the drop in the body's center of mass when the individual bends their knees before propelling upwards. As such, the CMJ is commonly used in sports performance-related research as it reflects the types of loading, magnitudes of loading, joint ranges of motion, and joint angular velocities observed in sport. Athletes also utilize an arm swing. Combined with the countermovement, these motions work to maximize power production and jump height during a vertical jump (24). Although testing athletes in the exact way they perform jumps in their sport increases external validity, it may compromise the results. In an attempt to isolate the motion and effects of the joints in the lower extremity, a maximal effort countermovement jump with hands affixed to the hips will be performed by participants in the present study. Several studies have used this paradigm for a more accurate representation of how the lower extremity performs during different conditions of a vertical jump (Lapole et al., 2013; Markovic, Mirkov, Nedeljkovic, & Jaric, 2014; Faiss et al., 2010; Bobbert, Jan, & Schenau, 1988; Thomas, Jones, Rothwell, Chiang, & Comfort, 2015).

Previous research has demonstrated a strong relationship between CMJ height and power production, an important component of many athletic movements like sprinting, jumping, and cutting. Regression analysis has shown that power production during the concentric phase may explain over 80% of the variation in CMJ height (13, 47). As force and velocity are components of power, these two biomechanical factors have a strong relationship with jump height as well. Total power is commonly calculated as the sum of individual lower extremity joint powers (34). Therefore, is appropriate to use both total and joint-level power production and its components during the CMJ to demonstrate differences in performance with varying shoe conditions.

Mechanisms of Improved Jumping Performance

Athletes benefit most when their sports equipment interacts with their musculoskeletal system in an optimal way. One of the most essential pieces of equipment in an athlete's arsenal is their footwear. Many components of the athletic shoe can be manipulated, but perhaps the most important changes are to the midsole. The midsole provides cushioning and dictates the positioning of the ankle joint upon impact. Ideally, these properties interact to improve an athlete's performance without increasing their risk for injury. The way in which this is achieved is by affecting properties of the musculotendinous structures in the lower limbs. The force-length relationship is one such property that plays a critical role in the athlete-equipment interaction (61).

The relationship between muscle length and the force that muscle can produce has been studied extensively. Muscles are composed of fibers that contain contractile elements called sarcomeres. Within each sarcomere are the myofilaments actin and myosin. These myofilaments overlap to form a cross-bridge that shortens as the muscle contracts and lengthens as the muscle elongates. Numerous studies have determined that the force a sarcomere can produce is linearly related to the amount of myofilament overlap, which in turn dictates a muscle's length (26). Force production increases as overlap increases until opposite sides of the myofilaments meet each other. After this point of 'double' overlap, force production decreases. Thus, there is an optimal length where force production is greatest; this is typically at a length slightly greater than a muscle's resting length (55). Sports shoe designers and engineers should ensure their product takes advantage of this relationship especially if force production is important to performance. Manipulating the midsole drop is an effective way of doing so.

One of the most important muscular components to jumping in the lower extremity is the triceps surae complex in the calf, which is responsible for producing a majority of the plantarflexion torque needed during jumping tasks (56). The medial and lateral gastrocnemius and soleus muscles are the three main muscles that comprise the triceps surae complex. In a traditional athletic shoe, the ankle is slightly plantarflexed, putting the muscles of the triceps surae complex in a shortened initial length. In this shortened position, these muscles are operating on the ascending limb of the force-length curve, limiting their potential for producing force. Increasing the initial length of these muscles would move their operating range further along the curve, towards optimal length and force production (42). Athletic shoes that put the ankle in a dorsiflexed position would certainly help provide this stretch to the calf musculature, increasing its potential for force production.

Research by Sale and colleagues demonstrated this phenomenon. They tested maximum voluntary contraction of the triceps surae complex at varying positions of the ankle joint, from 30° of plantarflexion to 20° of dorsiflexion. Maximum voluntary contractions (MVC) with knee bent at 90° assessed voluntary torque production. As the ankle moved from full plantarflexion into dorsiflexion, torque production during MVC drastically increased; magnitudes at 15° of dorsiflexion were almost 5 times greater than those at 30° plantarflexion (170.2 N m vs. 35.45 N m). These extreme values are not particularly practical for midsoles of athletic shoes, but values obtained at 5° plantarflexion and 5° dorsiflexion, more realistic slopes, still demonstrate a similar trend. From 5° plantarflexion to 5° dorsiflexion, MVC torque increased from 114.8 N m to 144.2 N m. It is evident from this study that putting the ankle in a dorsiflexed position can more effectively utilize the triceps surae complex and produce greater force, suggesting shoes that do so may be the optimal choice for jumping athletes (56).

The stretch-shortening cycle also works in conjunction with the force-length curve to produce greater force after changes in muscle length. During a jump, the downwards movement of the countermovement works to eccentrically lengthen muscles of the lower extremity, particularly the muscles of the triceps surae complex. The contractile elements mentioned previously are stretched during this phase, and this again shifts the muscle's operating range on the force-length curve (33). Research has also shown that this pre-stretch works to store elastic energy that is released during the concentric phase (8). Thus, the force produced during the concentric phase of jumping following a pre-stretch is enhanced.

Mechanisms of Injury During Jumping

In 1982 the National Collegiate Athletic Association (NCAA) developed an extensive system for monitoring injuries among college athletes in 16 sports. Between 1988-2004, the Injury Surveillance System (ISS) recorded more than 180,000 injuries. More than half of the reported injuries occurred in the lower extremity, with knee and ankle injuries accounting for a majority of those injuries (Hootman et al., 2007). Patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury are two of the most common knee injuries among female athletes who participate in jumping and pivoting sports. Both PFP and ACL injury can result in significant loss of playing time, high medical costs, and in some cases, career ending injuries. What's more, research has linked several of the same kinetic and kinematic variables to the increased risk of sustaining both injuries (65). Preventative exercise programs have been successful at reducing risk of PFP and ACL-causing mechanisms, but this method is time consuming and not always implemented (60). Just as the shoes athletes wear can affect jumping performance, they can also affect the mechanisms that increase injury risk. Lower extremity injury in sport is a pervasive issue, so designing shoes that reduce individuals' risk of injury would be extremely beneficial.

Changes to the midsole slope will most directly affect ankle angle during initial contact. When in contact with the ground, the lower extremity segments act in a closed kinetic chain, so changes to distal segments will result in changes to more proximal segments. Traditional athletic shoes put the ankle in a slightly plantarflexed position. This encourages a forefoot-to-heel landing pattern, which is the desired strategy for allowing optimal ankle joint ROM and absorption of energy during impact. Thus, shoes with negatively sloped midsoles may have the opposite effect on jump landing mechanics as the available dorsiflexion ROM is manipulated. Shoe design plays an integral role in the efficiency of the jump-landing sequence, but it is important to determine if the effect on jumping and landing is the same so overall athletic performance can benefit.

Foot positioning upon ground contact is a concern for risk of non-contact ACL injury, which accounts for a majority of ACL injuries. A video analysis of athletes in high risk sports like basketball and soccer indicated that all athletes who sustained a non-contact ACL injury landed on either the hindfoot or flatfooted while non-injured controls who performed similar movements contacted the ground with the forefoot or midfoot. This also led to a decrease in plantarflexion during impact in injured athletes, which reduces the ability of the ankle to absorb the tremendous ground reaction forces experienced when landing (5). Kovacs et al. explored this phenomenon during a drop-jumping study. Participants landed in a heel-toe or forefoot motion while lower extremity kinetics and kinematics were analyzed. Landing in a heel-toe position resulted in significantly greater vertical impact forces and more than 8 times smaller ankle angular displacement as the center of pressure shifted towards the calcaneus. Interestingly, knee and hip angular displacements were greater when landing heel-toe, but the significantly decreased ability of the ankle to absorb impact forces via a smaller ROM resulted in an overall stiffer heel-toe landing (34). Footfall position during impact thus has notable implications for lower extremity injury.

A prospective study of over 200 athletes observed significant kinetic and kinematic differences between those who sustained an ACL injury and those that remained injury-free. During the initial biomechanical screening, females who sustained an ACL injury landed with significantly greater knee valgus and abduction loads, 20% greater ground reaction forces, and smaller peak knee flexion angle during landing. Regression analysis revealed that the knee abduction moment, which contributes to knee valgus, was a significant predictor of ACL injury (27). Other studies have also contributed similar mechanisms to patellofemoral pain syndrome. A prospective study of female basketball players revealed that those who sustained PFP exhibited greater knee abduction moment at contact, greater maximum knee abduction load, and greater knee valgus (50). It is important to identify if these variables are affected when midsole drop is manipulated so risk of ACL or PFP injury is not increased.

Fong et al. demonstrated that passive dorsiflexion ROM may also contribute to PFP and ACL injury mechanisms. Individuals who had less passive dorsiflexion ROM landed with less knee flexion and greater vertical and posterior ground reaction forces during a drop jump task (18). Similarly, Sigward et al. observed greater knee valgus during landing in individuals with reduced passive dorsiflexion ROM (59). Furthermore, increasing available dorsiflexion ROM via a block placed under the heels reduces frontal plane knee movement during an overhead squat (3). Although studies of the effects of landing in negatively sloped shoes are extremely limited, Hagins et al. demonstrated a related phenomenon of landing on an inclined surface. Like collegiate athletes, professional dancers experience high rates of lower extremity injury. Research has shown that performing on a raked stage, one that is inclined, is a significant risk factor for injury (14). When dancers performed drop jumps onto an anteriorly inclined stage (a negative slope of 3.6°) they landed with higher knee valgus, higher posterior GRF, and less dorsiflexion after landing, all which increases the load on the knee joint and may contribute to PFP and ACL injury (Hagins et al., 2007; Pflum, Shelburne, Torry, Decker, & Pandy, 2004; Fong et al., 2011).

Optimal coordination of the lower extremity is required to maintain balance and absorb the ground reaction forces experienced during impact. Particularly important to energy absorption is the ankle joint, which absorbs more than 40% of the impact forces during landing (12). Joint or torsional stiffness is one way the body adjusts these impact forces during landing. Some level of joint stiffness is necessary to prevent the collapse of the lower extremity during high velocity actions like jumping and cutting. Too little may leave the body susceptible to musculotendinous injuries due to increased joint laxity, but too much stiffness increases the rigidity of the lower extremity kinetic chain and increases the risk for bony injuries like stress fractures due to higher loading rates (49).

This metric is calculated as the ratio of the change in joint moment to joint angular displacement in the sagittal plane from the time of ground contact to the time of maximal joint flexion (16). This requires a fairly linear relationship between joint moment and joint displacement. In drop landing and running paradigms where stiffness is commonly quantified, the relationship is typically linear (7, 16, 23). However, preliminary findings from the present study revealed a highly non-linear relationship for countermovement jumps. Thus, alternative measurements of energy absorption must be used.

During a drop-jumping study, stiff landings were associated with greater vertical ground reaction forces and significantly less energy absorption compared to soft landings. Energy absorption is quantified as the negative work done during the eccentric phase of landing. Notably, the ankle joint was responsible for most of the energy absorption compared to the knee and hip (44% vs 34% and 22%, respectively). Researchers also observed that the increased stiffness was a result primarily of a change in joint ROM rather change in joint moments. As such, stiff landings can be identified on the basis of joint displacement during landing. Greater joint displacements allow for greater absorption of landing forces (12, 34). These findings support that impact forces, negative work, and joint displacement may be analogues to joint stiffness when there is a non-linear relationship between joint moment and displacement.

Furthermore, a jump-training intervention focusing on softer landings in volleyball players led to not only a decrease in peak landing forces, but a concomitant decrease in knee abduction moments as well, a significant risk factor for both PFP and ACL injury (28). A prospective study on female basketball and floorball players concluded that stiffer landings with high vertical ground reaction forces and decreased knee flexion during landing increased athletes' risk of sustaining an ACL injury (39). It is thus possible that modifying impact forces and joint displacements will have implication for knee injury.

Taken together, it is expected that the positioning and ability of the ankle to absorb impact during landing will lead to compensations in joints along the lower extremity kinetic chain. As a result, variables significantly associated with increased risk of PFP and ACL injury may be negatively affected. It is thus important to address the gap in knowledge of how varying midsole slopes affects injury risk during jumping tasks.

Additional Tables of Outcome Variables

Table 4. Mean ± SD and *p*-value for whole-body jump performance outcome variables

	NEG	NTRL	POS	*p*
Jump Height (cm)	19.56 ± 4.64	19.43 ± 4.46	19.51 ± 4.19	0.951
RFD (N/s)	2152 ± 1642	1912 ± 1472	1955 ± 1272	0.085
Average Force (N)	747.89 ± 99	746.77 ± 100	743.46 ± 104	0.661
Contact time (s)	0.91 ± 0.23	0.89 ± 0.17	0.99 ± 0.48	0.385
Takeoff velocity (m/s)	1.95 ± 0.23	1.94 ± 0.22	1.95 ± 0.22	0.958
Peak vGRF at takeoff (N)	1249 ± 170	1220 ± 179	1218 ± 171	0.004

Table 5. Comparisons between shoe conditions for total power and its components at the instance of peak total power (*p*-value (Cohen's *d* ES)).

	NEG-NTRL	NEG-POS	NTRL-POS
Joint power (W/kg)			
Ankle	0.51 (0.13)	0.09 (0.21)	1.00 (0.08)
Knee	0.95 (0.11)	0.23 (0.18)	0.02 (0.29)
Hip	1.00 (0.02)	1.00 (0.11)	1.00 (0.08)
Angular velocity (deg/s)			
Ankle	1.00 (0.06)	0.19 (0.25)	0.51 (0.19)
Knee	1.00 (0.01)	1.00 (0.11)	1.00 (0.12)
Hip	1.00 (0.08)	1.00 (0.09)	1.00 (0.00)
Joint moment (N m)			
Ankle	0.35 (0.15)	<0.001 (0.39)	0.09 (0.21)
Knee	0.80 (0.13)	0.56 (0.15)	0.045 (0.27)
Hip	1.00 (0.02)	1.00 (0.10)	1.00 (0.07)

Table 6. Comparisons between shoe conditions for peak joint power and its components at the instance of peak joint power *(p*-value (Cohen's *d* ES)).

	NEG-NTRL	**NEG-POS**	**NTRL-POS**
Concentric peak joint power (W/kg)			
Ankle	0.30 (0.18)	<0.001 (0.47)	0.03 (0.30)
Knee	0.91 (0.10)	0.04 (0.23)	0.001 (0.33)
Hip	1.00 (0.04)	1.00 (0.12)	0.95 (0.16)
Angular velocity (deg/s)			
Ankle	0.05 (0.27)	<0.001 (0.47)	0.34 (0.17)
Knee	1.00 (0.0)	0.02 (0.27)	0.02 (0.26)
Hip	1.00 (0.19)	0.41 (0.32)	1.00 (0.14)
Joint moment (N m)			
Ankle	1.00 (0.08)	0.03 (0.31)	0.13 (0.22)
Knee	0.53 (0.14)	1.00 (0.06)	0.16 (0.20)
Hip	1.00 (0.16)	<0.001 (0.77)	0.006 (0.77)

Table 7. Comparisons between shoe conditions for whole-body jump performance variables *(p*-value (Cohen's *d* ES)).

	NEG-NTRL	**NEG-POS**	**NTRL-POS**
Jump Height (cm)	1.00 (0.03)	1.00 (0.01)	1.00 (0.02)
RFD (N/s)	0.06 (0.15)	0.17 (0.13)	1.00 (0.03)
Average Force (N)	1.00 (0.01)	1.00 (0.04)	1.00 (0.03)
Contact time (s)	1.00 (0.11)	0.99 (0.22)	0.67 (0.29)
Takeoff velocity (m/s)	1.00 (0.02)	1.00 (0.00)	1.00 (0.02)
Peak vGRF at takeoff (N)	0.01 (0.17)	0.004 (0.18)	1.00 (0.01)

Table 8. Mean ± SD and *p*-value for whole-body landing outcome variables

	NEG	**NTRL**	**POS**	***p***
Peak vGRF during landing (N)	1926 ± 443	1937 ± 458	1866 ± 456	0.061
Peak knee valgus angle (deg)	-0.50 ± 6.64	-0.62 ± 5.65	-0.51 ± 5.07	0.985
Knee valgus at IC (deg)	1.92 ± 5.51	2.03 ± 4.70	1.73 ± 4.08	0.868
Peak KAM (N m)	-27.51 ± 16.27	-27.38 ± 14.66	-28.72 ± 16.09	0.788
KAM at IC (N m)	-4.35 ± 1.72	-4.62 ± 1.99	-4.51 ± 2.26	0.903

Table 9. Comparisons between shoe conditions for all landing variables. (*p*-value (Cohen's *d* ES))

	NEG-NTRL	**NEG-POS**	**NTRL-POS**
Peak vGRF during landing (N)	1.00 (0.03)	0.16 (0.13)	0.06 (0.15)
Peak knee valgus angle (deg)	1.00 (0.02)	1.00 (0.00)	1.00 (0.02)
Knee valgus at IC (deg)	1.00 (0.02)	1.00 (0.04)	1.00 (0.07)
Peak KAM (N m)	1.00 (0.01)	1.00 (0.07)	1.00 (0.09)
KAM at IC (N m)	1.00 (0.15)	1.00 (0.08)	1.00 (0.05)
Eccentric work (J/kg)			
Total	1.00 (0.08)	0.12 (0.25)	0.02 (.34)
Ankle	0.77 (0.12)	0.05 (0.28)	0.001 (0.40)
Knee	0.19 (0.25)	0.01 (0.38)	<0.001 (0.63)
Hip	0.34 (0.21)	0.68 (0.18)	1.00 (0.05)
Average joint moment (N)			
Ankle	0.62 (0.16)	0.08 (0.29)	0.002 (0.47)
Knee	0.16 (0.3)	0.27 (0.27)	<0.001 (0.51)
Hip	0.45 (0.18)	0.31 (0.02)	1.00 (0.02)
Joint displacement (deg)			
Ankle	0.88 (0.14)	0.88 (0.15)	1.00 (0.0)
Knee	1.00 (0.25)	0.004 (0.38)	<0.001 (0.63)
Hip	1.00 (0.02)	1.00 (0.02)	1.00 (0.0)

Additional Figures of Outcome Variables

Jump Performance

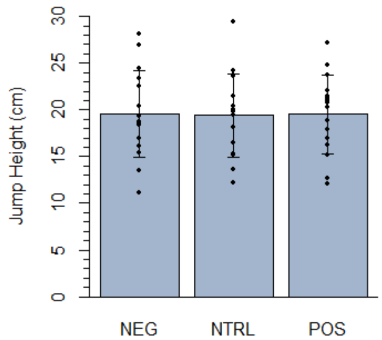

Figure 6. Jump height between conditions, with individual data points in black filled circles.

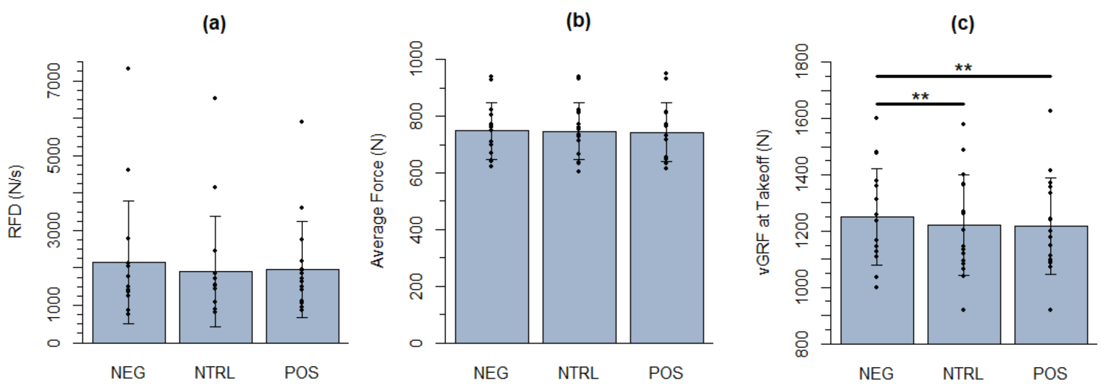

Figure 7. Kinetic variables: (a) rate of force development (RFD), (b) average force produced between initiation of countermovement and takeoff, and (c) peak vGRF produced before takeoff.

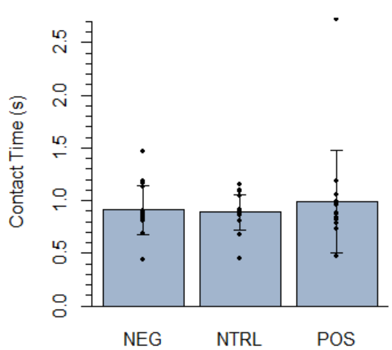

Figure 8. Time spent on the ground between initiation of countermovement and takeoff was similar between conditions.

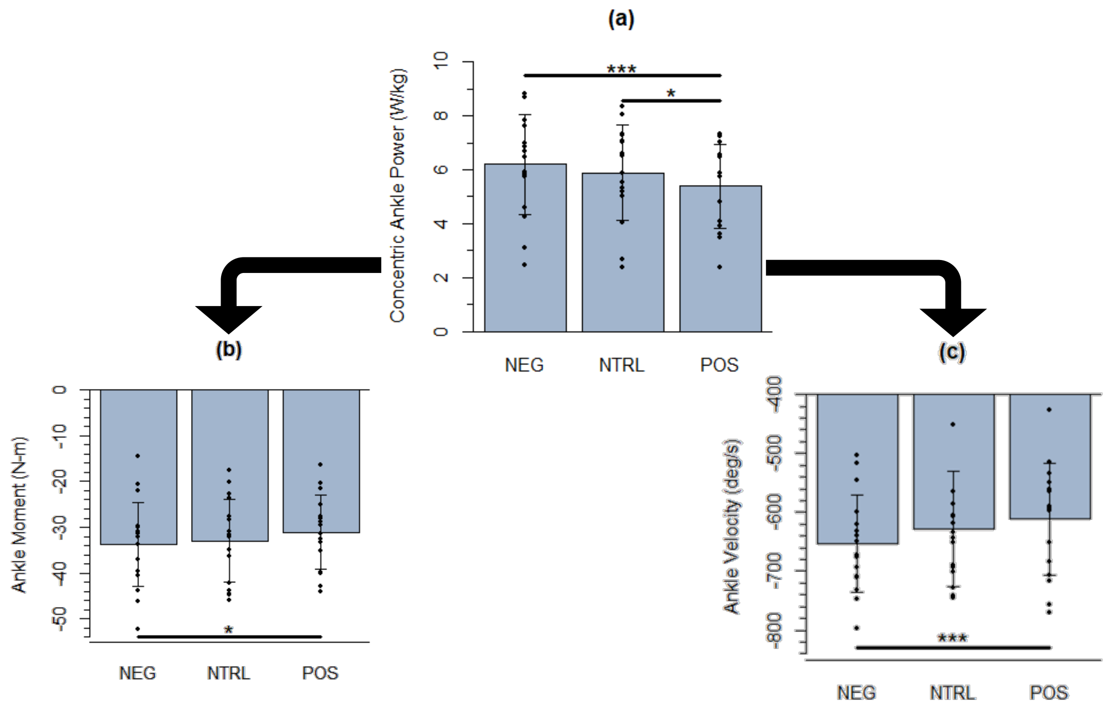

Figure 9. A schematic of peak concentric ankle power. Peak ankle power (a) is a product of the ankle joint moment (b) and angular velocity (c).

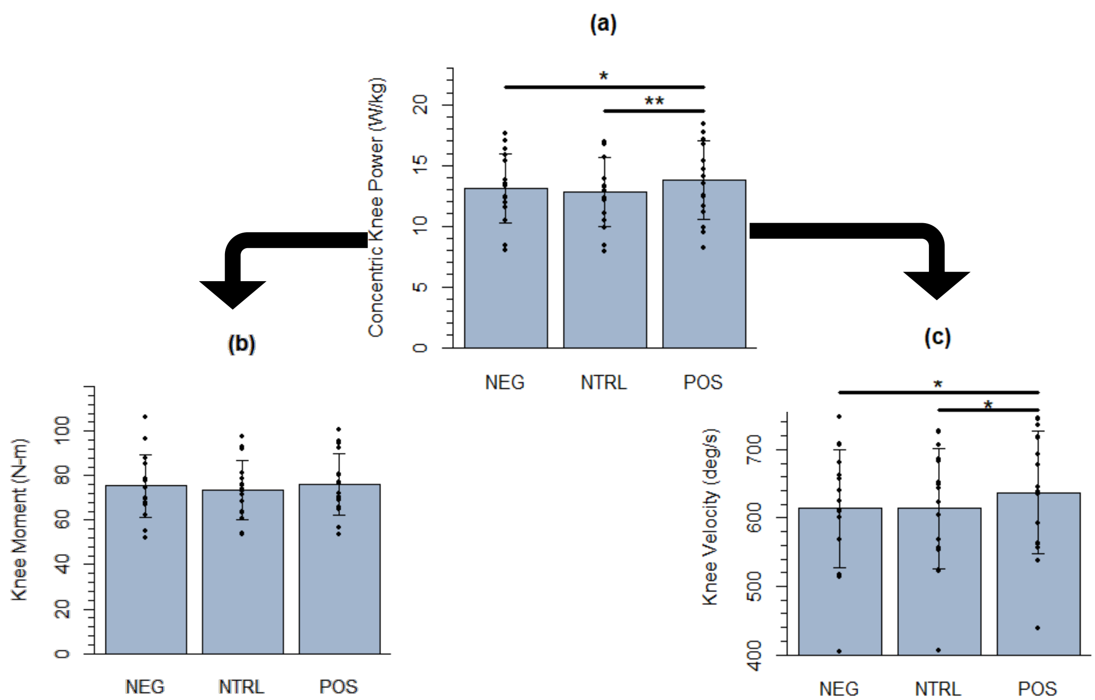

Figure 10. A schematic of peak concentric knee power. Peak knee power (a) is a product of the knee joint moment (b) and angular velocity (c).

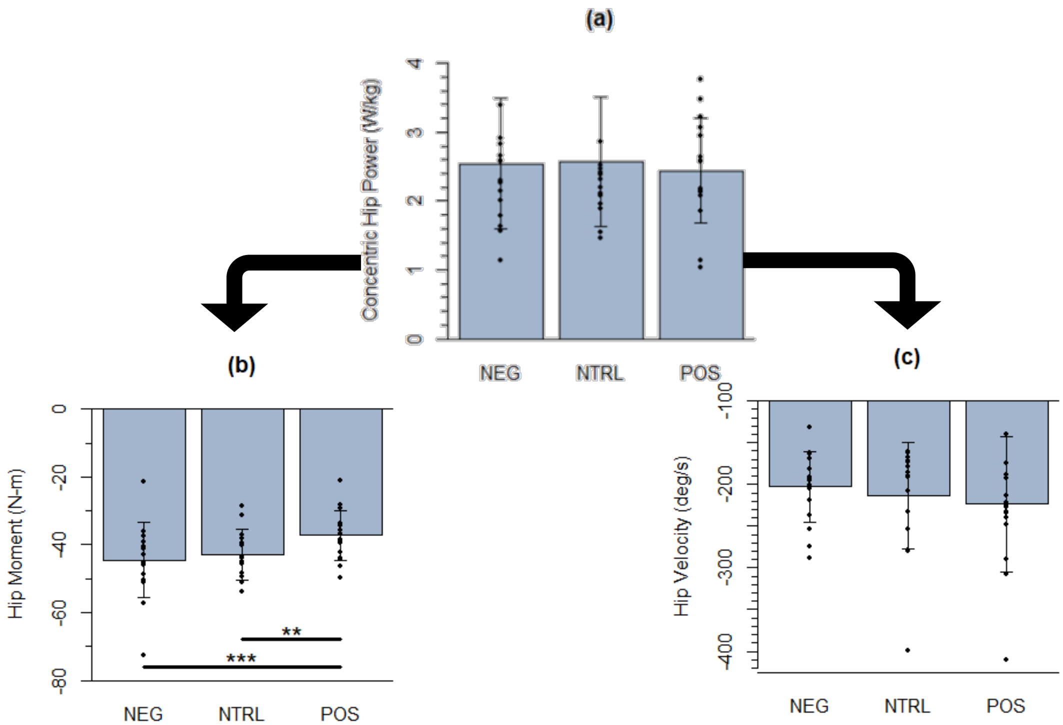

Figure 11. A schematic of peak concentric hip power. Peak hip power (a) is a product of the hip joint moment (b) and angular velocity (c).

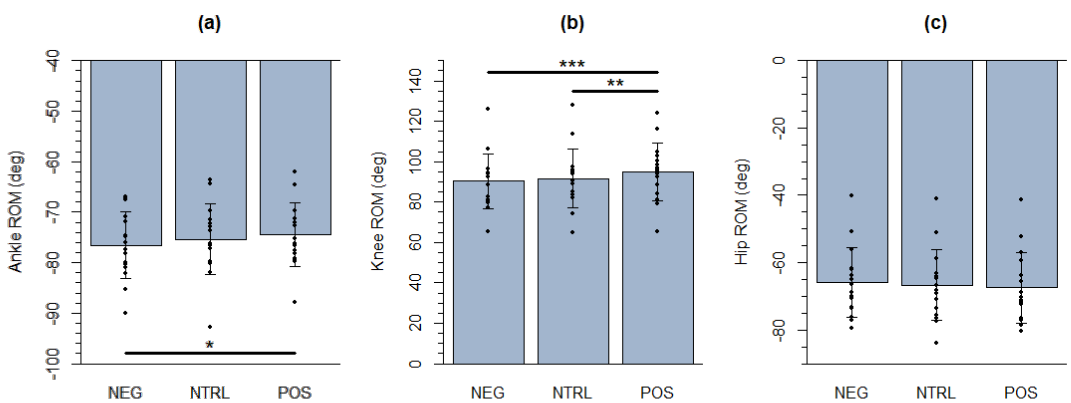

Figure 12. Joint range of motion between maximal joint flexion during the countermovement and takeoff for the (a) ankle, (b) knee, and (c) hip.

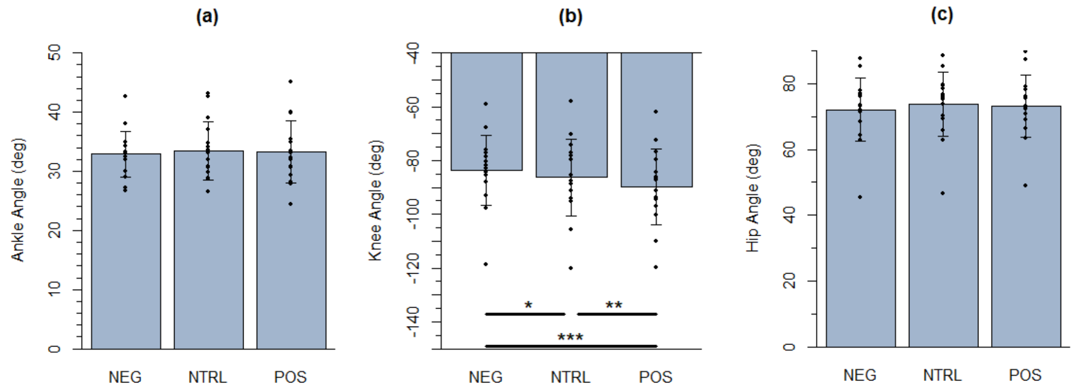

Figure 13. Joint angles at maximal joint flexion during the countermovement for the (a) ankle, (b) knee, and (c) hip.

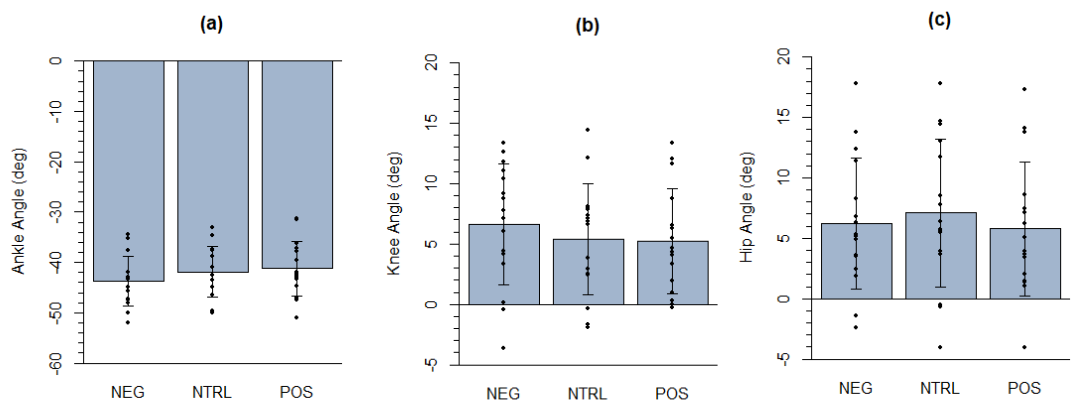

Figure 14. Joint angles at takeoff for the (a) ankle, (b) knee, and (c) hip.

Landing Mechanics

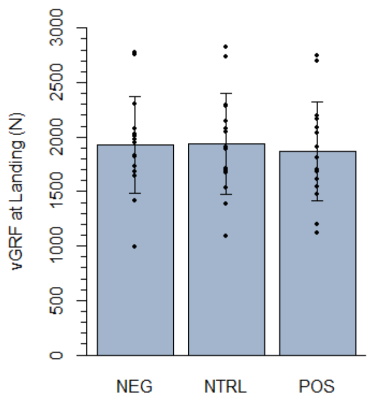

Figure 15. Peak impact force during landing was similar between conditions.

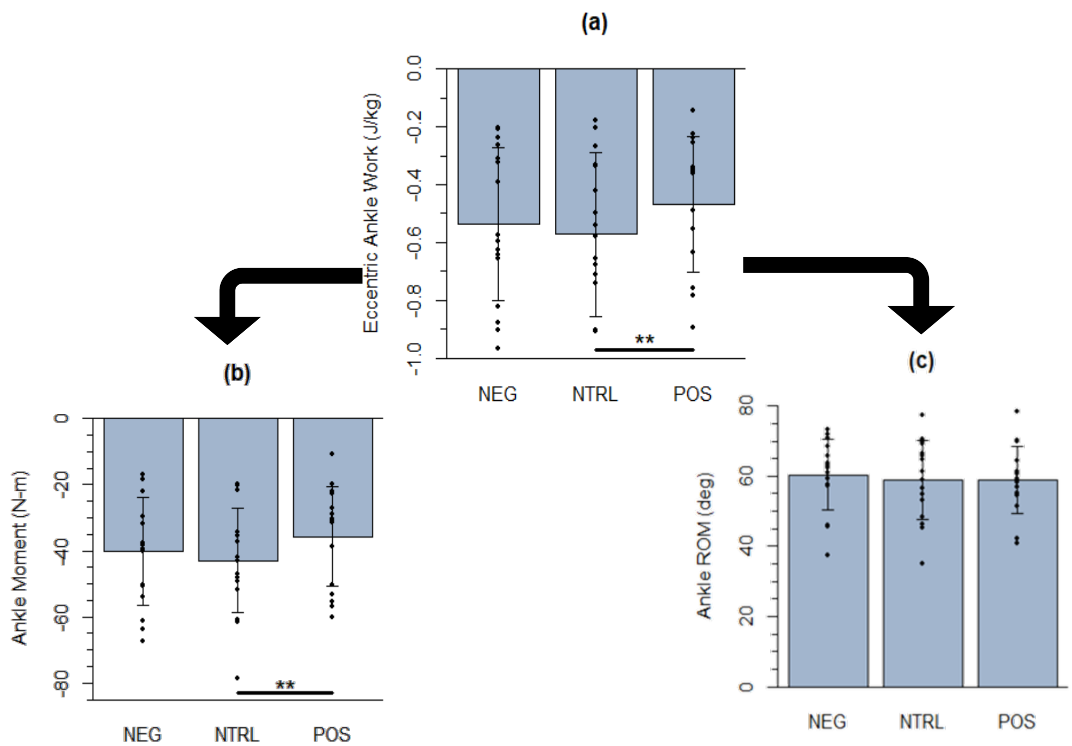

Figure 16. A schematic of eccentric ankle work during landing (initial contact to maximal joint flexion). Eccentric work (a) is a product of the average ankle moment (b) and ankle ROM during landing (c).

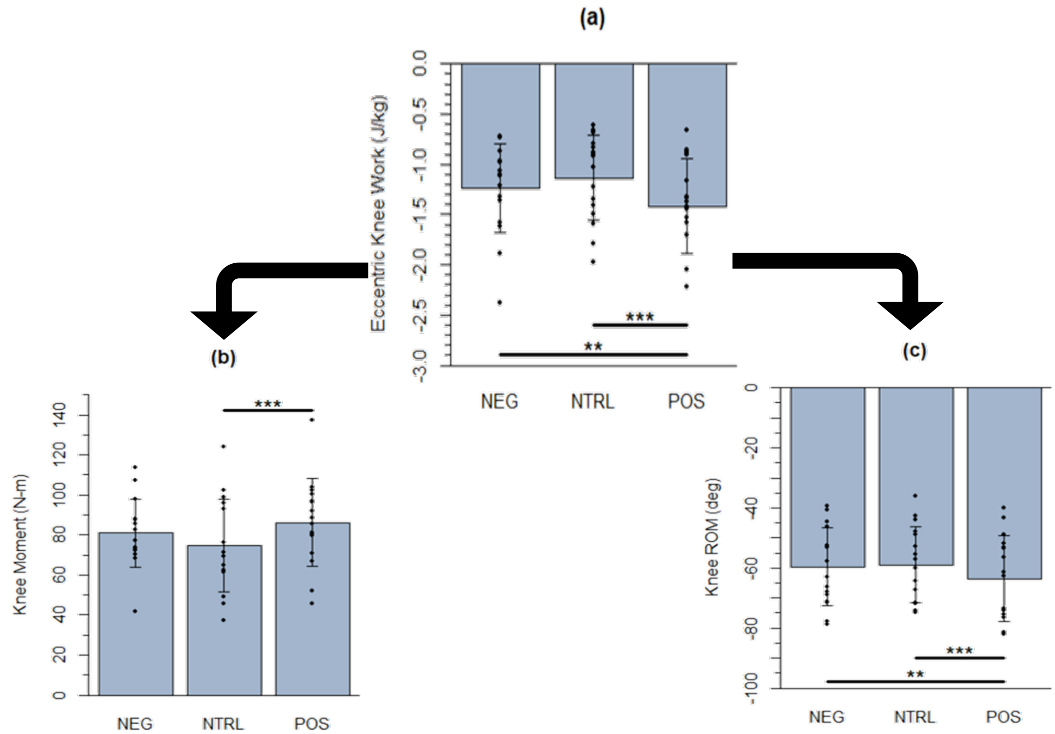

Figure 17. A schematic of eccentric knee work during landing (initial contact to maximal joint flexion). Eccentric work (a) is a product of the average knee moment (b) and knee ROM during landing (c).

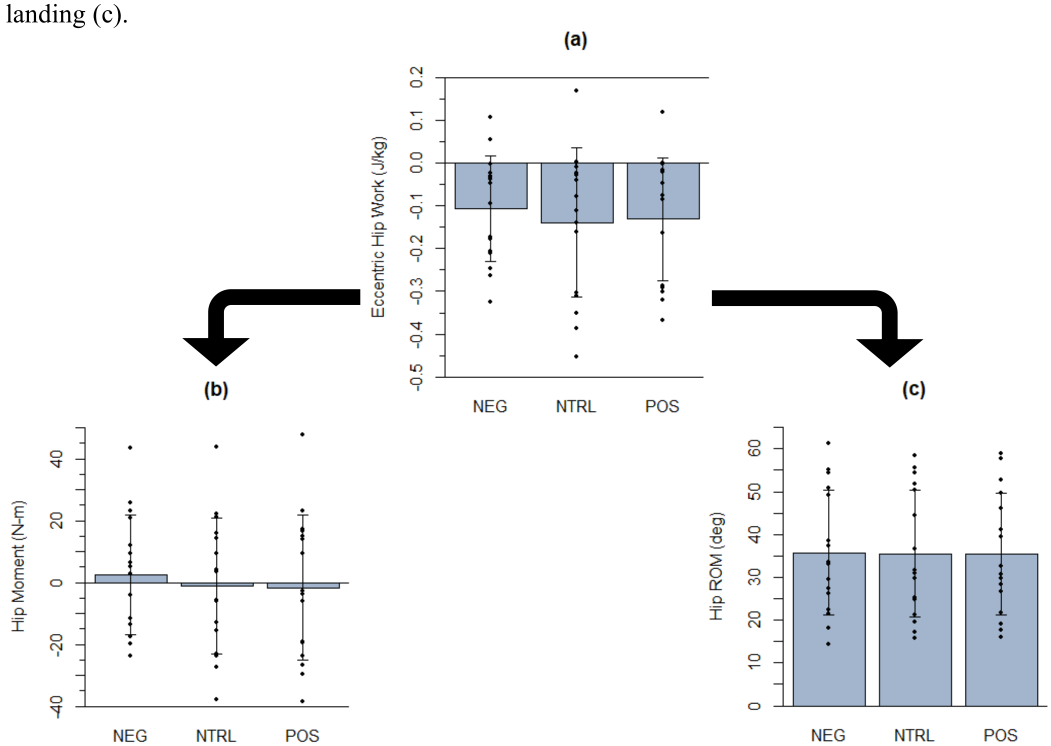

Figure 18. A schematic of eccentric hip work during landing (initial contact to maximal joint flexion). Eccentric work (a) is a product of the average hip moment (b) and hip ROM during landing (c).

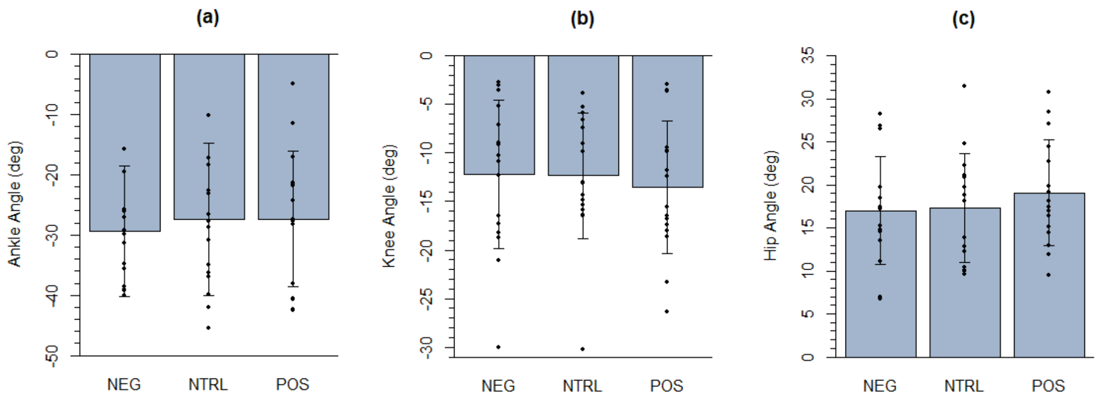

Figure 19. Joint angles at initial contact during landing for the (a) ankle, (b) knee, and (c) hip.

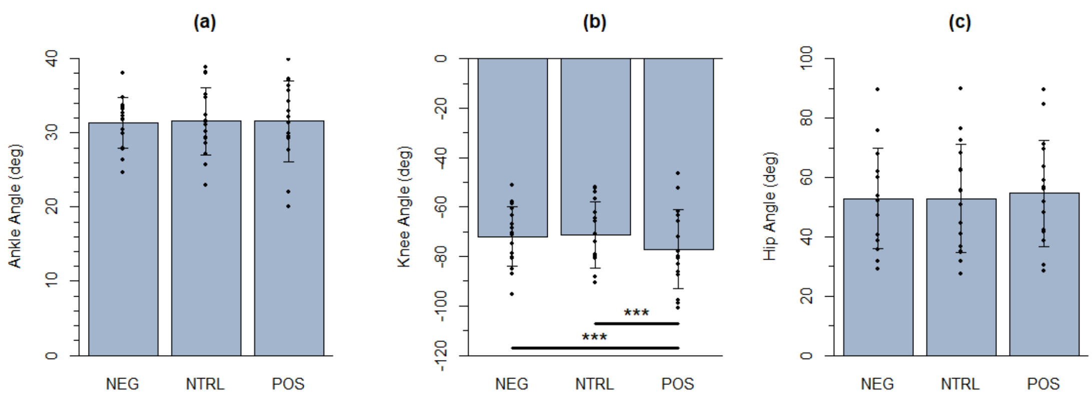

Figure 20. Joint angles at maximal joint flexion during landing for the (a) ankle, (b) knee, and (c) hip.

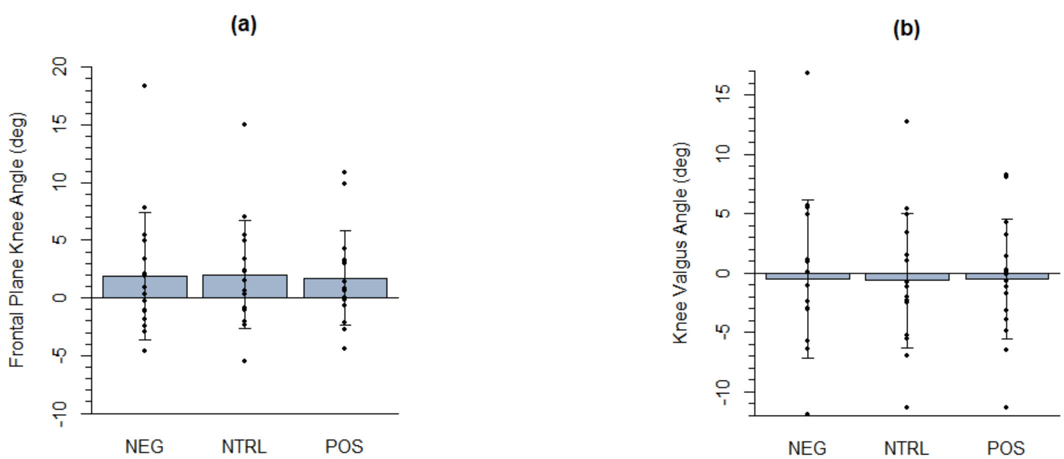

Figure 21. Frontal plane knee angle at (a) initial contact. Negative values indicate knee valgus. Peak knee valgus angles during landing are presented in (b).

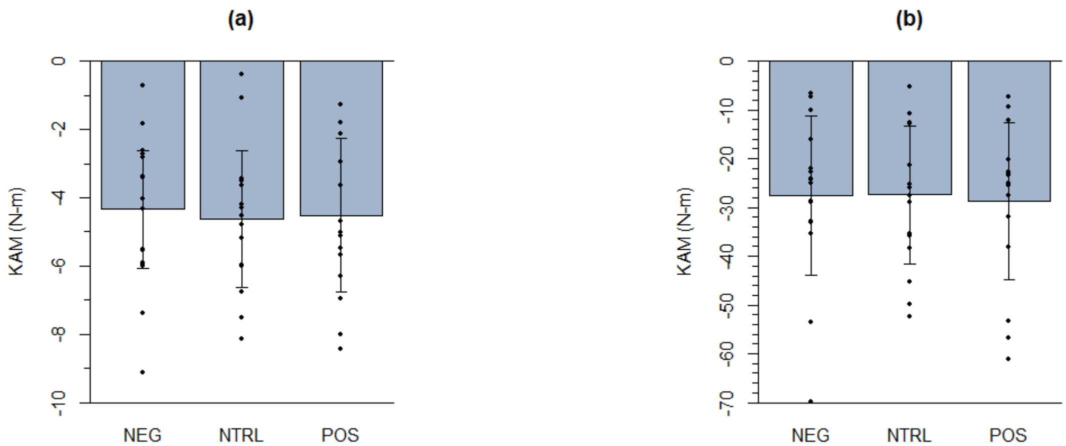

Figure 22. Knee abduction moment (KAM) at initial contact (a), and maximal KAM during landing (b).

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