

METATARSOPHALANGEAL JOINT MECHANICS DIFFER
BETWEEN OVERGROUND AND TREADMILL RUNNING

by

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A THESIS

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Common uses of treadmills range from product developers and physical therapists monitoring gait mechanics in a controlled environment to runners incorporating treadmill running into their training routines. With the widespread usage of treadmills, differences between overground and treadmill running need to be quantified in order to improve the accuracy of translating biomechanical data between the two conditions and identifying any potential mechanisms of injury. Prior research has established kinetic and kinematic differences between treadmill and overground running in the hip, knee, and ankle joints. However, no studies have assessed how metatarsophalangeal joint (MTPJ) mechanics differ between the two conditions. Differences in MTPJ moment, stiffness, and range of motion (ROM) between treadmill and overground running were compared. Additionally, this study examined contact time and duration of stance phase with the heel off the ground.

15 participants (4 female) were recruited from local running clubs and 12 were analyzed for this study. Significant results were found when running at 4.00 m/s in MTPJ mechanics as well as percent heel-off. MTPJ moment, MTPJ stiffness, and percent heel-off were significantly higher ($p < 0.05$) during treadmill compared to overground running. Metatarsophalangeal joint ROM showed a significant decrease in treadmill running ($p < 0.05$). No significant differences were found in contact time ($p = .970$). Implications of these differences need to be considered when conducting biomechanical testing and assessing potential injury mechanisms on treadmills.

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Introduction

Background

According to the US Running Trends Report in 2016, 507,600 participants finished a US marathon which marked an approximate 24% increase in finishers compared to 10 years prior in 2006 (Running USA, 2016). As the number of marathon participants in the United States has radically increased in recent years, the quality of marathoners globally has similarly experienced a boom. Of the 50 fastest female marathoners of all time, 37 of them have recorded personal bests since 2009 (International Association of Athletics Federation, 2019). Even more dramatically, of the top 50 male marathoners, 47 of them have recorded their fastest time in the past 10 years (International Association of Athletics Federation, 2019). This number includes an official world record of 2 hr 01 min and 39 s set by Eluid Kipchoge in 2018 (International Association of Athletics Federation, 2019).

Researchers have explored a number of potential internal and external factors to explain the widespread improvement in marathoners over time including sociological, environmental, physiological, and training-method factors (Torre, Vernillo, Agnello, Berardelli, & Rampinini, 2011; Weiss, Newman, Whitmore, & Weiss, 2016). However, with the extensive focus on the Nike Vaporfly 4% after the Breaking 2 project, no one factor has received more publicity in recent years than improvements in the biomechanics of shoe design (Hoogkamer et al., 2018; Hoogkamer, Kram, & Arellano, 2017). Whether the incredible performances inspired researchers to invest time into studying running or the performances represent the product of copious research, there

has been an undeniable link between athletic accomplishments and biomechanical feats in recent years.

Biomechanics of Running

Biomechanics plays a pivotal role in athletics and day-to-day living. In general biomechanics can be broken into three overarching categories which include sports biomechanics, occupational biomechanics, and rehabilitation biomechanics. Sports biomechanics, which encompasses running biomechanics, focuses on improving performance through biomechanical interventions and understanding injury mechanisms. Running-specific improvements target lengthening one's stride, increasing stride frequency, improving economy, and decreasing injury risk (Williams, 1985).

In order to assess the effects of interventions on one's stride, researchers study runners' gait cycles. The gait cycle represents the fundamental analytical unit of running biomechanics. As defined by Tom Novacheck the gait cycle begins when one foot makes initial contact with the ground and concludes when the same foot makes contact with the ground again (Novacheck, 1998) The gait cycle is further broken down into the stance phase which includes the time when the foot remains in contact with the ground and the swing phase which occurs after toe-off when the foot travels through the air (Figure 1). Analysis of the timing and position of limb segments during gait cycles can lead to modulations in shoe design or running technique to improve physiological measures and decrease the potential for injury (Novacheck, 1998).

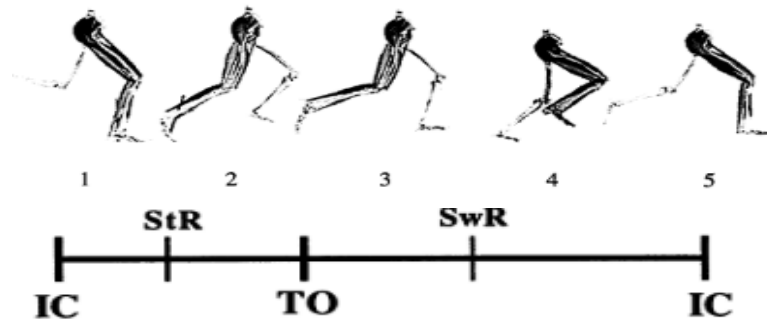


Figure 1: Gait cycle adapted from Tom Novacheck (Novacheck, 1998)

Example of one gait cycle for the right foot. Initial contact (IC) begins stance phase (StR) which ends with toe off (TO) followed by swing phase (SwR) and another initial contact (IC) to begin the next gait cycle.

Kinematics and Kinetics

Biomechanical analysis of the gait cycle occurs through two fundamental techniques that describe the motion of body segments and the forces that cause the observed motion. These two techniques are kinematics and kinetics respectively (Robertson, 2004). This section will provide a brief overview of how kinematic and kinetic data are collected as well as how they are utilized to calculate joint angles, joint reaction forces, joint moments, and bending stiffness.

Kinematic data describes how body segments, joints, and limbs move without respect to the forces that cause the motion. In a laboratory setting, kinematic data is collected through motion-capture systems which track the positions of retro-reflective markers over time (Robertson, 2004). By establishing a three-dimensional coordinate system, researchers can define each marker's coordinate in space in the x, y, and z planes. Tracking the position of these markers over time allows calculation of linear velocity and acceleration in the three planes of motion: sagittal, frontal, and transverse.

Additionally, tracking changes in the angular displacement of markers on the lower limb allows for calculation of angular velocities and accelerations (Sykes, 1975). Alone kinematics provides a valuable tool in analyzing running gait cycles. Common variables analyzed include the range of motion (ROM) of joints, the peak joint angles with respect to segments as well as global coordinates, and the accelerations experienced by segments during each phase of running.

Kinetics answers the question of why movement occurs by analyzing the linear forces and rotational moments that cause the motion (Novacheck, 1998). Collection of kinetic data is accomplished using anthropometrics and force platforms (Robertson, 2004). Anthropometrics and assumptions about mass distribution throughout body segments allow researchers to calculate how weight causes motion. Force platforms are commonly embedded in runways or treadmills and measure the force that the acts on the body when contacting the ground, known as a ground reaction force (GRF). While playing a critical role in inverse dynamic calculations (described below), kinetic running data can also be useful in examining the center of pressure, foot strike patterns, force-time data, and how interventions or injuries can change these variables (Cavanagh & Lafortune, 1980).

Utilizing data from retro-reflective markers and force plates, researchers can estimate the joint reaction forces and joint moments of the lower limb in a process known as inverse dynamics (Robertson, 2004). Inverse dynamics applies Newton's laws to solve for joint reaction forces and moments at the most distal joint. Then researchers can use these distal forces to calculate proximal forces and moments. Joint reaction forces are calculated using Newton's second law, $\Sigma F = m * a$, and moments are

calculated from the angular analog $M = F * MA$ where M = moment, F = force, and MA = moment arm. For a joint experiencing an acceleration, such as during running, the sum of the moments equals the moment of inertia (I) multiplied by the angular acceleration (α) ($\Sigma M = I * \alpha$). Applying Newton's third law, researchers can solve for the joint reaction forces and moments at the proximal joints using joint reaction forces at the distal joint, mass of the proximal segment, and accelerations from the retro-reflective markers. Figure 2 shows the variables needed to calculate the ankle joint reaction forces (F_{ankle_x} and F_{ankle_y}) and ankle moment (T_{ankle}) as an example of inverse dynamics (Figure 2).

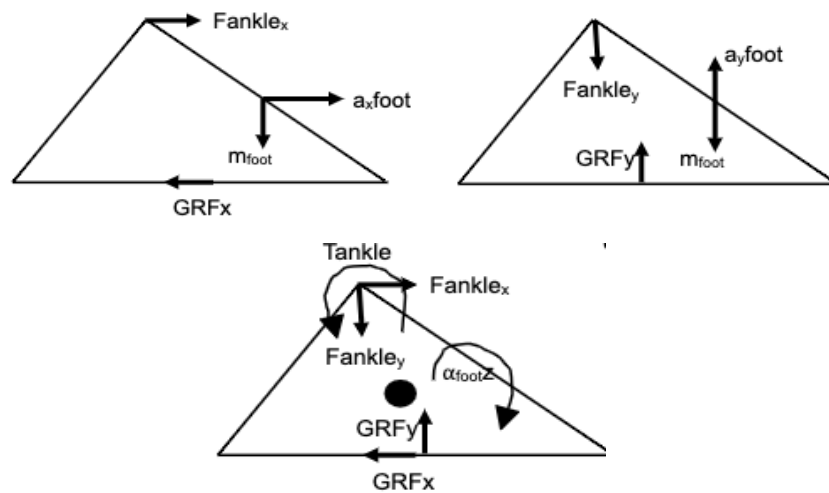


Figure 2: Simplified model of inverse dynamics adapted from HPHY 381 lecture slide
 Calculation of ankle reaction forces (F_{ankle_x} and F_{ankle_y}) and moment (T_{ankle}) with GRF components (GRF_x and GRF_y) and mass (m_{foot}) from kinetics as well as linear accelerations ($a_{x,foot}$ and $a_{y,foot}$) and angular accelerations (α_{foot_z}) from kinematics.

By calculating the joint reaction forces and joint moments standardized to individual subject's anthropometrics, researchers can estimate the force needed by a group of muscles to produce or counteract a movement (Novacheck, 1998). Knowing

the moment acting on a joint and the angular displacement of the segments about the joint, researchers can calculate the stiffness (k) of the joint $k_{joint} = \frac{\Delta Moment}{\Delta Angle}$ (Coleman, Cannavan, Horne, & Blazevich, 2012). Knowing the kinematic data, kinetic data, and inverse dynamic calculations allows researchers to relate specific mechanical variations to physiological measures or injury rates allowing them to design interventions with the goal of improving running performance.

Treadmill Running

Traditionally, biomechanical running data were collected overground; however, recent studies utilize treadmills in collection protocols because of their ability to control velocity, surface, and environmental factors (Miller et al., 2019) Despite the widespread usage of treadmills as a surrogate of overground running, concerns remain about potential differences between the two conditions.

A study by Van Ingen Schenau demonstrated that mathematically treadmill locomotion accurately reflects overground mechanics as long as the treadmill moves at a constant velocity and a moving coordinate system is used (van Ingen Schenau, 1980). A second computational study that investigated treadmills embedded with force plates found that transducers placed under the body of the treadmill would correctly measure GRF's compared to overground running (Willems & Gosseye, 2013). This study complemented the results observed by Kram et al. when they designed the force plate embedded treadmills, and was further validated in a study by Kluitenberg et al. who found that treadmill and overground vertical GRFs were similar (Kluitenberg, Bredeweg, Zijlstra, Zijlstra, & Buist, 2012; Kram, Griffin, Maxwell Donelan, & Chang,

1998). Based on the results of these studies, researchers commonly accept that differences between treadmill and overground running at a constant velocity come from changes in running biomechanics as opposed to changes in equipment.

Prior research focused on quantifying the biomechanical differences between overground and treadmill running largely found variable results depending on pace, number of participants, and familiarity of the participants with treadmill running (Williams, 1985). Most of the variability stems from different results when comparing stride length, stride frequency, and contact time between conditions. However, lower limb joint mechanics tend to show overarching trends across studies (Williams, 1985). The remainder of this section will catalog the results of studies conducted on the lower limb of distance runners beginning at the hip joint and moving inferiorly.

In general, hip kinematics tend to differ between conditions while kinetic properties tend to be similar. A study conducted by Sykes et al. found greater hip extension at toe-off on the treadmill compared to overground running (Sykes, 1975). Similarly, studies with a greater number of participants conducted by Schache et al. and Sinclair et al. found increased hip flexion, range of motion, and peak flexion in the treadmill condition (Schache et al., 2001; Sinclair et al., 2013). Hip extensor moment, abductor moment, and power absorption were found to be similar between conditions (Riley et al., 2008).

Conversely, knee kinematics tend to be similar between conditions while kinetic properties show significant differences. The studies by Sinclair et al., Riley et al., Fellin et al., and Willy et al. found that, with the exception of peak knee flexion which was decreased on the treadmill in the Riley study, knee kinematic tended to show no

significant differences between conditions (Fellin, Manal, & Davis, 2010; Riley et al., 2008; Sinclair et al., 2013; Willy, Halsey, Hayek, Johnson, & Willson, 2016). Kinetic properties such as knee flexion moment, extension moment, varus moment, and power generation were all significantly higher in overground compared to treadmill running (Riley et al., 2008; Willy et al., 2016).

While hip and knee biomechanical studies mainly focus on differences in sagittal plane motion, ankle kinematic and kinetic studies tend to incorporate sagittal and frontal plane mechanics as inversion/eversion has been commonly studied as an injury mechanism (Taunton, Ryan, Clement, McKenzie, & Lloyd-Smith, 2002; van Gent et al., 2007). In the frontal plane, kinematic studies have shown a significantly increased peak inversion angle in overground running (Fellin et al., 2010; Nigg, De, & Fisher, 1995; Sinclair et al., 2013). In the sagittal plane, ankle dorsiflexion has been shown to decrease during treadmill running (Fellin et al., 2010; Nigg et al., 1995; Wank, Frick, & Schmidtbleicher, 1998). Kinetic variables such as ankle plantarflexor moment and ankle power absorption have also been shown to be significantly decreased during treadmill running (Riley et al., 2008).

Metatarsophalangeal Joint Functions and Mechanics

To date, no studies have examined kinematic or kinetic differences between treadmill and overground running at the metatarsophalangeal joint (MTPJ). While anatomically a series of five joints connecting the metatarsal bones to the proximal phalanx of the phalanges, the MTPJ is often treated as one joint at the base of the toes that serves as an axis for rotation about the forefoot (Stefanyshyn & Nigg, 1997).

Because studies traditionally model the foot as one rigid segment, the MTPJ remains

relatively under-studied compared to the hip, ankle, and knee joints. However, free dorsiflexion of the MTPJ has been deemed essential for the proper function of the foot (Bojsen-Møller & Lamoreux, 1979). Calculations which neglect to incorporate the MTPJ have been shown to affect joint kinetics during accelerated sprinting (Bezodis, Salo, & Trewartha, 2012; Smith, Lake, Lees, & Worsfold, 2012). A brief review of the literature pertaining to the MTPJ follows.

Prior research on the MTPJ has shown the importance of the MTPJ in locomotion functionality and biomechanical calculation. By examining the transfer of energy across the MTPJ and modulating the stiffness of the forefoot through carbon plates in shoes, researchers can assess the effects of joint stiffness on performance measures. Researchers have found that during running the toes support 50-75% of the body mass load during late stance phase and assist ankle plantarflexors in generating lift (Hayafune, Hayafune, & Jacob, 1999; Stefanyshyn & Nigg, 1997). Additionally, several studies have shown that the MTPJ facilitates energy transfer during the stance phase between the plantar fascia and the arch (McDonald et al., 2016; Stefanyshyn & Nigg, 1997). Consequently, restricting the MTPJ causes changes in its energy transfer ability (Stefanyshyn & Nigg, 1997; Willwacher, König, Potthast, & Brüggemann, 2013). Recent studies have focused on increasing and decreasing bending stiffness of shoes at the MTPJ axis while measuring performance outcomes such as energy storage in the foot, running economy, and full body energetics (Madden, Sakaguchi, Tomaras, Wannop, & Stefanyshyn, 2015; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Willwacher et al., 2013).

Purposes and Hypothesis

The vast majority of studies pertaining to the MTPJ have and continue to collect data using force plate embedded treadmills even though there is a gap in our knowledge on potential differences between MTPJ biomechanics overground compared to treadmill running. Therefore, the primary purpose of this study was to quantify the differences in sagittal plane MTPJ ROM, moment, stiffness, and percent of stance where the forefoot served as the base of support (heel-off). We hypothesized that MTPJ ROM would decrease, moment would increase, stiffness would increase, and percent heel-off would increase on the treadmill compared to overground. This study also examined the contact time per stride. We hypothesized that the contact time would not significantly differ between the conditions. These hypotheses were based off of PhD dissertation work conducted by Evan Day, who noticed differences in MTPJ biomechanics between his treadmill based research and overground literature.

Methods

Participants

Fifteen participants (4 female) were recruited for this study (Table 1). Inclusion criteria for this study specified that the participants ran at least 30 miles per week, had 5000-meter personal bests faster than 18:00 (male) or 20:00 (female), and were injury free during testing. Unofficial exclusion criteria included injuries of the Achilles tendon or musculoskeletal structure of the feet that altered training at least two weeks prior to testing. All participants signed written informed consent prior to testing. This study was approved by the Institutional Review Board of the University of Oregon.

Participants	Age (Years)	Height (cm)	Weight (kg)	Weekly mileage (miles)	Shoe size (US men)
15 (4 F)	23 ± 3	175 ± 6	66.1 ± 6.1	54 ± 22	8.7 ± 1.6

Table 1: Anthropometric data averages ± standard deviation for recruited participants

Equipment

All data were collected, processed, and analyzed in the Bowerman Sports Science Clinic. In order to control for different properties of shoes, participants all wore Nike Streak 6 Flyknit, a common neutral racing shoe.

Treadmill

An eight-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz was used to record three-dimensional marker coordinates. A

force-instrumented treadmill (Bertec, Inc) sampling at 1000 Hz was used to collect ground reaction force data.

Overground

A ten-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz recorded three-dimensional marker coordinates. Ground reaction force data were recorded at 1000 Hz. The force plate was positioned in the middle of a 20-m runway.

Marker Placement

Static calibration trials contained 15 retroreflective markers placed on bony landmarks on the right knee (2), shank (4), ankle (2), rearfoot (3), and forefoot (3) as well as one marker placed on the sacrum for calculating running velocity during overground trials (Figure 1). Knee markers were placed on the lateral and medial femoral epicondyles. The shank segment was tracked by a quadrad of markers taped to the shank in line with the lateral epicondyle marker. Ankle markers were placed on the medial and lateral malleoli. Three rearfoot markers were placed on the lateral, medial and posterior aspects of the calcaneus. Three forefoot markers were placed on the 1st metatarsal head, 5th metatarsal head, and the distal phalanx of the hallux. Medial femoral epicondyle and medial malleolus markers were removed during dynamic trials.

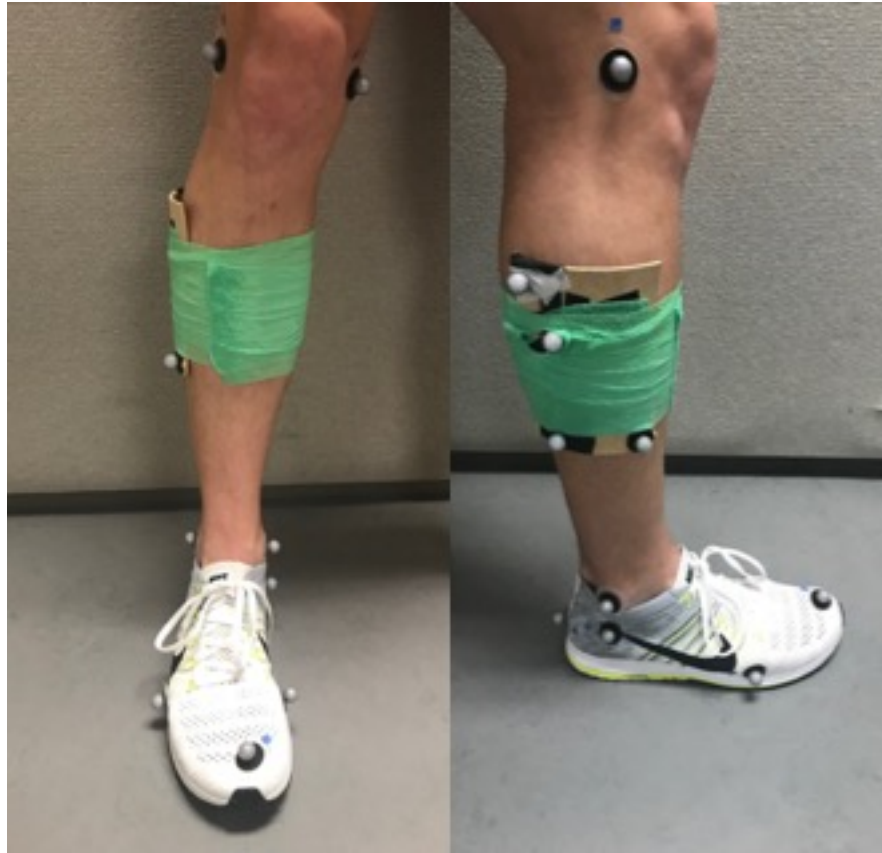


Figure 3: Anterior and lateral views of marker placements

Protocol

Because of practical limitations in calibrating the cameras in the lab space as well as standardizing warm-up protocols, conditions were not randomized, and treadmill testing occurred first. Before both the treadmill and the first overground dynamic trials, a static trial was captured in order to remove bias angles and limit marker offset when analyzing the data. For static trials participants were instructed to remain in a relaxed stance with hands on hips until all markers were visible to the cameras.

After the static trial, the medial epicondyle and medial malleolus markers were removed and participants entered a warm-up and treadmill familiarization stage

(Padulo, Chamari, & Paolo Ardigò, 2014). For this study, the familiarization stage consisted of one minute of running at 3.00 m/s, one minute of running at 3.50 m/s, and one minute at the testing pace of 4.00 m/s to ensure comfort at this velocity. After the acquaintance stage participants were brought to rest. Participants were then brought up to 4.00 m/s and data were recorded for ten gait cycles (about 15 seconds).

Participants then entered the overground portion of the study which consisted of collecting five trials where the right foot made full contact with a force plate at a velocity of 4.00 m/s \pm 5%. Medial femoral epicondyle and medial malleolus markers were put back on and a second static trial was collected using the overground system. Participants were then instructed to complete at least three trial runs to acquaint themselves with the runway and estimate the starting position they would need in order to hit the force plate accurately. Participants then entered the collection phase where their trials were recorded and checked for the correct velocity. The following equation was used to calculate velocity.

$$V = \left(\frac{x_f - x_i}{f_f - f_i} \right) \left(\frac{1}{200} \right)$$

Where V is the velocity of the sacrum marker, x_f is the final position of the sacrum marker ten frames (f_f) after they leave the force plate, x_i is the initial position of the sacrum marker ten frames before (f_i) the participant landed on the force plate, and $1/200 \text{ Hz}^{-1}$ represents the time (in seconds) per frame. Trials were disqualified if the velocity was below 3.80 m/s or greater than 4.20 m/s, if the participant did not make full contact with the force plate, or if the participant qualitatively compromised their stride pattern (i.e. participants overstepped or stutter stepped) in order to hit the force plate. Participants repeated trials until five velocity-validated stance phases were

collected. This concluded the data collection, and participants were allowed to leave after markers and shoes were removed.

Data Analysis

All data were processed, trimmed, and exported using Cortex (Motion Analysis Corp., Santa Rosa, CA) and analyzed using a custom-written routine in MATLAB (MathWorks, Inc., Natick, MA). Knee joint center was estimated as the mid-point between markers placed on the lateral and medial femoral epicondyles. Ankle joint center was similarly estimated using markers placed on the medial and lateral malleolus. A two-segment foot model was defined as the primary axis of motion being defined by a vector from the first to fifth metatarsal markers (Smith et al., 2012). Foot marker trajectories and ground reaction force data were low-pass filtered at 20 Hz. The midpoint of the MTPJ axis defined the joint center for kinetic analysis (Hoogkamer, Kipp, & Kram, 2019; Oh & Park, 2017; Roy & Stefanyshyn, 2006). Moments were estimated using an inverse dynamics procedure and considered zero until the GRF acted distal to the MTPJ axis (Stefanyshyn & Nigg, 1997). Joint stiffness of the MTPJ was defined by the ratio of the change in MTPJ moment to maximum MTPJ dorsiflexion (Oh & Park, 2017). The phase of stance when the forefoot acted as the base of support was quantified as the total time the center of pressure acted anterior to the MTPJ axis. Joint angles were calculated using a Euler/Cardan rotation order of flexion/extension, abduction/adduction, and internal/external rotation. Sagittal plane joint angles and moments were used for analysis.

Statistical Analysis

A dependent two-tailed t-test ($\alpha=.05$) was used to analyze within-subject differences between overground and treadmill running on MTPJ range of motion, peak moment, stiffness, contact time, and total time the forefoot served as the base of support during stance.

Results

Table 2: Average results \pm standard deviation (SD) for kinetic and kinematic variables.

	Overground	Treadmill	P
MTP Range of Motion (deg)	33.8 \pm 3.2	30.7 \pm 4.8	0.012
MTP Peak Moment (N-m/kg)	0.45 \pm .23	0.71 \pm 0.25	<0.001
Bending Stiffness (N-m/kg/deg)	0.005 \pm 0.016	0.008 \pm 0.003	0.006
Contact Time (s)	0.200 \pm 0.012	0.199 \pm 0.009	0.970
Heel-off (% Stance)	54 \pm 15	67 \pm 15	0.004

Significant differences ($p < .05$) bolded

Of the 15 participants recruited only 12 were analyzed because of equipment failure in three trials. Metatarsophalangeal joint range of motion, moment, bending stiffness and heel-off all showed a significant difference between overground and treadmill running ($p < .05$) (Table 2).

Average MTPJ ROM (degrees) was significantly greater in overground running compared to treadmill running ($p = .012$). 10 of the 12 participants demonstrated an increased ROM during overground trials. Qualitatively, the kinematic curves differed at initial contact, peak dorsiflexion, and toe-off with the treadmill condition being less dorsiflexed in all conditions (Figure 4).

Average peak moment normalized to body mass (N-m/kg) was significantly higher in treadmill running compared to overground running ($p < .001$). All participants showed greater moment values during treadmill running. Kinetic curves of the two conditions showed differences at the onset of rapidly increased moment with treadmill

beginning at approximately 35% stance phase compared to overground which began at approximately 50% stance phase (Figure 5). Another notable difference was a decreased moment immediately before toe-off (Figure 5).

Average bending stiffness (N-m/kg/degree) between the two conditions showed significantly greater bending stiffness during treadmill running ($p=.006$). Nine participants had greater bending stiffness during treadmills trials, two participants had greater bending stiffness during overground trials, and one participant had similar values between the conditions. The load-displacement curves for the two trials show very different patterns as the treadmill has a greater slope while the moment increased, a greater peak moment, and a sharper transition into plantarflexing (Figure 6). The overground load-displacement curve shows a plateau during dorsiflexion which transitions into a rounded entrance into plantarflexing (Figure 6).

Average heel-off (% stance) was significantly larger during treadmill running ($p=.004$) (Figure 7). 10 of the 12 participants followed this trend while the other two participants had increased heel-off in overground running trials.

No significant differences were found between average contact time between conditions ($p=.970$) (Figure 8). Seven of the participants had increased contact time during treadmill trials while the remaining five participants showed decreased contact time during the treadmill trials compared to overground trials.

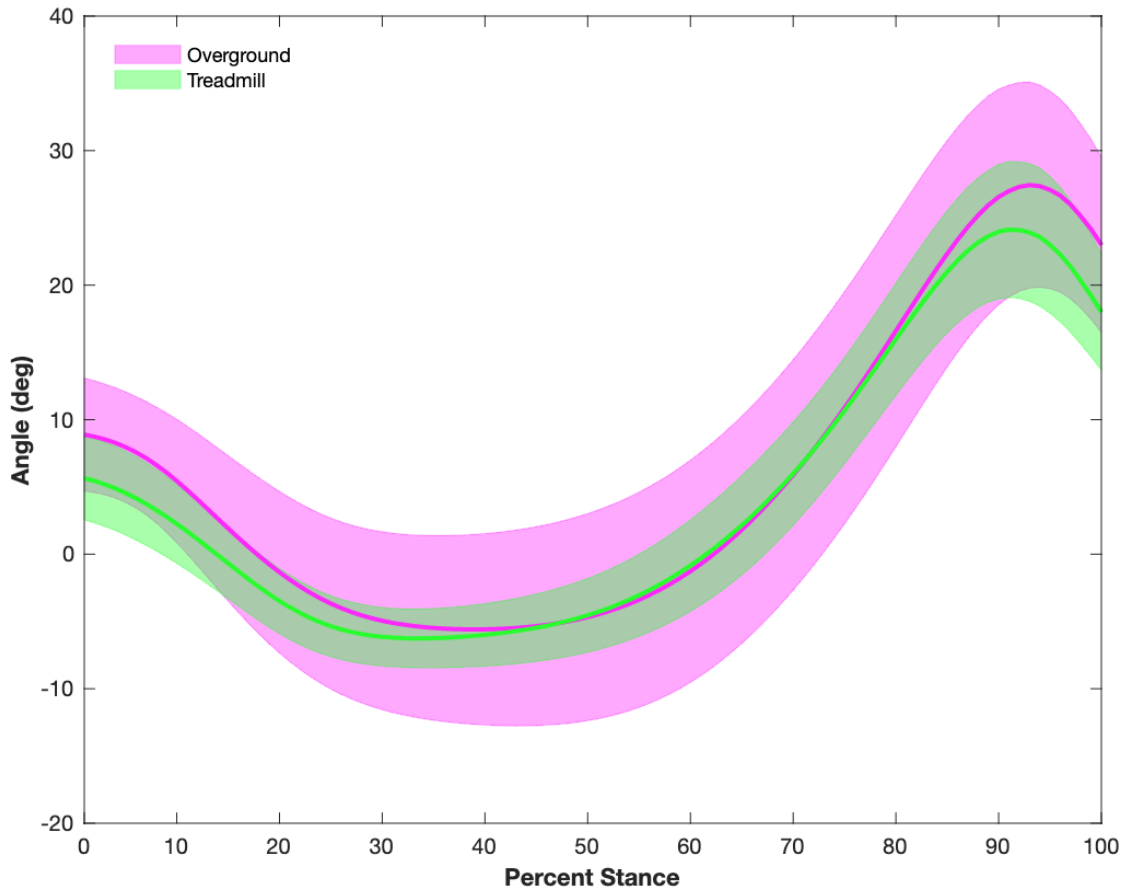


Figure 4: Metatarsophalangeal joint range of motion (deg) during stance phase

Average MTPJ range of motion during stance phase for treadmill (green line) and overground (purple line) with standard deviations indicated by the shaded areas.

Positive angle values indicate dorsiflexion, negative values indicate plantarflexion compared to static trial.

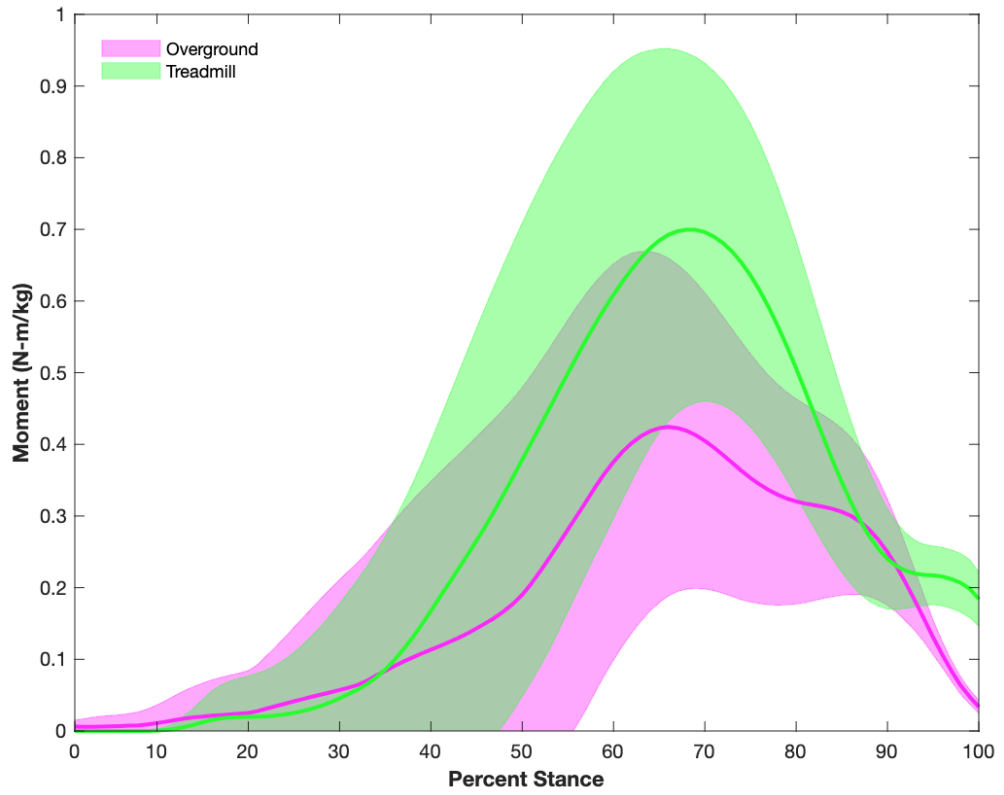


Figure 5: Metatarsophalangeal joint moment (N-m/kg) during stance phase

Average MTPJ moment during stance phase for treadmill (green line) and overground (purple line) with standard deviations indicated by the shaded areas.

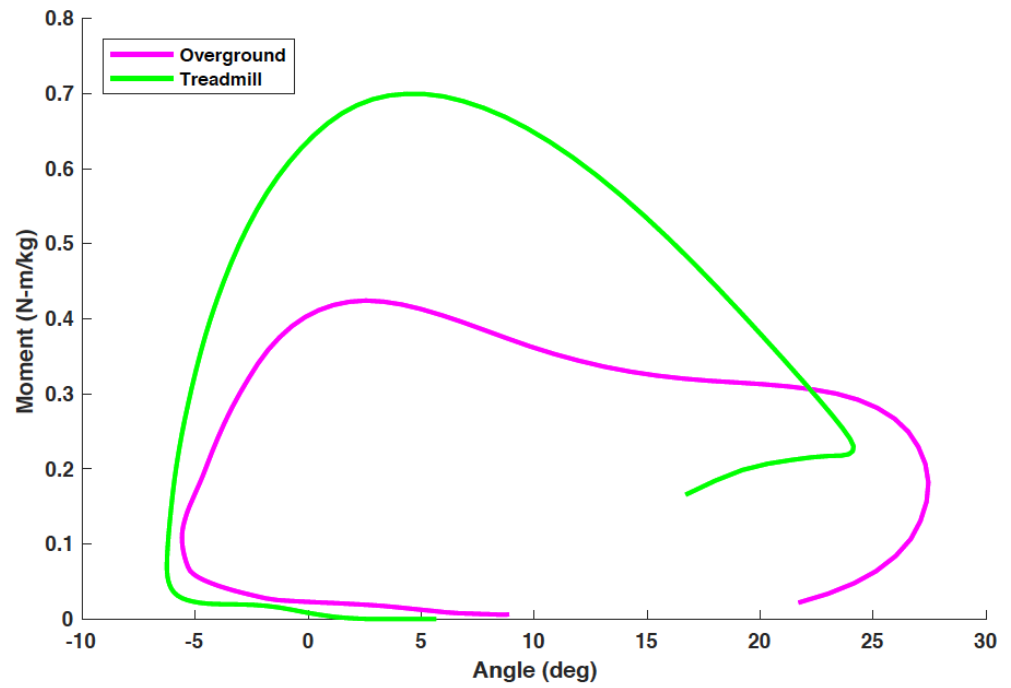


Figure 6: Metatarsophalangeal joint load-displacement plot

MTPJ bending stiffness (K_{cr}) calculated as the slope of the curve between initial contact, indicated on the graph when the moment is zero, and the maximum angular displacement. Positive angles indicate dorsiflexion while negative angles indicate plantarflexion compared to static trial.

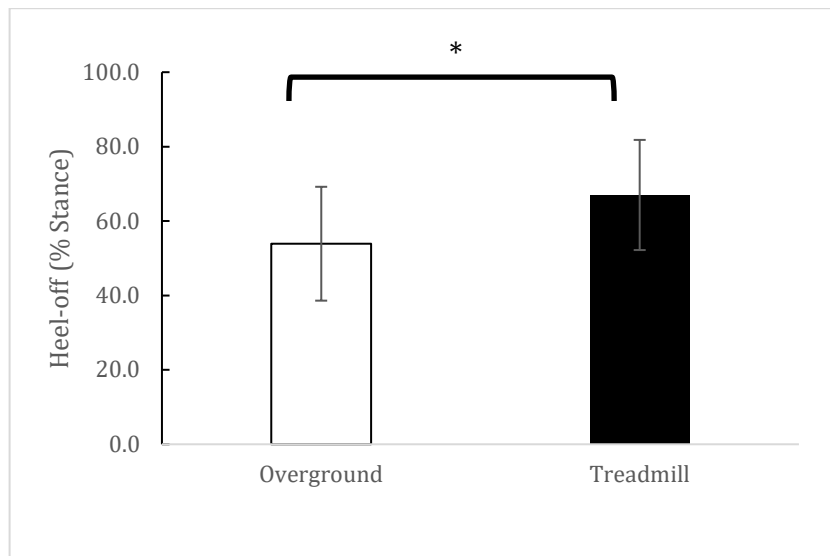


Figure 7: Comparison of average heel-off (% stance) between overground and treadmill conditions. Error bars indicate standard deviation.

Average heel-off was a greater percentage of stance phase in treadmill running compared to overground running ($p=.004$).

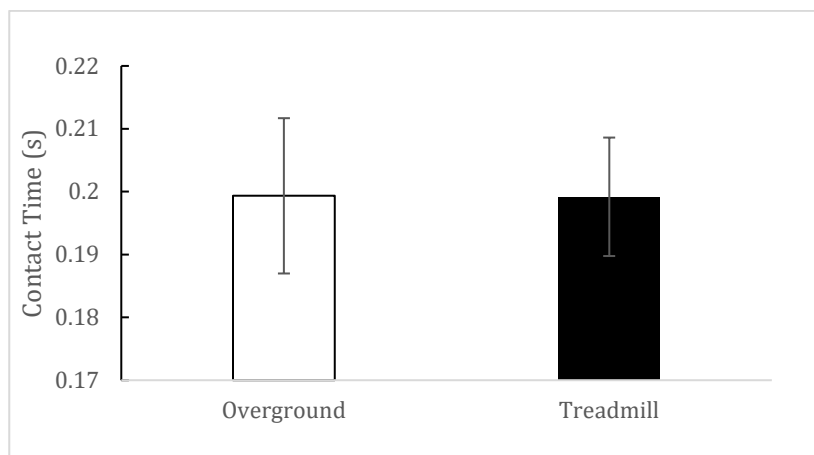


Figure 8: Comparison of average contact time (s) between overground and treadmill conditions. Error bars indicate standard deviation.

Average contact time was not significantly different between the two conditions ($p=.970$).

Discussion

The purpose of this study was to examine differences between sagittal plane MTPJ ROM, moment, stiffness, heel-off during stance phase, and contact time between overground and treadmill running. We hypothesized that MTPJ ROM would decrease, moment would increase, stiffness would increase, heel-off during stance would increase, and that contact time would be similar for treadmill running compared to overground running. Our results suggest that MTPJ ROM does decrease while moment, stiffness and heel-off all increase during treadmill running versus overground running. Additionally, our results suggest that contact time is not significantly different between the two conditions.

Results from MTPJ ROM showed a decreased ROM when running on treadmills. While this is the first study to report ROM for both conditions within subjects, our results qualitatively and quantitatively resemble ROM values reported in prior literature. Both the treadmill and overground ROM curves exhibited expected qualitative patterns of dorsiflexion and plantarflexion found throughout the literature. Quantitatively, a recent treadmill study conducted by McDonald et al. showed similar temporal results for plantar/dorsi-flexion events, while a study by Oh and Park was also similar with the exception that participants did not enter into plantarflexion (McDonald et al., 2016; Oh & Park, 2017). The Oh & Park study likely differed because of marker placement on the hallux: the more distal the hallux marker was placed the less the angle during the static trial. In our study the hallux marker was placed on the distal phalanx which caused a greater angle during the static trial. When subtracted out, the angle appeared plantarflexed, however; the toe was not truly plantarflexed it was only

plantarflexed compared to the static trial. Metatarsophalangeal joint average ROM in the McDonald paper was reported as 30.1 ± 2.8 degrees with a peak dorsiflexion angle of 28 degrees, which closely resembled our results of 30.7 ± 4.8 degrees and 29 degrees respectively (Table 2) (McDonald et al., 2016). Overground results of this study were similar to results from papers by Roy & Stefanyshyn, Madden et al., and Willwacher et al.: the latter two showed plantarflexing occurring at 20% of stance phase and average peak dorsiflexion of 28 degrees which resembled our observed results, like the Oh & Park study the angle was never recorded to be less than zero (Madden et al., 2015; Roy & Stefanyshyn, 2006; Willwacher et al., 2013).

Notable differences between treadmill and overground MTPJ ROM observed in this study include a lesser degree of dorsiflexion at initial contact and a decreased peak dorsiflexion (Figure 4). One potential hypothesis suggests that the lesser degree of dorsiflexion at initial contact represents an increased tendency to forefoot or midfoot strike during treadmill running. Studies by Wank et al., Fellin et al., and Nigg et al., have shown decreased ankle dorsiflexion and increased ankle plantarflexion during treadmill running (Fellin et al., 2010; Nigg et al., 1995; Wank et al., 1998). Although no studies have specifically quantified MTPJ dorsiflexion differences between forefoot and rearfoot striking, MTPJ dorsiflexion has been shown to directly correlate with ankle dorsiflexion (Lundberg, Goldie, Kalin, & Selvik, 1989). This association happens through the activation of the extensor hallucis longus and extensor digitorum longus which have been shown to cause dorsiflexion at both the MTPJ and ankle (Lundberg et al., 1989). Because rearfoot strikers have shown a higher degree of ankle dorsiflexion at initial contact, it follows that MTPJ dorsiflexion at initial contact would also be greater

(Ahn, Brayton, Bhatia, & Martin, 2014). Therefore, a higher incidence of forefoot or midfoot striking could potentially explain the decreased dorsiflexion observed at initial contact.

The second observed difference between treadmill and overground MTPJ ROM was a decreased peak dorsiflexion angle occurring qualitatively earlier in the stance phase during treadmill running. This observation, as well as the decreased average ROM, may be explained by participants taking less time to gain full contact with the treadmill. Nigg et al. hypothesized that participants adopt a midfoot foot strike pattern and gain full contact with the treadmill faster in order to provide an increased feeling of stability (Nigg et al., 1995). The mechanism for decreasing the time to gain full contact would be a decreased time during the loading phase of stance and earlier entrance into push off. This may explain our observed results of earlier peak dorsiflexion; however, one would expect a more pronounced difference in loading rate during early stance phase between the treadmill and overground conditions (Figure 4). A second hypothesis proposed by Hong et al. suggests that there is a reduction in the propulsive phase during treadmill running (Hong, Wang, Li, & Zhou, 2012). Attenuation of the propulsive phase would explain why the peak dorsiflexion angle and MTPJ ROM were reduced. As the treadmill belt pulls the foot backwards, the foot does not need to push off the ground. It only needs to lift off and the hip pulls the lower limb forward to complete the gait cycle. Without the push off phase, the MTPJ may remain less dorsiflexed throughout stance phase.

Regarding the MTPJ moment, some recent studies have not normalized their results to body weight while some do. Our normalized results were similar to studies by

Day & Hahn as well as McDonald et al. for the treadmill condition, and Willwacher et al. for the overground condition (Day & Hahn, 2019; McDonald et al., 2016; Willwacher et al., 2013). While the numerical values of our moments cannot be compared to non-normalized moments reported in other studies, our treadmill moment began increasing quickly at approximately 35% of stance phase which was similar to approximate values of 25%, 30%, 40%, 40%, and 35% shown in figures by Day & Hahn, Stefanyshyn & Nigg, Roy & Stefanyshyn, Oh & Park, and McDonald et al., respectively (Day & Hahn, 2019; McDonald et al., 2016; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 1997). Our result of overground MTPJ moment quickly increasing at 50% matched that of Willwacher who also showed a marked increase at 50% (Willwacher et al., 2013).

The most likely mechanism explaining the observed trends of a greater peak MTPJ moment and an earlier increase in moment was that participants adopted a forefoot strike during treadmill running. In a study conducted by Kleindienst et al., participants who forefoot struck had a greater maximum plantarflexion moment that occurred later in the stance phase compared to rearfoot striker (Kleindienst, Campe, Graf, Michel, & Witte, 2007). Our results follow this trend with a greater moment during treadmill running which qualitatively occurs later in the stance phase.

Additionally, moment was considered zero until the GRF acted distal to the MTPJ axis. As shown by the Kleindienst study, and replicated in most studies conducted on rearfoot versus forefoot striking, vertical GRF in rearfoot striking shows a transient peak when the heel hits the force plate which is not present in forefoot striking (Kleindienst et al., 2007). The continuous increase that characterizes forefoot striking could explain the

earlier onset of moment found in our results as the transient peak would not register as a moment because the GRF is acting proximal to the MTPJ during that time.

The second notable aspect of the moment compared to the stance phase graph was the plateau in overground running and the lower moment during toe-off. One potential hypothesis mentioned before, proposed by Hong et al., suggest that the propulsive phase is shortened in treadmill running because less propulsive force is needed to maintain running speeds on treadmills (Hong et al., 2012). If true, the first peaks in moment observed in our results could be the moment of the body passing over the MTPJ which would be present in both results. The second peak would indicate the moment associated with push-off and would be absent or decreased in treadmill running. The increased moment immediately before toe-off during treadmill running was likely caused by the increased anterior GRF, shown by Riley et al., acting more distally which would lead to an increased moment (Kleindienst et al., 2007; Riley et al., 2008). One potential limitation that could lead to complications in data interpretation of this figure would be the large standard deviation values which could obscure trends during both conditions. This limitation will be addressed fully in the limitations section.

As observed in our results bending stiffness increased from overground to treadmill running (Table 2), and the angular load-displacement curves show qualitatively different trends between conditions (Figure 6). Quantitatively and qualitatively, our treadmill results resemble reported bending stiffness and angular load-displacement curves of foot-shoe complexes that were relatively less stiff in the Oh & Park study (Oh & Park, 2017). This similarity was expected, as the Nike Streak 6 Flyknit testing shoes are designed as a relatively less stiff racing flat as advertised by

the company. However, our results showed sharper plantarflexing leading up to toe-off (Figure 6). Two potential reasons for this difference were that the bending stiffness of the testing shoes was unknown and could be less stiff than the least stiff shoe tested by Oh & Park, or that the decreased testing speed (2.78 m/s) in their trial led to a smoother entrance into plantarflexion. Both possibilities cannot be ruled out without further testing. Qualitatively our results differed from angular load-displacement curves presented by Oleson et al., which showed a curve similar to the treadmill only with a less pronounced entrance into plantarflexion (Oleson, Adler, & Goldsmith, 2005). This difference is likely attributable to increased variance between participant's preferred strike pattern as this study did not control for rearfoot versus forefoot striking and Oleson only compared rearfoot strikers to other rearfoot strikers (Oleson et al., 2005).

As stated above, the main differences between the load-displacement curves of overground versus treadmill running concern the sharpness of entering plantarflexion during toe-off and the shape of the curve in general. Differences in peak moment have already been described and the gentler curve into plantarflexion in the overground condition could be because of increased propulsion during toe-off. Because treadmill running has been hypothesized to be associated with a decreased propulsion phase, the MTPJ never reaches the same degree of dorsiflexion compared to overground running (Figure 4). As such the load-displacement curve does not extend as far to the right compared to overground running, and the range of motion during terminal plantarflexion also decreases meaning the slope will be less steep over a shorter duration of time (i.e. a sharper turn around at the far right extreme).

As demonstrated by Figure 7, the percent stance that the heel was off the ground increased during treadmill running. Prior research has both agreed and disagreed with these results as listed in the Williams review (Williams, 1985). These results further support the hypothesis that treadmill running could be associated with a greater incidence of forefoot striking, as prior research has shown an increased sole angle in forefoot striking compared to rearfoot striking (Kleindienst et al., 2007). An increased sole angle in this study represented the time the heel was off the ground and created an angle between the sole and horizontal (Kleindienst et al., 2007).

Finally, our results indicate that contact time remains similar between conditions (Figure 8). Similar results were found in a study by Nelson et al.; however, an increased contact time during treadmill running was found in Garcia-Perez et al. and Schache et al., while an increased contact time during overground running was found in Riley et al (García-Pérez, Pérez-Soriano, Llana, Martínez-Nova, & Sánchez-Zuriaga, 2013; Nelson, Dillman, Lagasse, & Bickett, 1972; Riley et al., 2008; Schache et al., 2001). Differences between studies were likely due to running experience of participants and familiarization with treadmills (Williams, 1985). The similar contact times exhibited between conditions were likely because the population in this study contained highly trained runners who were familiarized with treadmills.

Implications

If the proposed hypotheses that treadmill running is associated with higher incidence of midfoot or forefoot striking remains valid, shoe designers and physical therapists need to be aware of the potential implications. Specifically, shoe designers attempting to improve running economy or gait biomechanics need to factor in the

increased likelihood to rearfoot strike when extrapolating their results to overground conditions. Additionally, consumers need to be aware that results of studies touting 4% improvement in economy were conducted under different testing conditions and do not necessarily reflect overground running.

Besides biomechanical differences in the MTPJ indicated in our results, differences in plantar pressure, plantar fascia strain, and Achilles tendon loads have been observed in prior studies. In a study by Hong et al. lower maximum pressures in treadmill running compared to overground running were recorded (Hong et al., 2012). These results are consistent with described pressure patterns during forefoot running (Rooney, 2011). Decreased plantar pressure could be one mechanism for attenuating injury in subjects with lower extremity injuries (van Gent et al., 2007). Similarly, plantar fascia strain has been shown to be reduced in subjects with decreased MTPJ ROM (McDonald et al., 2016). Decreased plantar fascia strain has also been shown to decrease the incidence of plantar fasciitis (McDonald et al., 2016). Taken together these results indicate that treadmill running may be beneficial in helping attenuate plantar injuries or tibial stress fractures as shown by Milgrom et al. (Milgrom et al., 2003)

However, a potential implication of the decreased ROM and increased moment at the MTPJ is an increased load at the Achilles tendon (Lieberman, Raichlen, Pontzer, Bramble, & Cutright-Smith, 2009). Prior research has shown an association between treadmill running and an increased Achilles load (Willy et al., 2016). This study provides a potential contributing mechanism to the increased load and cautions the use of treadmills when dealing with Achilles issues. Differences between MTPJ biomechanics and their impact on bony or tendinous structures need to be taken into account as

potential injury mechanisms when assessing the usefulness of treadmills for rehabilitation.

Limitations

One potential limitation in this study that could have obscured trends in both conditions, but was especially prevalent in overground running was the variability shown as a large standard deviation. Although the average standard deviations do not show a trend between overground and treadmill running (Table 1), kinematic and kinetic graphs show a larger area of standard deviation during overground running for all conditions that standard deviation was reported (Figures 4, 5, 7, 8). The likely mechanism responsible for this observed trend is that overground trials measured the average of five non-consecutive foot strikes as opposed to the treadmill trials which were the average of five consecutive foot strikes recorded in quick succession. In general, the large standard deviations could be due to variations between subjects' specific gait patterns. In order to decrease the standard deviation of overground trials, future studies should look to increase the amount of collected foot strikes or find methods of collecting consecutive footsteps overground such as large pressure pads or multiple force plates in series.

Potential limitations for extrapolating data include recording only one speed for this study as well as using a population of participants who were at least moderately acquainted with treadmill running. Because of differences in speed reported by Nigg et al., comparative values from this discussion section were based on studies with speeds of 3.5-5.0 m/s except when otherwise stated (Nigg et al., 1995). Further studies should look to incorporate more speeds in order to observe how changes in velocity affect the

kinematic and kinetic values reported in this study. Similarly the degree of familiarization with a treadmill has been shown to impact biomechanical comparisons between overground and treadmill running (Williams, 1985). This study only retrospectively asked for the qualitative familiarity of participants with treadmills and did not use the information as a disqualifier. Future studies may look to compare how the degree of familiarity impacts MTPJ kinematics and kinetics when running on a treadmill versus overground.

Conclusion

This study attempted to fill the current gap in knowledge of MTPJ kinematic and kinetic differences between treadmill and overground running. Our study reported decreased MTPJ ROM, increased moment, increased stiffness, increased percentage of stance with heel-off, and similar contact time for the treadmill condition compared to overground running. Specific differences between conditions need to be taken into account when conducting biomechanical tests on treadmills with the intent of extrapolation to overground running. Similarly, potential effects to plantar pressure, plantar fascia strain, and Achilles tendon loading associated with differences in MTPJ kinematics and kinetics need to be assessed before utilizing treadmills in rehabilitation protocols.

Although many studies have observed lower ankle dorsiflexion during treadmill running compared to overground running, none have specifically categorized the incidence of forefoot versus rearfoot striking between conditions. Future studies should look to quantify the relationship between treadmill and overground running with forefoot and rearfoot running as well as assess the implications of those results on injury risk when treadmill running is prescribed for rehabilitation. Additionally, future studies should assess differences in the frontal and transverse plane MTPJ kinematics and kinetics in order to gain a full understanding of the MTPJ motion when running on a treadmill or overground.

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