Patellofemoral joint and Achilles tendon loads during overground and treadmill running

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Key words: running, patellofemoral joint, Achilles tendon, biomechanics

Compliance with Ethical Standards:

The authors have no declared conflicts of interest and there are no disclosures of professional relationships with companies or manufacturers who may/will benefit from the results of this present study. Written and verbal consent was obtained from all participants prior to enrollment in this investigation. Prior to initiation of this study, the research protocol was approved by the East Carolina University Human Subjects Research Board.

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Abstract

Study design: Level 4: Controlled laboratory study.

Background: Little is known regarding potential differences between treadmill and overground running in regards to patellofemoral joint and Achilles tendon loading characteristics.

Objectives: We sought to compare measures of loading to the patellofemoral joint and Achilles tendon across treadmill and overground running in healthy, uninjured runners.

Methods: Eighteen healthy runners ran at their self-selected speed on an instrumented treadmill and overground while three-dimensional running mechanics were sampled. A musculoskeletal model derived peak load, rate of loading and estimated cumulative load per 1 kilometer of continuous running for the patellofemoral joint and Achilles tendon for each condition. Data were analyzed via paired T-tests and Pearson's correlations to detect differences and assess relationships, respectively, between the two running mediums.

Results: No differences ($p>0.05$) were found between treadmill and overground running for the peak, the rate of loading, or estimated cumulative patellofemoral joint stress per 1 kilometer of continuous running. However, treadmill running resulted in 21.5% greater peak Achilles tendon force ($p<0.001$), 15.6% greater loading rate of Achilles tendon force ($p<0.001$) and 14.2% greater estimated cumulative Achilles tendon force per 1 kilometer of continuous running ($p<0.001$) compared with overground running. There were strong ($r>0.70$) and moderate agreements ($r>0.50$) for most patellofemoral joint and Achilles measures, respectively, between treadmill and overground running.

Conclusions: No differences were observed in loading characteristics to the patellofemoral joint between running mediums, yet treadmill running resulted in greater Achilles tendon loading compared with overground running, Future investigations should determine if sudden bouts of treadmill running places the Achilles tendon at risk for mechanical overload in runners who habitually train overground.

Key words: Knee, ankle, biomechanics, musculoskeletal model

Introduction

The patellofemoral joint and Achilles tendon are among the most common sites of injuries sustained by runners. More specifically, patellofemoral pain and Achilles tendinopathy represents up to 25% and 9.5% of all running injuries, respectively. [31, 46] As a result of the high prevalence associated with these injuries, it is not surprising that individuals with these injuries make up a large portion of patients in sports medicine clinics.[15, 35]

Factors previously related to patellofemoral pain and Achilles tendinopathy in runners include injury history, age, strength deficits, training errors, structural issues, biological sex and biomechanical overloading.[12, 19, 32, 33, 37, 39, 54] Biomechanical loading of anatomical structures during running is complex and multifaceted. Specifically, large biomechanical loads (i.e., peak loads) are generally applied at a rapid rate (i.e., loading rate) and in a highly repetitive manner (i.e., cumulative loads) to articular structures and tendons through the course of a run.[1, 9, 12] Thus, measures of peak loads, the loading rate and total cumulative loads of the patellofemoral joint cartilage and Achilles tendon should all be considered in biomechanical investigations of these structures.

Treadmills are commonplace in training and rehabilitation settings. Treadmills are convenient, particularly during inclement weather or when options for outdoor running are restricted. Treadmills are also routinely used in clinical gait analysis and gait retraining programs due to the ability to evaluate and retrain running mechanics in a controlled environment.[4, 13, 43] Further, treadmills are often a fixture in training programs and return to running programs after injury to the patellofemoral joint or Achilles tendon.

Instrumented treadmills are now commonly used in biomechanical studies of ankle and knee mechanics during running.[8, 29, 30, 40, 52] In particular, instrumented treadmills enable the study of repetitive gait cycles and facilitate more in-depth analyses, such as exertion and gait modification studies.[23, 51] Despite their common use in either of these applications, little is known regarding the potential differences of loading to the patellofemoral joint and the Achilles tendon during overground and treadmill running.

Seminal biomechanical comparisons between treadmill and overground running suggest that these running mediums have largely similar knee and ankle kinematics, particularly in the sagittal plane.[20, 40] However, potential differences in joint kinetics exist, suggesting that there are differences in loading characteristics of the patellofemoral joint and Achilles tendon between overground and treadmill running. For instance, treadmill running has been reported to result in an approximately 27% lower peak internal knee extensor moment compared with overground running.[40] The peak knee extensor moment likely closely relates to peak quadriceps force [2] which in turn greatly influences patellofemoral joint reaction force.[52] However, as knee flexion may also be less during treadmill running,[20, 40] a corresponding reduction in patellofemoral contact area would also occur.[5] Therefore, it is unclear if there are differences in patellofemoral joint stress (patellofemoral joint stress= patellofemoral joint reaction force/patellofemoral contact area) between treadmill and overground running. Conversely, the peak plantar flexor moment and eccentric ankle joint power may be as much as 14% and 16% higher, respectively, during treadmill running [40] suggesting greater Achilles tendon demands.

Previous work has also investigated temporospatial differences between treadmill and overground running that can have an important effect on cumulative loading for the patellofemoral joint and Achilles tendon. Compared with overground, runners tend to adopt 1-5% shorter step length during treadmill running.[18, 40] This potentially important temporospatial difference may have consequences for patellofemoral joint and Achilles tendon loading. Firstly, a shorter step length during treadmill running may indicate a shorter stance phase which may, in turn, result in a greater loading rate of the patellofemoral joint and Achilles tendon if peak loads are of the same or greater magnitude as overground running. Secondly, the shorter step length associated with treadmill running may result in a greater number of steps i.e., loading cycles, to cover a given distance which may in turn increase cumulative loading on the patellofemoral joint and Achilles tendon during a sustained run.

The purpose of this study was to assess peak loads, rate of loading and cumulative loading of the patellofemoral joint and the Achilles tendon during treadmill and overground running. Due to a reduced knee extensor moment, we hypothesized that treadmill running would result in reduced peak patellofemoral joint stress and patellofemoral joint stress loading rate. Conversely, we hypothesized that there would be greater Achilles tendon loading and loading rate during treadmill running. Finally, we hypothesized that greater cumulative patellofemoral joint stress and Achilles tendon loading would result due to a reduced step length during treadmill running.

Methods

Prior to study initiation, the research protocol was approved by the East Carolina University Institutional Human Subjects Research Board. An *a priori* sample size estimate was conducted to determine the number of participants necessary to detect differences between conditions. Using $\alpha = 0.05$, $\beta = 0.2$, and means and variability of the peak knee extensor and plantarflexor moments between running overground and on a treadmill from Riley and colleagues[40], 18 participants were conservatively determined to be necessary to adequately power this study. For this investigation, we recruited 18 recreational runners (9 males, 9 females) from a large university and area running clubs.

All participants provided written and verbal consent prior to enrollment. In order to qualify, all participants were required to be habitual runners (defined as at least 10 km/week for at least the previous 6 months), free of any lower extremity surgeries and injury-free for at least the previous 3 months. Participants were limited to 18-35 years of age to limit heterogeneity in biomechanics and Achilles tendon properties that may be introduced by a greater age range.[16, 41] Comfort with treadmill running can affect running mechanics. [38] Therefore, only volunteers who were comfortable with treadmill running, defined as a score of at least "8" on a visual analog scale ("0" and "10" corresponding to completely uncomfortable versus completely comfortable, respectively), were enrolled. While not an inclusion/exclusion criterion, continuous involvement in endurance running ("running experience") was also collected. Please see TABLE 1 for demographics of the cohort of runners in this investigation.

Fifty-six retroreflective markers were affixed to the bilateral lower extremities, pelvis and trunk of each participant. Static calibration and dynamic hip trials[28] were collected. The pelvis coordinate system was defined by markers placed on the midline of the iliac crests and the greater trochanters. The thigh coordinate system was defined proximally by the calculated hip joint center from the dynamic hip trial and distally by the femoral condyles. The shank coordinate system was defined proximally by the tibial condyles and distally by the malleoli. Finally, the foot was defined proximally by the malleoli and distally by the 1^{st} and 5^{th} metatarsal heads and the distal aspect of the shoe. Tracking markers consisted of markers placed on the anterior superior iliac spines and shell-mounted clusters on the sacrum, posterolateral aspect of the thigh and shank, and a cluster of three markers on the rearfoot. This is a common marker set configuration and was similar to the marker set used by Fellin et al. (2010), a study of comparison for the present investigation.[20]

After a 6-minute treadmill accommodation period,[34] 3-dimensional running mechanics were sampled for 10 seconds at each participant's self-selected running speed. Participants were cued to choose this speed based on perception of their running pace during the middle of a standard training run. The self-selected running speed was established, based on the participant's feedback, during the final 4 minutes of the treadmill accommodation period. Ground reaction forces and marker trajectories were sampled at 1000 Hz by the instrumented treadmill (Bertec, Worthington, Ohio, USA) and 200 Hz by a 10-camera motion capture system (Qualysis Corp., Gothenburg, SWE), respectively. Prior to study initiation, treadmill speed calibration during running was performed using a digital tachometer every 0.2 m/sec up to 4.0 m/s. (HT-5500, Ono Sokki Corp., Yokohama, Japan). The treadmill running trial was not longer than 5 minutes of sustained running and an approximately 10-minute rest period was provided to each runner between the end of treadmill testing and initiation of overground testing to minimize fatigue.

Next, 3-D overground running mechanics were sampled as runners traversed a 25-meter runway at their same self-selected running speed (±3%) used during the treadmill running. Each runner practiced execution of the overground trials for several minutes to accommodate to the overground collection procedures, including establishment of running speed and runway starting position. Displacement of a single marker attached to the sacrum has previously been demonstrated to correspond to the displacement of a runner's estimated center of mass.[21, 22] Therefore, we tracked the anterior velocity of a sacral marker in real-time to measure running speed as the runner traversed force plates flush with the runway floor (AMTI, Watertown, Mass, USA). In post-processing, this method for tracking overground running velocity was highly correlated to the anterior velocity of the runner's estimated center of mass (correlation between anterior velocity of the sacral marker and estimated center of mass: Pearson's $r = 0.96$ $p<0.001$ with a root mean square error= 0.1 m/sec). Any trials that fell outside the velocity range, in which the participant was visibly changing velocity in the capture volume or when the force plates were targeted by the participant were discarded. The rationale for excluding trials in this manner was that different gait velocities and force plate targeting can have marked effects on the magnitudes of segmental velocities, joint moments and powers.[3, 7] Marker trajectories (Qualysis) and ground reaction forces were sampled with the exact same parameters as those utilized during the treadmill trial (200 Hz and 1000 Hz for kinematics and kinetics, respectively).

The order of testing (treadmill first followed by overground testing) was chosen to determine each participant's safe self-selected running speed for the treadmill trials. In testing during protocol development, pilot subjects tended to self-select a running speed for overground trials that was faster and not representative of a running speed that could be sustained by the runner on the treadmill. We felt that this mismatch in speeds was due to the fact that sustained running is not tested in overground trials, whereas treadmill running requires sustained running.

Data processing and musculoskeletal model

Using a sagittal-frontal-transverse plane Euler angle sequence, joint coordinates were calculated with a 6-degree of freedom model (The MotionMonitor, Chicago, Ill, USA). Marker and ground reaction forces were filtered with 15-Hz cutoff frequency via a low pass, fourth order Butterworth recursive filter. Matched cutoff filter frequencies are recommended to minimize non-physiological signal artifacts during inverse dynamic routines that might occur in high impact activities, such as running.[6, 26] Internal joint moments were then derived using an inverse dynamic routine with published segmental inertial parameters[14] and reported in the coordinate system of the distal segment. The dominant limb was used for all subsequent analyses. Separate, time-synchronized files of the vertical ground reaction force data were digitally filtered at 50 Hz using a low pass, fourth order Butterworth recursive filter and used for the purpose of identifying stance. Initial contact during the running trials was defined as the time when the vertical ground reaction force exceeded 20 N. Five stance phases of the dominant lower extremity (limb used to kick a ball) were analyzed from both the treadmill and overground running trials. We retained the first 5 complete stance phases from the 10 second treadmill trial for analysis. For the overground trials, we chose the 5 trials with gait velocities that were closest to the treadmill gait speed to minimize the potential error that may be introduced by differing speeds between the two testing modes

To calculate patellofemoral joint stress and Achilles tendon forces, we utilized a musculoskeletal model that has been described fully elsewhere[17, 52, 53] but will briefly be described here. This model uses an inverse dynamics approach to calculate hamstrings, quadriceps, gastrocnemius and soleus muscle forces. As such, this procedure accounts for knee joint co-contraction from the hamstrings and gastrocnemius.[52] From the net hip extensor moment, hamstring force was calculated utilizing published hamstring and gluteus maximus cross sectional areas and muscle moment arms as a function of hip angle.[36, 50] The net plantarflexor moment and the Achilles tendon muscle moment arm were then used to derive the Achilles tendon force.[25, 45] Achilles tendon force was further proportioned to the gastrocnemius and the soleus based on the physiological cross sectional area of each muscle.[50] To account for co-contraction about the knee, hamstring and gastrocnemius torque was calculated using their respective moment arms at the knee and then summed with the internal knee extension moment.[24, 44, 45, 49] Quadriceps force was then derived as the quotient of the adjusted quadriceps moment and the quadriceps moment arm.[24, 48] Patellofemoral joint reaction force was then calculated utilizing the quadriceps force as a function of knee joint angle.[47] See **FIGURE 1** for a comparison of patellofemoral joint reaction force output for our model compared with published values from other musculoskeletal models of varying complexities.[10, 29, 42] Finally, patellofemoral joint stress was estimated as the quotient of the patellofemoral joint reaction force and sex-specific patellofemoral contact areas.[5]

A custom written LabVIEW code (National Instruments, Austin TX, USA) was used to calculate discrete variables. First, step length (m) was calculated. For patellofemoral joint stress and Achilles tendon force, we calculated the peak, the loading rate and the impulse (time integral) for each stance phase. Loading rates were calculated as the middle 60% of the rising curve between initial contact and for the respective peaks of patellofemoral joint stress and Achilles tendon force (**FIGURE 2 and FIGURE 3**) for each stance. Cumulative patellofemoral joint stress and cumulative Achilles tendon force were estimated as the load per 1 km of continuous running as the product of impulse per stance and number of strides to complete 1 km of continuous running (500 m/step length). To assist with interpreting our results, we also included peak knee extensor moment and peak plantar flexor moment in our analysis. Additionally, we calculated eccentric and concentric power for the ankle plantar flexors (joint power= sagittal plane angular velocity x joint moment) as these measures likely relate closely to energy storage and release of the plantarflexors.

All statistical analyses were performed with SPSS Version 20 (IBM, Houston, TX, USA). To detect differences between the two running modes, motion data were analyzed with a series of paired, two-tailed T-Tests ($\alpha=0.05$). Effect sizes (d) were also calculated to assess the magnitude of any differences, with a small effect corresponding to $d=0.2\text{-}0.4$, a moderate effect corresponding with $d=0.4\text{-}0.8$ and a large effect corresponding with $d\geq0.8$.[11] To assess the relationship between two running modes, discrete variables of interest were analyzed with Pearson's r ($\alpha=0.05$).

Results

We found no differences and there was excellent correlation for gait speed between overground and treadmill running for our participants (**TABLE 2**). All overground trials utilized in the analysis were inside ±2.6% of the treadmill running speed. However, step length was significantly shorter (*p<0.001, d=-0.62*) during treadmill running compared with overground running. This difference was associated with a moderate effect size (*d=-0.62*), yet had an excellent correlation (p<0.001, r=0.86) between the two running modes. Interestingly, stance duration was not different and was highly correlated between the two running conditions.

Regarding all knee and patellofemoral joint measures, we found no differences between overground and treadmill running (**TABLE 2, FIGURE 1, FIGURE 2**). We also found moderate to excellent correlations for all knee measures, except for patellofemoral joint stress loading rate, which was not correlated. Specifically, peak knee flexion (*p=0.96, d=0.01; r=0.58, p=0.01*) and peak knee extensor moment (*p=0.28, d=0.19; r=0.77, p<0.001*) were not different between the two running modes. Peak patellofemoral joint reaction force (*p=0.99, d= 0.00; r=0.81, p<0.001*), peak patellofemoral joint stress (*p=0.73, d=0.04; r=0.86, p<0.001*) and loading rate of patellofemoral joint stress (*p=0.09, d=0.55)* were also not different between conditions. However, there was a nonsignificant correlation between the running modes for the loading rate of patellofemoral joint stress (*r=0.39, p=0.11).* Despite the additional 23 strides estimated to run 1 km continuously during treadmill running, estimated cumulative patellofemoral joint stress per 1 kilometer of continuous running (*p=0.21, d=0.21; r=0.88, p<0.001*) during treadmill running was not different than the overground condition.

In contrast, we found moderate to large differences at the ankle between overground and treadmill running (**TABLE 3, FIGURE 3**). With the exception of peak plantarflexor moment and estimated cumulative Achilles tendon force per 1 kilometer of continuous running, all ankle and Achilles values were moderately to strongly correlated between the two running modes. While we found no difference in peak dorsiflexion angle (*p=0.32, d= -0.15; r=0.81, p<0.001*), the peak plantar flexor moment (*p=0.001, d=-1.17*) was significantly greater and not correlated *(r=0.36, p=0.14)* during treadmill running compared with overground running. Additionally, peak Achilles tendon force (*p<0.001, d=1.01; r=0.52, p=0.03*), Achilles tendon loading rate (*p<0.001, d=0.61; r=0.62, p=0.006*), Achilles tendon force impulse per stance (*p=0.02, d=0.63; r=0.52, p=0.02*) and estimated cumulative Achilles tendon force per 1 kilometer of continuous running (*p<0.001, d=1.04; r=0.39, p=0.12*) were all significantly greater during treadmill running. Treadmill running was also associated with greater concentric ankle joint power (*p=0.001, d=1.18; r=0.69, p<0.001*), but there was no significant difference in eccentric joint power (*p=0.25, d=0.23; r=0.69, p<0.001*) between the two modes of running.

Discussion

We sought to determine if there were differences between running overground and running on a treadmill in regards to patellofemoral joint loading and Achilles tendon forces. We found no differences in peak patellofemoral joint reaction force or any measure of patellofemoral joint stress between overground and treadmill running. Due to moderate to strong correlations, this study suggests that findings from studies that utilize instrumented treadmills to assess loading of the patellofemoral joint may be largely applied to overground running and vice versa. In contrast, ankle concentric power and all measures of Achilles tendon force and were greater during treadmill running**.** While the Achilles tendon loads were moderately proportional between treadmill and overground running, caution should be used when extrapolating absolute values of Achilles tendon loads obtained via instrumented treadmill running to overground running.

The cohort of runners in the present investigation was a sample of convenience and was fairly representative of a typical university setting. However, the enrolled runners reported a relatively long length of continuous participation in endurance running of greater than 7 years. While the study was open to runners who ran as few as 10km/week, the range for running volume was 13.0-96.6 km/week. Overall, we felt the length of continuous participation in endurance running, coupled with a high level of comfort with treadmill running (9.6/10), was the best representation of running skill level. In contrast, running volume likely fluctuates throughout the year.

Counter to our hypothesis, we found no differences between overground and treadmill running in respect to sagittal knee joint mechanics, which are major influences on patellofemoral joint reaction force and stress. Based on the previous literature, we expected reduced knee flexion kinematics and reduced knee extensor moments during treadmill running.[20, 40] There are several potential reasons for the discrepancy with the previous literature. Firstly, the kinematic differences reported by Fellin et al. were small (~1.3° less knee flexion during treadmill running) and may simply be due to small differences in running speed between overground and treadmill modes. Secondly, the only previous comparison of knee joint kinetics utilized different signal filtering parameters when processing treadmill and overground trials.[40] The present investigation utilized identical filtering parameters when processing overground and treadmill trials. The lower low pass filter cutoff utilized by Riley et al. during treadmill running when compared to their overground running data may have attenuated the knee extensor moment signal, resulting in the slightly lower peak knee extensor moment during treadmill running reported in their study.[40] Finally, the present study examined runners during their normal endurance training pace (2.9 m/sec), whereas previous investigations used the estimated 10 km race pace(~3.8 m/sec) [40] or a standardized pace (3.35 m/sec).[20] Therefore, differences in sagittal plane knee and patellofemoral joint kinetics between overground and treadmill running may occur at higher running speeds than what were sampled in the present investigation.

There were no differences for the peak, loading rate and estimated cumulative patellofemoral joint stress per kilometer of continuous running. We estimated that 23 additional strides were required to run 1 km continuously on a treadmill which was insufficient to increase the estimated cumulative patellofemoral joint stress per kilometer of continuous running. It has been suggested that the measures of peak, loading rate and cumulative joint stress play independent roles in the degradation of articular structures.[9] Therefore, future study should be undertaken to determine if return to running programs for the treatment of patellofemoral pain result in similar outcomes if conducted on a treadmill or overground. Further, strong relationships ($r \geq 0.85$) were found between overground and treadmill running for peak patellofemoral joint reaction force, peak and impulse patellofemoral joint stress as well as the estimated cumulative patellofemoral joint stress to run 1 km continuously. Thus, treadmill and overground running appear to yield similar estimates of patellofemoral joint reaction force and stress measures.

In contrast to the patellofemoral joint, measures of Achilles tendon loading and concentric ankle joint power were considerably greater during treadmill running.

Interestingly, peak ankle dorsiflexion was not different during treadmill running. Rather, the peak plantarflexion moment was greater during treadmill running and this difference was associated with a large effect size. Thus, measures of peak and loading rate of Achilles tendon force as well as estimated cumulative Achilles tendon force to run 1 km continuously were correspondingly greater (*d=0.62-1.04*) during treadmill running. As stance duration was not different between overground and treadmill running, the greater peak Achilles tendon force was most likely responsible for the higher loading rate of the Achilles tendon. The sagittal ankle power data revealed that concentric ankle joint power was also greater during treadmill running whereas eccentric ankle joint power was not. This finding contrasts with the previous investigation of ankle joint powers during treadmill and overground running that found greater eccentric ankle joint power during treadmill running but similar concentric ankle joint power with overground running.[40] Potential reasons for this difference between investigations include differences in tested gait velocity (present study: ~2.8 m/sec vs, Riley et al.: 3.8 m/sec) and differences in overground runway length (present study: 25 meters vs. Riley et al.: 15 meters). Nevertheless, we found moderate correlations for most of the Achilles, ankle joint power and ankle kinematic measures between the two running modes. However, the moderate to large absolute differences that we found at the ankle suggest that caution should be exercised when interpreting Achilles data collected during treadmill running and extrapolating it to overground running and vice versa.

The greater estimated cumulative Achilles tendon force to run 1 km continuously during treadmill running may have implications for future study and potential clinical applications.[12, 27] We estimated that treadmill running would expose the Achilles tendon to an additional 45 body weights of cumulative force to run 1 km continuously compared with overground running. Tendon's well-documented response to acute bouts of loading suggests further investigation may be warranted to determine if an acute bout of treadmill running results in greater collagen turnover in the Achilles tendon when compared to an equal volume of overground running. Further study is necessary to determine if there are differences in Achilles tendon qualities or greater prevalence of Achilles tendinopathy in individuals who run solely on a treadmill versus solely overground.

Limitations

There are several limitations to the present investigation that should be kept in mind when interpreting these results. Firstly, all participants were tested first on the treadmill followed by overground. This testing order was deliberate so that a realistic self-selected running speed could be established that could then be maintained both overground and during treadmill running. Regardless, an order effect may have been introduced. Secondly, the musculoskeletal model used in this investigation was not entirely subject-specific, utilized muscle architectural parameters from the literature, and represents estimates of *in vivo* tissue loads. However, any added benefit of a subject-specific model inputs would be negligible due to the within-subject design. As implanted strain gauges are not presently feasible to measure *in vivo* joint and tendon loads, musculoskeletal models are generally accepted as estimates of these loads. Patellofemoral joint reaction force and Achilles tendon loads found in the present investigation are within those in recently published investigations using different musculoskeletal models.[1, 29, 42] Secondly, the overground runway utilized in this investigation was 25-meters in length with the force plates imbedded at approximately the half-way point. Due to the relatively short runway distance, it is possible that participants were not at a constant speed when traversing the capture volume. This laboratory design is fairly standard and ubiquitous across gait laboratories that study running mechanics. The key papers of comparison for this investigation used 15-meter(Riley et al., 2008)[40] and 25-meter runways (Fellin et al., 2010).[20] As a longer track-based laboratory is neither common nor practical for most settings, the use of emerging wearable technologies during continuous outdoor running may provide the most practical comparison with continuous treadmill running. Additionally, the horizontal velocity of the sacral marker was used to provide feedback on running velocity during overground running trials whereas the treadmill controller was used to control gait speed during treadmill trials. As a result, undetected variations in treadmill gait velocity may have occurred if subjects' positions drifted anterior-posterior on the treadmill during data collection. However, we only collected data when subjects' positions were stationary on the treadmill in an effort to minimize this potential influence. Finally, our participants were injury-free and young and there was a relatively wide range in habitual weekly running volume among the cohort. Therefore, care should be exercised when applying the results of this study to injured or older populations.

Conclusions

In conclusion, treadmill and overground running yielded similar estimates of patellofemoral joint reaction force and stress. In contrast, treadmill running resulted in greater Achilles tendon loads when compared to overground running. Further study is necessary to determine the clinical implications of these findings in return to running programs or in assessing the risk of Achilles tendon injury in runners who undergo acute bouts of treadmill running. These findings also suggest that measures of patellofemoral joint reaction force and stress during instrumented treadmill running are a reasonable representation of those same loads during overground running. In contrast, Achilles tendon force estimates obtained during instrumented treadmill running appear to be moderately proportional to, yet greater than overground running.

Conflict of interest: None

Key Points

Findings: Estimates of patellofemoral joint loading did not differ between treadmill and overground running. However, Achilles tendon loads and concentric ankle power were significantly greater during treadmill running compared with overground running.

Implications: Patellofemoral joint loading during treadmill running appears to be consistent with overground running. Therefore, the findings of studies examining patellofemoral joint loading during treadmill running can be applied to overground running. Conversely, measures of Achilles tendon loading during treadmill running were moderately correlated, yet greater than overground running. Future study should determine if acute bouts of treadmill running places the Achilles tendon at risk for mechanical overload in runners who customarily perform their training overground.

Caution: Caution should be exercised when extrapolating these results to individuals with patellofemoral pain or Achilles tendinopathy.

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FIGURES

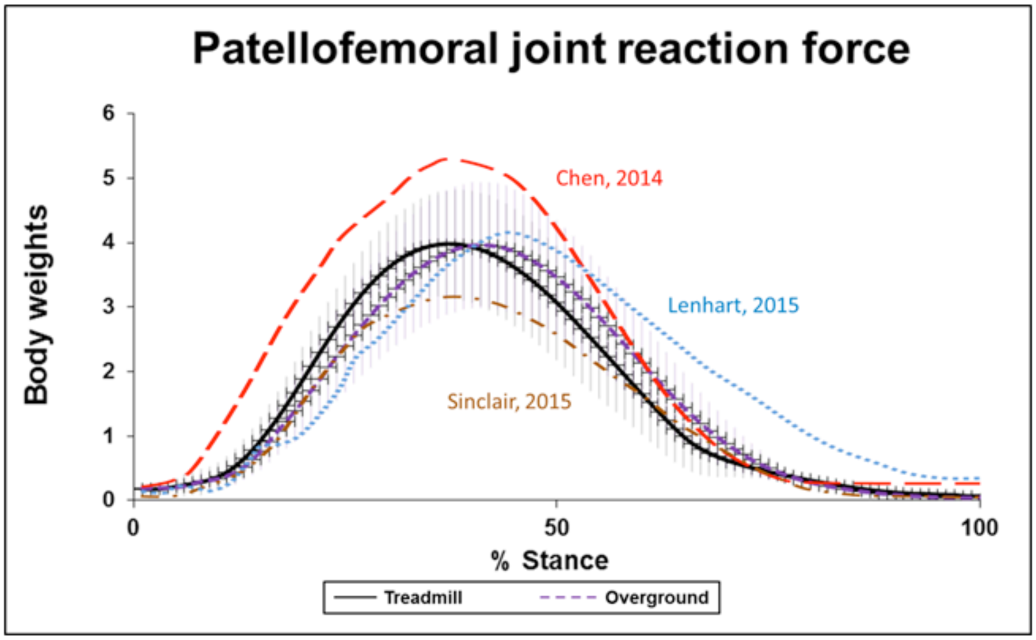

FIGURE 1. Patellofemoral joint reaction forces from both overground and treadmill running in the present study (hash marks correspond to ±1 standard deviation) contrasted with other published values of patellofemoral joint reaction forces during running.[9,29,42] Chen and Powers (2014) utilized faster running velocity (present investigation:2.9 m/sec, Chen and Powers: 3.33 m/sec) which may partly explain the higher values.[9] In contrast, Lenhart et al., (2015) utilized nearly identical running velocities as those in the present investigation (2.8 m/sec).[29] Both the Chen and Powers (2014) [9] and the Lenhart et al. (2015) [29] models accounted for co-contraction of the knee musculature, as did the model utilized in the present investigation. In contrast, the model used by Sinclair and colleagues (2015)[42] did not account for co-contraction of the knee musculature which may have contributed to their lower patellofemoral joint reaction force values.

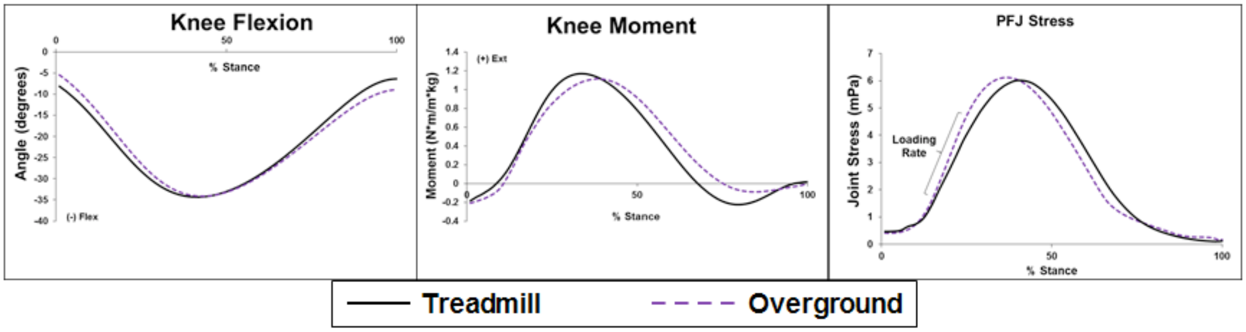

FIGURE 2. Time series data for group mean data for sagittal plane knee kinematics and kinetics and patellofemoral joint stress during treadmill and overground running. Abbreviations: mPA= megaPascals.

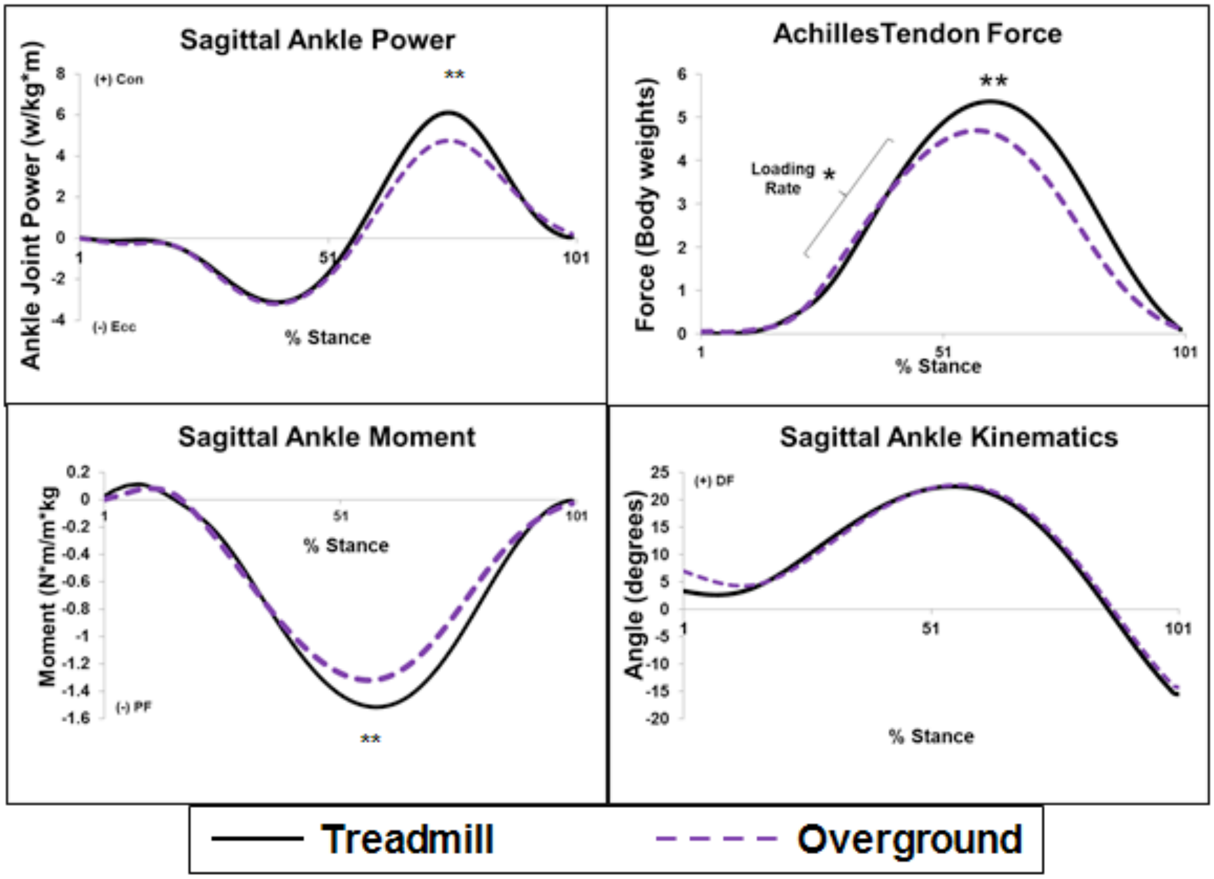

FIGURE 3. Time series data for group mean data for sagittal plane ankle kinematics and kinetics and Achilles tendon loading during treadmill and overground running. **Significant at p<0.005 . Abbreviations: mPA= megaPascals.

TABLE 1: Demographics for participants. Mean (SD).
Abbreviations: BMI= body mass index.

	Mean (SD), n=18
Age (years)	23.6 (3.5)
BMI (kg/m^2)	22.2 (2.6)
Running Volume (km/week)	36.7 (26.5)
Running experience (years)	7.4 (3.6)
Self-paced running velocity (m/s)	2.9 (0.3)
Treadmill comfort score (x/10)	9.6 (0.5)
Tegner Score (x/10)	6.9 (0.6)

TABLE 2. Group mean data (SD) during treadmill (TM) and overground (OG) running for temporospatial and knee measures. Abbreviations: m/sec= meters per second, m=meters, ms=milliseconds, BW= body weights, N= Newtons, PFJ= patellofemoral joint, mPA= megaPascals, Cumulative PFJ Stress 1km= estimated patellofemoral joint stress to run 1 kilometer continuously.

Discrete Variables	TM	OG	*p*	Effect Size	Pearson's *r*
Gait speed (m/sec)	2.88 (0.26)	2.89 (0.27)	*0.50*	*-0.04*	***0.97****
Step Length (m)	1.04 (0.10)	1.10 (0.12)	***<0.0001****	*-0.62*	***0.86****
Stance duration (ms)	273.1 (30.6)	277.3 (26.1)	*0.23*	*-0.15*	***0.88****
Peak Knee Flexion Angle (°)	-34.2 (3.5)	-34.3 (3.8)	*0.96*	*0.01*	***0.58****
Peak Knee Ext. Moment (N*m/m*Kg)	1.18 (0.20)	1.14 (0.27)	*0.28*	*0.19*	***0.77****
Peak PFJ reaction force (BW)	4.0 (1.0)	4.0 (0.8)	*0.99*	*0.00*	***0.81****
Peak PFJ Stress (mPA)	6.2 (1.4)	6.1 (1.5)	*0.73*	*0.04*	***0.86****
PFJ Stress Avg Loading Rate (mPA/sec)	131.5 (26.9)	155.6 (61.3)	*0.09*	*-0.55*	*0.17*
PFJ Stress Impulse (mPA*sec)	0.71(0.22)	0.71(0.16)	*0.84*	*-0.03*	***0.85****
Cumulative PFJ Stress 1km (mPA*sec/km)	344.5 (118.5)	324.7 (73.3)	*0.21*	*0.21*	***0.88****

* Significant at p<0.05
** Significant at p<0.005

TABLE 3. Group mean data (SD) during treadmill (TM) and overground (OG) running for ankle and Achilles tendon discrete variables. Abbreviations: °= degrees, m=meters, N= Newtons, BW= body weights, BW/km: Cumulative Achilles load in body weights to run 1 kilometer continuously, W= Watts.

Discrete Variables	TM	OG	t-test	Effect Size	Pearson's r
Peak Dorsiflexion Angle (°)	22.4 (3.0)	22.8 (3.0)	0.32	-0.15	0.81**
Peak Plantarflexor Moment (N*m/m*Kg)	-1.52(0.20)	-1.33(0.12)	0.001**	1.17	0.36
Peak Achilles Force (BW)	5.35 (0.782)	4.68 (0.533)	<0.001**	1.01	0.52*
Achilles Loading Rate (BW/sec)	65.1 (10.8)	54.7 (10.5)	<0.001**	0.61	0.62**
Achilles Impulse (BW*sec)	0.66(0.13)	0.59(0.08)	0.02*	0.63	0.53*
Cumulative Achilles Force (BW/km)	315.8 (44.4)	270.8 (41.8)	<0.001**	1.04	0.39
Eccentric Ankle Power (W/kg*m)	-3.15 (0.82)	-3.32 (0.67)	0.25	0.23	0.69**
Concentric Ankle Power (W/kg*m)	6.19 (1.54)	4.84 (0.75)	0.001**	1.18	0.69**

*Significant at p<0.05

**Significant at p<0.005