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Original research

Tibial acceleration and shock attenuation while running over different surfaces in a trail environment

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ABSTRACT

Objectives: Increased tibial axial acceleration and reduced shock attenuation are associated with running injuries and are believed to be influenced by surface type. Trail running has increased in popularity and is thought to have softer surface properties than paved surface, but it is unclear if trail surfaces influence tibial acceleration and shock attenuation. The purpose of this study was to investigate peak triaxial and resultant tibial acceleration as well as axial and resultant shock attenuation among dirt, gravel, and paved surfaces.
Design: Fifteen recreational runners (12 females, 3 males, age = 27.7 ± 9.1 years) ran over dirt, gravel, and paved surfaces in a trail environment while instrumented with triaxial tibial and head accelerometers.
Methods: Differences between tri-planar peak tibial accelerations (braking, propulsion, axial, medial, lateral, and resultant) and shock attenuations (axial and resultant) among surface types were assessed with one-way ANOVAs with Bonferroni post-hoc tests.
Results: No significant differences were found for tibial accelerations or shock attenuations among surface types ($p > 0.05$).
Conclusions: Dirt and gravel trail running surfaces do not have lower tibial accelerations or greater shock attenuation than paved surfaces. While runners are encouraged to enjoy the psychological benefits of trail running, trail surfaces do not appear to reduce loading forces associated with running-related injuries.

Practical Implications

- Tibial accelerations are not lower when running over dirt and gravel surfaces compared to paved surfaces.
- Shock attenuation is not greater when running over dirt and gravel surfaces compared to paved surfaces.
- Trail running surfaces like dirt and gravel do not appear to change loading forces commonly associated with running-related injuries compared to pavement.

1. Introduction

Running is a popular mode of physical activity; over 55 million Americans run regularly each year[1]. While running has numerous positive health benefits, running-related injuries (RRIs) are a prevalent risk of frequent running. The incidence of RRIs is between 19.4% to 79.3%[2], or 7.7 to 17.8 injuries per 1000 h of running exposure in novice and recreational runners[3]. With each step taken during running, there is a rapid deceleration of the body resulting in the transmission of a shock wave up the body from the ground; often measured by segment accelerations. It is believed that excessive magnitudes and prolonged exposure to these accelerations lead to an increased risk of sustaining an "overuse" RRI, particularly tibia stress fractures[4,5].

The measurement of accelerations using segment-mounted accelerometers is becoming increasing popular as a surrogate measure of loading forces and rates (the speed at which loading forces impact the body). Though limitations apply, evidence is available supporting the validity of segment-mounted accelerometer use for assessing surrogate loading forces during running by quantifying axial and resultant accelerations of the tibia[6,7]. Segment-mounted accelerometers also allow for the measurement of shock attenuation, or the process of dissipating loading forces. Shock attenuation quantifies the ability of body tissues to reduce forces between the foot and head[8] and is measured as the change in acceleration between segments[6]. A reduction in shock attenuation has

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previously been reported to increase the risk of sustaining an overuse injury[9]. These results suggest accelerometers may be useful equipment for monitoring load-related running patterns that have implications for RRIs.

Studies have begun to investigate how variables including running speed[10,11], fatigue[9,12], stride length[13], footwear[14], and running surface[10,16,18] influence tibial acceleration and shock attenuation; however, results have been contradictory and inconclusive. Specific to running surfaces, peak loading forces, as measured by force plates, were not different between asphalt, acrylic, and rubber-modified surface, but average loading rate was lower when running over the surface with the lowest mechanical stiffness (e.g. rubber-modified surface)[15]. Inconsistent results have also been reported when measuring tibial accelerations on different surfaces using segment-mounted accelerometers. Recent studies have reported no differences in tibial acceleration on surfaces with lower mechanical stiffness[10,16], while others reported lower tibial accelerations when running on “softer” surfaces[17,18].

Trail running, defined as unpaved running over variables surfaces[19,20], has increased in popularity over the last decade. Exercising in nature has been reported to improve mental well-being[21] and habitual trail runners demonstrate different running patterns compared to habitual road runners that are believed to reduce the risk of RRI[19]. Most previous work investigating the influence of surface type on running parameters were conducted in laboratory settings[16–18]. Recent studies have reported that tibial accelerations measured in a laboratory setting do not capture tibial accelerations that occur in the field[22,23]. To our knowledge, only one study investigated tibial accelerations on a trail surface in an outdoor setting, comparing concrete, synthetic running track, and woodchip trail surfaces; they reported no differences in tibial accelerations when running at a self-selected speed[10]. Trail running may more often expose runners to dirt and gravel surfaces, and investigation of these surfaces is absent in the current literature. Therefore, the aim of this study was to explore the differences in tibial accelerations and shock attenuations when running over dirt, gravel, and paved surfaces in a trail environment. It was hypothesised dirt and gravel would produce 1) lower tibial accelerations than running over a paved surface, 2) greater shock attenuation than running over a paved surface, and 3) no differences in tibial accelerations or shock attenuations between dirt and gravel running surfaces.

2. Methods

Seventeen recreational runners volunteered as participants for the study. All participants were free from injury at the time of testing and reported at least 30 min of continuous activity five days per week, with at least three days of weekly running, over the past three months. Participants were excluded if they had a history of any physical injury within the past six months that affected running performance. Approval for all procedures was obtained from the University's Institutional Review Board. All participants gave their written informed consent before commencing this study. Sample sizes were determined based on the predicted power to detect a difference of 15%, as reported by Milner et al[4].

The study was a repeated measures design where participants ran on three separate pathways of different surface types (dirt, gravel, paved) in the same nature environment at a single public park. The distances among all pathways were within 100 m. Participants ran in a standard shoe (Saucony Jazz; Saucony, Richmond, IN) and were instrumented with automatically synced, triaxial accelerometers (range = 24 g, weight = 0.028 kg; TeleMyo DTS 3D Accelerometer; Noraxon USA Inc., Scottsdale, AZ) over the skin on the forehead and right medial distal tibia per literature-established recommendations[7]. Two-sided adhesive tape and an elastic band

Fig. 1. Marked 50 m running pathway. The participant accelerated and decelerated in the first and last 10 m and maintained speed (±5% self-selected speed) in the middle 30 m.

secured the accelerometers. An adjustable belt was secured around the participant's waist and contained the accelerometer belt receiver.

Prior to data collection, participants completed a dynamic warm-up for three minutes[24] including skipping, high knees, walking quadriceps stretch, and toe and heel walking. Following the warm-up, participants completed three runs on the paved surface pathway. Cones were placed along the pathway at 0 m, 10 m, 40 m, and 50 m (Fig. 1). The first and last 10 m of the pathway allowed the participants a period to accelerate to self-selected speed and decelerate from self-selected speed and participants were asked to maintain speed in the middle 30 m of the pathway. To determine self-selected running speed, a user-operated stopwatch recorded the time it took to run the middle 30 m of the pathway. Average speed was calculated across the three trials to determine the participant's self-selected running speed.

After self-selected speed wad identified, participants ran over three pathways of different surface types in the following order: 1) dirt, 2) gravel, and 3) paved. Each pathway had an average slope of <10°. For each pathway, a 50 m pathway was marked with cones at 0 m, 10 m, 40 m, and 50 m (Fig. 1). A user-operated stopwatch recorded the time it took to run the middle 30 m of the pathway. Running speed was calculated following each trial and trials were repeated until four runs on each surface were ±5% of the participant's self-selected running speed. Trials with running speeds >5% different from the self-selected running speed were excluded from analysis. Participants completed all trial runs over one pathway before progressing to the subsequent pathway. Participants were granted a minimum of two minutes and up to five minutes to rest and walk to the next pathway.

Accelerometers sampled data at 1500 Hz. A custom MATLAB code (MathWorks, Inc.; Natick, MA) analysed the raw accelerometer data. Data were filtered with a band-pass (10–60 Hz), second-order Butterworth filter per recommendations[7]. While axial acceleration is most commonly reported, recent reports recommend assessing resultant acceleration[7,22]. As movement occurs throughout all three planes, isolating a single plane fails to consider movement in the other planes. Resultant acceleration alleviates this concern as it is a metric of tri-planar accelerations[7]. To account for positive and negative acceleration values in different axes when calculating resultant acceleration, anterior/posterior, axial, and medial/lateral accelerations were squared, and the vectors were added together[25]. Resultant tibial and head accelerations were then calculated by taking the square root of the summed vectors for the tibia and head, respectively. Initial foot contacts were identified as local minima that occurred in the 75 ms prior to a local maxima in resultant tibial acceleration profile (Fig. 2)[25]. To control for accelerating or decelerating during the run-up and slow-down segments of the pathway, the first and last five steps were excluded from analysis. Strides were identified from one initial foot contact to the next sequential initial foot contact. Stride rate (strides/minute) was calculated using the following equation:

$$Stride\ Rate = 60 \,/\, \frac{IC\,(i+1) - IC\,(i)}{sampling\ frequency}$$

Where IC(i) is the frame of the ith initial foot contact.

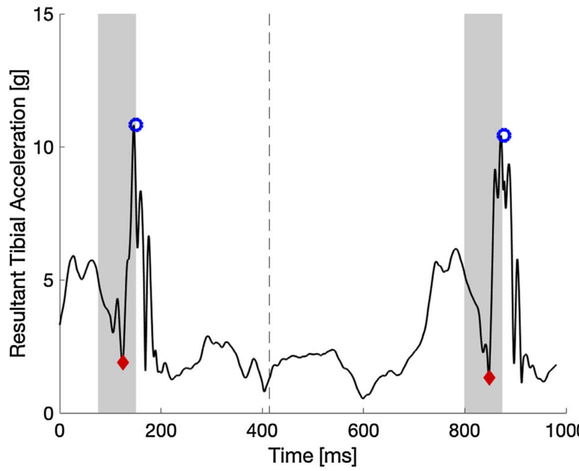

Fig. 2. Representative resultant tibial acceleration profile for one stride. Diamond = foot initial contact; Circle = peak tibial resultant acceleration; Grey area represents 75 ms window region prior to peak tibial resultant acceleration where local minima is identified for foot initial contact. Dashed line represents first 40% of stride (diamond to diamond).

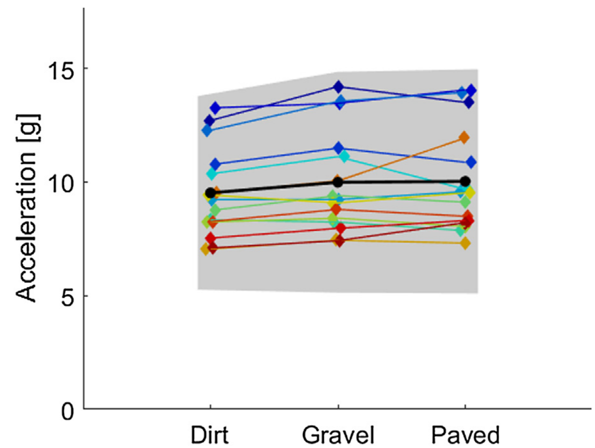

Fig. 3. Dot density plot of axial acceleration over dirt, gravel, and paved surfaces. Diamonds = individual participant; Circle = group mean; Grey region = 95% confidence interval.

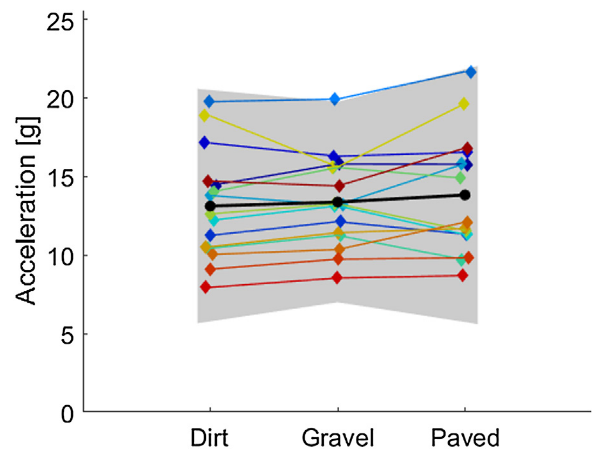

Fig. 4. Dot density plot of resultant acceleration over dirt, gravel, and paved surfaces. Diamonds = individual participant; Circle = group mean; Grey region = 95% confidence interval.

Within the first 40% of each stride, peak tibial braking (positive x-axis), propulsion (negative x-axis), axial (positive y-axis), medial (positive z-axis), lateral (negative z-axis), and resultant acceleration as well as peak head axial and resultant acceleration were extracted. Axial and resultant shock attenuation were calculated using previously described methods[6]. The greater the shock attenuation, the more the loading forces are dissipated by the body. For each participant, mean peak accelerations and shock attenuations were calculated for each variable of interest.

One-way ANOVAs were performed in SPSS (version 26, IBM Crop.; Armonk, NY) to compare average number of strides analysed, stride rate, peak tibial braking, propulsion, axial, medial, lateral, and resultant acceleration as well as axial and resultant shock attenuation among the three surface types. A Bonferroni correction post-hoc test was used for multiple comparison if ANOVA results demonstrated a statistically significant difference. For all tests, significance was set at $p \le 0.05$.

3. Results

Two male participants were removed from analysis due to data collection errors leaving a total of 15 participants included in analysis (female = 12, male = 3, age = 27.7 ± 9.1 years, height = 1.65 ± 0.06 m, mass = 65.9 ± 13.1 kg). No significant differences were found between the average number of strides analysed for each running surface (dirt = 29.9 ± 12.2; gravel = 30.3 ± 11.9; paved = 30.5 ± 8.5; p=0.99). No significant differences (Table 1) were found among running surfaces for stride rate (p = 0.83), peak tibial braking acceleration (p = 0.89), peak tibial propulsion acceleration (p = 0.91), peak tibial axial acceleration (p = 0.78; Fig. 3), peak tibial medial acceleration (p = 0.95), peak tibial lateral acceleration (p = 0.85), peak tibial resultant acceleration (p = 0.85; Fig. 4), axial shock attenuation (p = 0.87), or resultant shock attenuation (p = 0.90).

4. Discussion

The current study analysed tibial acceleration and shock attenuation during running over dirt, gravel, and paved surfaces in a trail environment. It was hypothesised that dirt and gravel would produce 1) lower tibial accelerations than running over a paved surface,

Table 1
Stride rate, tibial acceleration, and shock attenuation across running surfaces (mean ± SD).

Variable	Dirt	Gravel	Paved	ES	p-value
Stride Rate (strides/min)	87.0 ± 5.8	87.4 ± 5.3	88.3 ± 5.7	0.01	0.83
Peak Tibial Braking Acceleration (g)	9.1 ± 3.5	9.0 ± 3.1	9.6 ± 3.8	0.01	0.89
Peak Tibial Propulsion Acceleration (g)	6.6 ± 3.7	6.5 ± 3.2	7.1 ± 4.4	<0.01	0.91
Peak Tibial Axial Acceleration (g)	9.5 ± 2.0	10.0 ± 2.3	10.0 ± 2.3	0.01	0.78
Peak Tibial Medial Acceleration (g)	5.4 ± 2.8	5.4 ± 2.4	5.7 ± 3.2	<0.01	0.95
Peak Tibial Lateral Acceleration (g)	3.9 ± 2.0	3.8 ± 1.8	4.2 ± 2.2	0.01	0.85
Peak Tibial Resultant Acceleration (g)	13.1 ± 3.4	13.4 ± 3.0	13.8 ± 3.8	0.01	0.85
Axial Attenuation (%)	67.8 ± 5.8	68.8 ± 5.7	68.7 ± 6.4	0.01	0.87
Resultant Attenuation (%)	74.8 ± 6.1	75.5 ± 4.8	75.7 ± 6.1	<0.01	0.90

ES = effect size, Significant differences $p \le 0.05$.

2) greater shock attenuation than running over a paved surface, and 3) no differences in tibial accelerations or shock attenuations between dirt and gravel surfaces. The first and second hypotheses were not supported while the third hypothesis was supported as no differences were found among peak tibial braking acceleration, peak tibial propulsion acceleration, peak tibial axial acceleration, peak tibial medial acceleration, peak tibial lateral acceleration, peak tibial resultant acceleration, axial shock attenuation, or resultant shock attenuation.

Our results agree with previous studies that reported no differences in peak tibial axial acceleration when running over concrete, synthetic running track, grass or woodchip trails when running at a self-selected speed[10,16]. However, when running speed was controlled, peak tibial axial acceleration was lower when running over woodchip trails compared to concrete and synthetic track[10]. Tibial axial acceleration is positively correlated with increased running speed[26]. In the previous study[10], the controlled speed was slower than the average self-selected speed, which may have influenced the lower peak tibial axial acceleration. Our findings indicate that running on dirt or gravel surfaces does not lower tibial axial acceleration, a measure associated with RRIs[4], when running at a self-selected speed; however, it is unknown how running speed influences tibial axial acceleration when running over these surfaces compared to pavement.

No significant differences were found across surfaces for peak tibial resultant acceleration. Resultant accelerations limit the influence of accelerometer alignment and considers loading forces from all three axes[7]. A previous study comparing rearfoot and non-rearfoot strike runners found no differences in peak tibial axial acceleration but greater peak tibial anterior-posterior acceleration and peak tibial resultant acceleration in non-rearfoot strikers highlighting the importance of analysing multiplanar, resultant accelerations[27]. To our knowledge, our study is the first study to investigate tibial braking, propulsion, medial, and lateral accelerations during dirt and gravel running. As running surface did not influence these accelerations, foot strike patterns have more influence on non-axial tibial accelerations than surface stiffness. Further research is warranted to determine if non-axial tibial accelerations on various surfaces are different among runners with different foot strike patterns.

Shock attenuation measures the body's ability to dissipate impact forces[8]. Results from the current study demonstrated no differences in axial or resultant shock attenuation among paved, gravel, and dirt surfaces. Runners adjust leg stiffness dependent on running surface stiffness in order to maintain the same effective vertical stiffness and centre of mass vertical displacement[28]. While not measured in the current study, a change in leg stiffness may explain lack of differences in shock attenuation when running over different surface types. To our knowledge, this is the first study to report resultant shock attenuation during running on dirt and gravel surfaces. Similar to resultant acceleration, it is likely resultant shock attenuation is a more appropriate method to quantify shock attenuation since accelerations are not constrained to one axis. Reduced shock attenuation has been measured during fatigued treadmill running[9] and likely contributes to increased risk of injury[29]. However, it is unknown how fatigue may influence shock attenuation during prolonged trail running. Future investigation is warranted to determine if shock attenuation during trail running is influenced similarly or differently than shock attenuation during treadmill running. Interestingly, approximately 70% of the axial shock were attenuated while close to 90% of the resultant shock were attenuated, regardless of surface type. This finding suggests runners are more proficient at attenuating non-axial accelerations. Further research is warranted to understand the importance of non-axial shock attenuation, especially as it relates to RRIs.

The results of this study should be interpreted in the context of its limitations. The power analysis was reported from a study that only included female runners and minimal sample sizes ranged from 9 to 20 participants. It is possible the study may be underpowered with data from only 15 participants included in analyses. However, we are confident in the results as all ANOVA comparison p-values were far from statistical significance set at $p \leq 0.05$ and demonstrated small effect sizes ($\leq$0.01). All running trials were screened in real time with a user-operated stopwatch to ensure the participant was ±5% of his or her predetermined self-selected running speed. However, due to a collection error, the speed of each trial was not recorded and therefore we are unable to report on the average running speed for each surface condition. Stride rates were found to be consistent among surface conditions suggesting running speed was maintained. While the potential source of user-error from manually operating the stopwatch and collection error recording the time of each trial are limitations, the consistency in stride rates among the conditions in the current study allows us to be confident in the validity of the results. It is also unclear if the 10 m region at the start of the pathway allowed runners enough time to achieve typical running patterns; however, by eliminating the first and last five strides from analysis, we are confident participants achieved consistent running speed for the analysed strides. The order of surface running was not randomized. However, as participants ran in a non-fatigued state and were allowed rest breaks between surfaces, we are confident accelerations and shock attenuations were not influenced by fatigue. The standard shoe used for the study was not designed for trail running. It is possible trail running shoes may influence tibial accelerations and shock attenuations and this warrants further investigation. The mechanical stiffness of the surfaces was not measured. It is possible the dirt and gravel surfaces had similar stiffnesses compared to the paved surface which could explain the lack of differences among surface types.

This study may not fully capture the natural environment of trail running due to the variability of trail running terrain. In some regions, trail running is often characterized by uneven terrain with frequent changes in elevation. The pathways participants ran over in the current study were relatively level (<10°). While tibial accelerations were not found to change during a prolonged trail run[30], perhaps cumulative tibial accelerations experienced by a runner are different during prolonged runs in a trail environment where runners experience a variety of elevation changes compared to runs on roads and sidewalks. The primary purpose of this study was to compare running surface types in a trail environment. This study highlights trail running surfaces of similar elevation profiles do not appear to influence loading forces. Further work remains necessary to better understand how loading forces over trail surfaces may be influenced by additional variables such as duration of run, fatigue, and elevation change.

5. Conclusion

Triaxial tibial accelerations, resultant tibial acceleration, axial shock attenuation, and resultant shock attenuation are not different among dirt, gravel and paved surfaces during running in a trail environment. While runners are encouraged to enjoy the psychological benefits of trail running, trail surfaces do not appear to reduce loading forces associated with RRIs.

Ethical compliance

All procedures performed in studies involving human participants were in accordance with the ethical standards of Carroll University Institutional Review Board (IRB#: 16–024) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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