Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry

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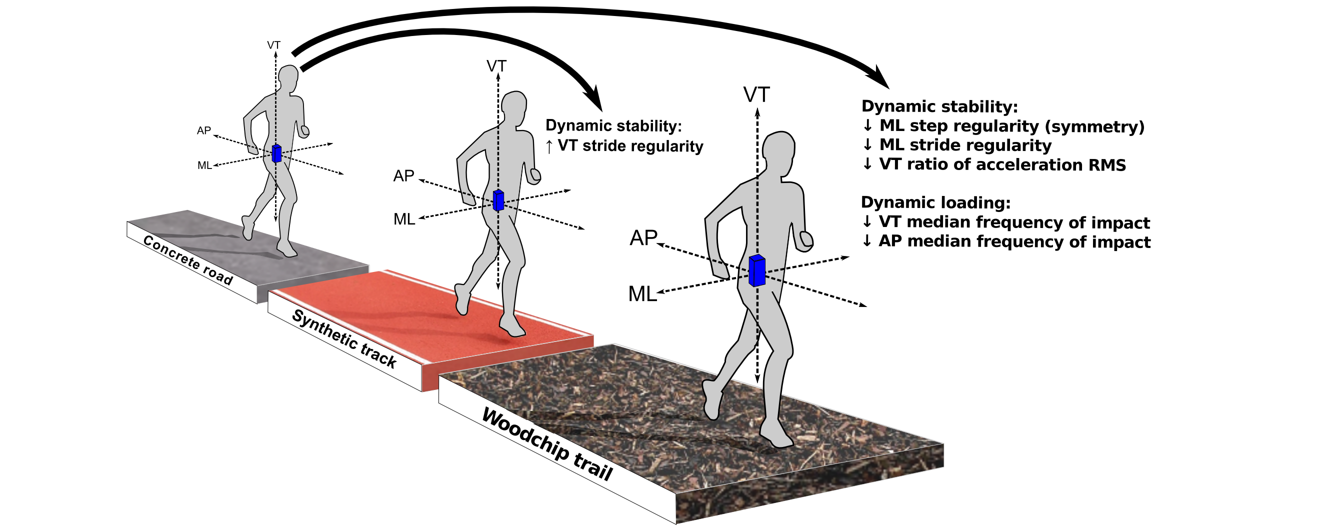

VT
AP
ML
Concrete road
VT
AP
ML
Dynamic stability:
↑ VT stride regularity
Synthetic track
VT
AP
ML
Dynamic stability:
↓ ML step regularity (symmetry)
↓ ML stride regularity
↓ VT ratio of acceleration RMS
Dynamic loading:
↓ VT median frequency of impact
↓ AP median frequency of impact
Woodchip trail

ABSTRACT

Despite frequently declared benefits of using wireless accelerometers to assess running gait in real-world settings, available research is limited. The purpose of this study was to investigate outdoor surface effects on dynamic stability and dynamic loading during running using tri-axial trunk accelerometry. Twenty eight runners (11 highly-trained, 17 recreational) performed outdoor running on three outdoor training surfaces (concrete road, synthetic track and woodchip trail) at self-selected comfortable running speeds. Dynamic postural stability (tri-axial acceleration root mean square (RMS) ratio, step and stride regularity, sample entropy), dynamic loading (impact and breaking peak amplitudes and median frequencies), as well as spatio-temporal running gait measures (step frequency, stance time) were derived from trunk accelerations sampled at 1024 Hz. Results from generalized estimating equations (GEE) analysis showed that compared to concrete road, woodchip trail had several significant effects on dynamic stability (higher AP ratio of acceleration RMS, lower ML inter-step and inter-stride regularity), on dynamic loading (downward shift in vertical and AP median frequency) , and reduced step frequency ($p < 0.05$). Surface effects were unaffected when both running level and running speed were added as potential confounders. Results suggest that woodchip trails disrupt aspects of dynamic stability and loading that are detectable using a single trunk accelerometer. These results provide further insight into how runners adapt their locomotor biomechanics on outdoor surfaces *in situ*.

Keywords: Running gait, running surface; trunk accelerometer; dynamic stability; dynamic loading.

Introduction

Worldwide millions of people participate in recreational and competitive running. It is an easily accessible sport with numerous proven health benefits. However, repetitive collisions with the ground also make running a sport with a high incidence of chronic overload injuries [1]. Dynamic loading related variables such as higher vertical loading rates [2] or peak tibial accelerations [3] have been prospectively associated with lower-limb overuse running injuries such as stress fractures. It is commonly believed that these dynamic loads and subsequently overuse injury risk is exacerbated on harder surfaces such as concrete or asphalt. However, epidemiological research has thus far failed to find any relationship between surface hardness and injury, possibly due to difficulty in accurately quantifying time and intensity on typical running surfaces [4]. Identifying how dynamic loads are moderated on typical running surfaces could therefore add insights into appropriate preventative strategies for overuse running injury.

Laboratory studies have shown that small alterations in running surface can induce changes in human running mechanics. For example, it is known that softer [5–7] or uneven [8,9] running surfaces cause runners' to rapidly increase their leg stiffness, while peak ground reaction forces are mostly moderated with a stable centre of mass (CoM) trajectory [5–7]. Although, Dixon et al., [10] reported individual specific adaptations in knee kinematics between asphalt and a softer rubber-modified surface, they [10] also observed an overall reduction in vertical loading rates when switching to the softer surface. While these aforementioned studies provide essential insights, the mechanisms for moderating are perhaps not directly applicable to "real-world" running surfaces that naturally vary in composites of hardness, evenness, and gradient.

In attempt to secure ecological validity, some researchers have investigated how runners adapt their loading and mechanics to typical outdoor running surfaces. Using cinematography, Creagh et al., [11] found that running in long grass decreased step lengths while increased hip vertical displacement, knee lift and peak upper leg angles compared to running on tarmac. Others who have used portable wearable devices such as in-shoe plantar pressure measurements or tibial accelerometry have found conflicting results. For example, Tessutti et al., [12] reported higher central and lateral peak plantar pressures along with shorter contact times when running on asphalt compared to natural grass. In contrast, no differences in peak plantar pressure [13], impulse [14] , tibial shock [13] or contact times [13,14] have been found between concrete, grass, or synthetic track. Discrepancies in findings could be attributed to large inter-individual responses [10]. It appears that there is a need for a better understanding of how runners moderate their loading and gait in response to “real-world” surfaces.

Measures derived from wireless tri-axial trunk accelerometers have become a popular approach to reliably and unobtrusively capture dynamic loading and CoM stability in various environments. The acceleration root mean square (RMS) as well as the autocorrelation-based coefficients referred to as inter-step and inter-stride regularity have identified a wide variety of impaired or asymmetrical stability patterns related to ageing [15], lower limb prosthesis [16], hemiplegia [17], and gross motor function [18]. When applied to running gait, these measures can detect compensations in dynamic stability due to fatigue [19,20], predict oxygen consumption [21], and classify athletes based on their training background [22]. The current paper includes stability and impact frequency components of running gait, which may be more sensitive to changes in surface relative to other measures i.e. spatio-temporal or impact peaks. However, these accelerometer measures have usually been investigated on a single running surface, thus limiting multi-terrain generalizability.

Woodchip trails are becoming popular running surfaces that are specifically constructed to have “structural dampening” to reduce impact-loading related injuries and enhance participation of recreational running. Indeed, animal studies suggest that woodchip surfaces have injury preventative properties. For example, adult sheep that were exposed to prolonged activities on woodchips were less prone to development of knee osteoarthritis compared to sheep exposed to activities on hard concrete [23]. In addition, hoof impact accelerations were significantly more dampened when horses trotted at ~4 $m \cdot s^{-1}$ on woodchip surface compared to asphalt [24].

Unfortunately, previous research on human running has primarily focused on other outdoor surfaces such as grass [11–14], with no apparent evidence on woodchip trails. The purpose of this study was to investigate outdoor surface effects on dynamic stability and loading during running using tri-axial trunk accelerometry. Based on previous laboratory research indicating smoothness of CoM trajectory under different surface conditions, we hypothesized that trunk accelerometry measures of dynamic stability and loading would be minimally affected by running surface.

Methods

Participants

Two predetermined age-matched groups of endurance runners aged 18 to 33 years of mixed gender (# women 14, 50 %) were recruited for this study; highly-trained runners (mileage > 50 km·week^{-1}, n = 13) and recreational runners (mileage < 30 km·week^{-1}, n = 17). All participants were screened to have no history of lower extremity injury within the past three months. Written informed consent was received from all runners prior to participation in accordance with the Declaration of Helsinki. The study was approved by the local ethics committee (Commissie Medische Ethiek KU Leuven).

Experimental protocol

All runners (n = 17 recreational; n = 13 highly-trained) performed a standardized warm-up. Outdoor running was performed on 90m of straight and flat concrete road, synthetic track, and woodchip trail. Photo electronic timing gates (RaceTime 2 system, Microgate, Bolzano, Italy) were positioned to capture average running speed from the 10m to 70m mark. A practice trial was provided to familiarize participants to each surface. The self-selected running speed on concrete was used as control speed on the other surfaces, and trials on subsequent running surfaces were discarded if the running speed differed by ± 1 m·s^{-1} of control speed. The order of the other two surfaces was randomized. To avoid any fatigue effect runners were allowed to rest during five minutes between each surface.

Accelerometry measurements

Tri-axial accelerometry (X50-2 wireless accelerometer, range ± 50g, sampling at 1024 Hz, 0.016g/count resolution, 33g weight, Gulf Coast Data Concepts, MS, USA) was acquired during each running trial. The accelerometer was securely positioned over L3 spinous process of the trunk [25], and directly mounted to the skin using double sided tape and adhesive spray. Accelerometer position was unaltered between all running trials and was routinely checked between running trials for security. Trials were discarded in the case the investigators deemed the accelerometer to be not securely fastened upon its removal (after data collection).

All signal processing of acceleration curves was performed using customized software in MATLAB version 8.3 (The Mathworks Inc., Natick, MA, USA). Accelerometry-derived parameters were computed from the middle ten consecutive strides of the 10-70m measurement zone, that were first trigonometrically tilt-corrected and filtered using a zero-lag 4^{th} order low-pass Butterworth filter (cut-off frequency 50 Hz) [20,25]. Accelerometry-derived parameters were averaged over two running trials per surface per participant.

Outcome measures

Spatio-temporal parameters were quantified by step frequency and stance time. The former was acquired using the time lag of the first dominant peak of the vertical acceleration's unbiased autocorrelation [20,25]. The latter was acquired based on the heuristic that as long as the body is accelerating upwards, the foot should still be in contact with the ground [26]. Therefore, zero crossings of vertical accelerations identified periods where the vertical acceleration was positive and accelerating upwards (initial contact to final contact) [26].

Dynamic postural stability parameters were quantified from tri-axial (vertical, ML, AP) accelerations firstly using the ratio of each linear acceleration axis root mean square (RMS) relative to the resultant vector RMS to capture variability [21]; secondly using step and stride regularity (unbiased autocorrelations procedure) to capture symmetry and consistency of running steps and strides respectively, with perfect regularity equivalent to one [25]; and thirdly using sample entropy from raw accelerations to capture the waveform predictability, with higher values indicating less periodicity or more unpredictability [27]. Detailed procedures and algorithm inputs for the computation and extraction of these dynamic postural stability parameters are explained previously [20].

Dynamic loading parameters during stance were computed from extracted stance phases firstly in the time domain and secondly in the frequency domain. The former was acquired by extracting the peak positive vertical (impact) and peak negative anteroposterior (breaking) accelerations identified between 1% and 20% stance. The latter was acquired from the median frequency of vertical and AP accelerations of the entire stance phase calculated as the centroid of the power spectral density (PSD) curves within the 1 – 100 Hz range [28]. PSD was calculated from the Fast Fourier Transform (FFT) of unfiltered vertical stance phase accelerations from 0 to the Nyquist (F_N) frequency, that were first processed in line with previous methods [29]: detrended, padded with zeros to equal 2048 data points (ensuring 2^n periodicity), and interpolated to 1 Hz bins.

Statistical analysis

Group descriptive characteristics were compared using independent t-tests. Each accelerometry-derived parameter was individually evaluated for normality; skewness between >-1 and <1 was accepted. Subsequently, normally distributed data was analyzed by means of linear regression using generalized estimating equations (GEE). GEE analysis is more sophisticated than linear regression because it takes into account that measures within one subject are correlated with repeated observations. An exchangeable correlation structure was used for the GEE analysis in this study since it fit the data well (high within-subject correlations) and for simplicity to minimize the number of parameters needed. The effect of surface type on accelerometry-derived parameters was evaluated in three models: Firstly an unadjusted model, the effect of surface type (woodchips and synthetic) compared to concrete (control reference category) on each accelerometry outcome measure. Secondly, we assessed if training status (highly-trained vs. recreational) was a confounding variable to the model, since trunk accelerometry parameters have been found to significantly differ between trained and untrained runners [21]. From this step, training status was only included in the model if it significantly changed any of the regression coefficients for surface type (>10%). Thirdly, we assessed the potential role of running speed as a confounder to surface type by adding it as a time-dependent continuous covariate, since some trunk accelerometry parameters show strong relationships with gait speed during running [21].

Results

Two subjects from the group of competitive runners were excluded from analysis since the investigator deemed the attachment of their accelerometer to not be securely fasted upon removal, and body sweat interfered with attempts at reattachment. Characteristics of the remaining participants are shown in **Table 1**.

GEE results of the crude analysis for surface effects on accelerometry-derived parameters are shown in **Fig. 1**. Synthetic track did not significantly change from concrete besides one dynamic stability parameter (higher vertical stride regularity). Woodchip trail changed significantly from concrete for several parameters, including spatio-temporal (lower step frequency), dynamic stability (lower vertical but higher AP ratio of acceleration RMS, and lower step regularity and stride regularity in the ML direction only) and dynamic loading (lower vertical and AP median frequencies). The downward shift in vertical and AP median frequencies during stance from concrete to woodchips can be observed in **Fig. 2**, overlaid with plots of trunk acceleration signals during stance in the frequency domain.

When either training status (model two) or running speed (model three) were added as potential confounders, statistical outcomes related to surface effects were unchanged. Therefore all results pooled trained and untrained runners together (n = 28) and results from the crude analysis on surface effects were reported (**Table 2**).

Discussion

Despite the frequently cited benefits of using wireless accelerometers to asses running gait in ecological (i.e. real-world) rather than traditional (i.e. laboratory) settings, few studies have actually done so. Therefore, this study sought to investigate outdoor surface effects on dynamic stability and loading during running using tri-axial trunk accelerometry. Importantly, were that there were no significant ($p > 0.05$) differences in all parameters with exception to vertical stride regularity between concrete and synthetic track. In contrast, woodchip trail altered measures of dynamic stability compared to concrete; revealing significantly higher AP ratio of acceleration RMS as well as lower ML inter-step and -stride regularity. Woodchip trail additionally decreased median frequencies of both vertical (impact) and AP (breaking) accelerations compared to concrete. In light of these results, it is reasonable to hypothesize that differences may exist in injury risk and performance between concrete and woodchip running surfaces.

In agreement with previous research [5,13,14], we found that contact time was unaffected by running surface. On the other hand, we did find significantly reduced step frequencies on woodchips. Thus, our hypothesis based on the principle of smoothness of CoM trajectory under different surface conditions [5] , active "self-stabilization" [8,9] or maintenance of global support kinematics over different terrain [5,6] was not completely supported. From a biomechanical perspective, woodchip trails differ fundamentally from concrete road and synthetic track due to the presence of variously sized detached or scattered particles. Both compression and displacement of the woodchips under the foot may then occur with each consecutive running stride, causing dynamic instability and forcing lower-limb musculature to provide additional work to the point of reaction force on the surface [26]. Therefore, the irregular nature of woodchips could have interfered with the step length-step frequency relationship, as has previously been observed when running on irregular [30] or rough [11] terrain.

The directional-shift in variation (ratio of acceleration RMS) from vertical to AP as well as the decrease in inter-step and inter-stride regularity mediolaterally could indeed also be directly related to the woodchip properties. This is consistent with past research, which has shown similar destabilizations and directional shift from vertical to horizontal accelerations when walking on uneven ground [31]. Thus, the runner's dynamic stability may be compromised as a result of the irregularity of the uneven woodchips. Based on previous research in our laboratory [20], running-related fatigue on an indoor treadmill results in a 13% increase in the AP ratio of acceleration RMS. The runners in this study showed a 7% increase in the AP ratio of acceleration RMS from concrete to woodchip surface. Thus, although both internal (fatigue) and external (surface) factors contribute to destabilizing the stability of running, the magnitude of changes due to running surface appear to be relatively smaller. It would be interesting to examine the destabilizing running-related fatigue effects on a range of running surfaces, including woodchips, since energy expenditure is increased when running on uneven terrain [8]. This could provide insight into weather uneven surfaces such as woodchips are more detrimental to a runner's stability when in a fatigued state.

Dynamic loading parameters were analyzed to provide information on magnitude and proportion of propagated shock waves reaching the spine. We found no significant surface effects for the amplitudes of vertical impact shock or AP breaking peak in the time domain. It is possible that the amplitude of impact shock accelerations reaching the spine were unaffected due to initial impact attenuations by the lower extremity, acting as a low-pass filter [32]. However, we also analyzed the frequency content of impact shock waves to gain better insights in the distribution of the power content of impact, and observed a significant downward shift in the median frequencies of vertical impact and AP breaking accelerations on woodchips. Visual inspection of the frequency curves in **Figure 2** indicates that on woodchips a larger proportion of both vertical and AP accelerations during stance were contained in the low frequency component (4-8 Hz), while the proportion in the high frequency "impact" component (10-20 Hz) appeared relatively unaltered. These results suggest that during stance a greater proportion of accelerations may be needed for voluntary movements [29] and stability of the CoM on woodchips, rather than any additional "structural dampening" provided as has anecdotally been suggested.

Although we observed no confounding influence of training status, it is reasonable to argue that maintaining dynamic stability could be more difficult for recreational compared to highly trained runners [21]. Unfortunately, effect modification i.e. surface type x group interaction was not directly investigated here due to low sample size and is a limitation of the current study. Secondly, given that competitive runners were more familiar with synthetic track while recreational runners were more familiar with wood chip trail, another limitation worth mentioning is that surface habituation was unaccounted for. However, all participants had at least some experience with running on all three surfaces and familiarization trials were provided for each running surface to help minimize any immediate psychological adjustments.

We found that all surface effects were unaffected when running speed was added to the GEE model as a covariate. The need to control for running speed was warranted given that previous research has indicated that adjustments in running mechanics can often be explained by variable running speed [21], presenting a major analytical problem. Additionally, running speed in itself may be an adjustment to outdoor surfaces, even when pacing methods are enforced [11]. In contrast, our in-field and statistical approach to deal with running speed as a potential confounder enabled our runners to self-select speeds that were comfortable to them, with arguably more real-world applicability.

Conclusion

The current results suggest that woodchip trails alter running mechanics by disrupting aspects of dynamic stability and loading. The analysis presented here provides further insights into running gait adaptions in typical, real-world settings.

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Conflict of Interest Statement

No conflicts of interest exist.

Table 1. Descriptive results of participant characteristics.

	Mean (SD)
n	28
Male (female)	14 (14)
Age (years) (SD)	22.62 (3.07)
Height (m) (SD)	1.76 (6.24)
Weight (kg) (SD)	63.05 (5.57)
Training volume (km·week^{-1}) (SD)	41.22 (9.91)
Recreational (n = 17)	9.56 (11.88)*
Highly-trained (n = 11)	72.88 (7.94)
Concrete road running speed (m·s^{-1}) (SD)†	3.79 (0.51)
Recreational (n = 17)	3.56 (0.44)*
Highly-trained (n = 11)	4.02 (0.58)
Synthetic track running speed (m·s^{-1}) (SD)†	3.73 (0.45)
Recreational (n = 17)	3.54 (0.42)*
Highly-trained (n = 11)	3.92 (0.48)
Woodchip trail running speed (m·s^{-1}) (SD)†	3.73 (0.45)
Recreational (n = 17)	3.47 (0.23)*
Highly-trained (n = 11)	3.99 (0.51)

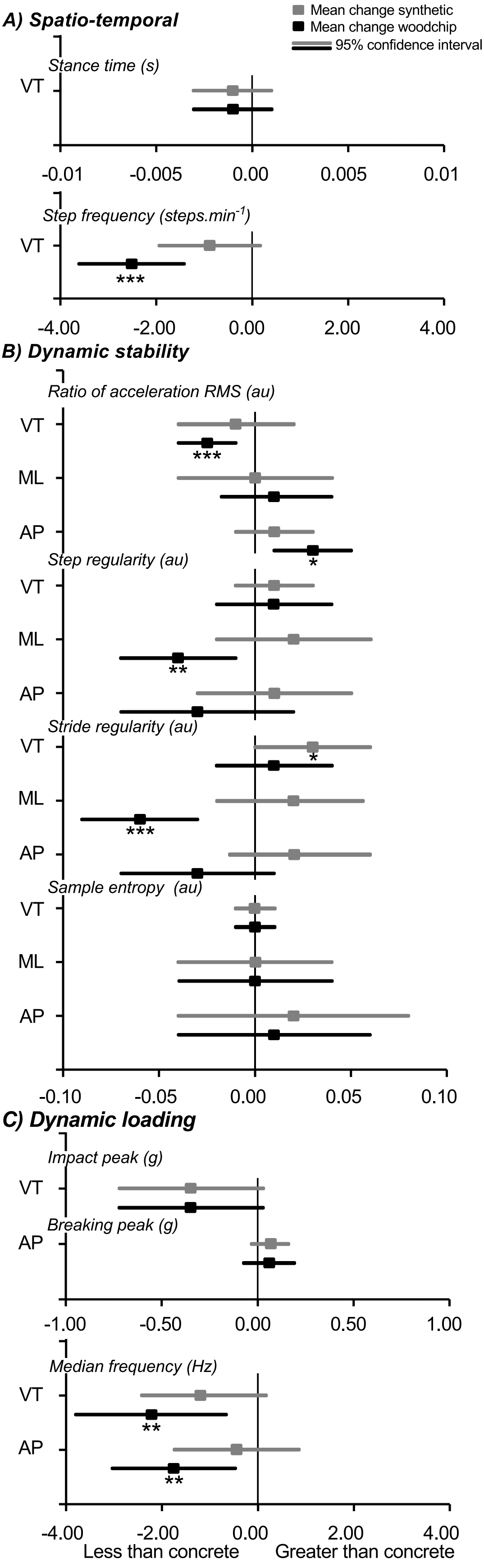
†: based on self-selected speeds acquired from timing gates

*: t-test detected significantly different from highly-trained group ($p < 0.05$).

Table 2. Descriptive results (mean; SD) of accelerometry-derived parameters for repeated measures (n = 28).

Running gait parameter	**Axis**	Concrete road	Synthetic track	Woodchip trail
Spatio-temporal				
Step frequency (steps.min^{-1})	VT	169.75 (7.73)	169.03 (8.75)	167.4 (7.31)
Stance time (s)	VT	0.22 (0.02)	0.22 (0.02)	0.22 (0.02)
Dynamic stability				
Ratio of acceleration RMS (a.u)	VT	1.10 (0.08)	1.09 (0.07)	1.07 (0.07)
	ML	0.47 (0.11)	0.48 (0.11)	0.49 (0.11)
	AP	0.42 (0.10)	0.43 (0.10)	0.45 (0.09)
Step regularity (a.u)	VT	0.8 (0.09)	0.82 (0.08)	0.81 (0.08)
	ML	0.55 (0.13)	0.57 (0.12)	0.51 (0.12)
	AP	0.58 (0.12)	0.59 (0.13)	0.55 (0.11)
Stride regularity (a.u)	VT	0.81 (0.09)	0.84 (0.06)	0.82 (0.08)
	ML	0.69 (0.12)	0.70 (0.09)	0.64 (0.10)
	AP	0.65 (0.12)	0.67 (0.13)	0.63 (0.12)
Sample entropy (a.u)	VT	0.12 (0.02)	0.12 (0.02)	0.12 (0.02)
	ML	0.32 (0.07)	0.32 (0.07)	0.32 (0.07)
	AP	0.37 (0.10)	0.38 (0.11)	0.38 (0.11)
Dynamic loading				
Impact peak (g)	VT	4.02 (1.54)	3.91 (1.39)	3.67 (1.40)
Breaking peak (g)	AP	1.77 (0.60)	1.85 (0.70)	1.84 (0.66)
Median frequency during stance (Hz)	VT	16.19 (5.90)	14.82 (5.29)	13.90 (4.14)
	AP	15.55 (5.34)	14.99 (5.17)	13.72 (5.04)

VT: vertical; ML: mediolateral; AP: anteroposterior; a.u: arbitrary units



A) Spatio-temporal
Mean change synthetic
Mean change woodchip
95% confidence interval
Stance time (s)
VT
-0.01
-0.005
0.00
0.005
0.01
Step frequency (steps.min-1)
VT
***
-4.00
-2.00
0.00
2.00
4.00
B) Dynamic stability
Ratio of acceleration RMS (au)
VT
***
ML
AP
*
Step regularity (au)
VT
ML
**
AP
Stride regularity (au)
VT
*
ML
***
AP
Sample entropy (au)
VT
ML
AP
-0.10
-0.05
0.00
0.05
0.10
C) Dynamic loading
Impact peak (g)
VT
Breaking peak (g)
AP
-1.00
-0.50
0.00
0.50
1.00
Median frequency (Hz)
VT
**
AP
**
-4.00
-2.00
0.00
2.00
4.00
Less than concrete
Greater than concrete

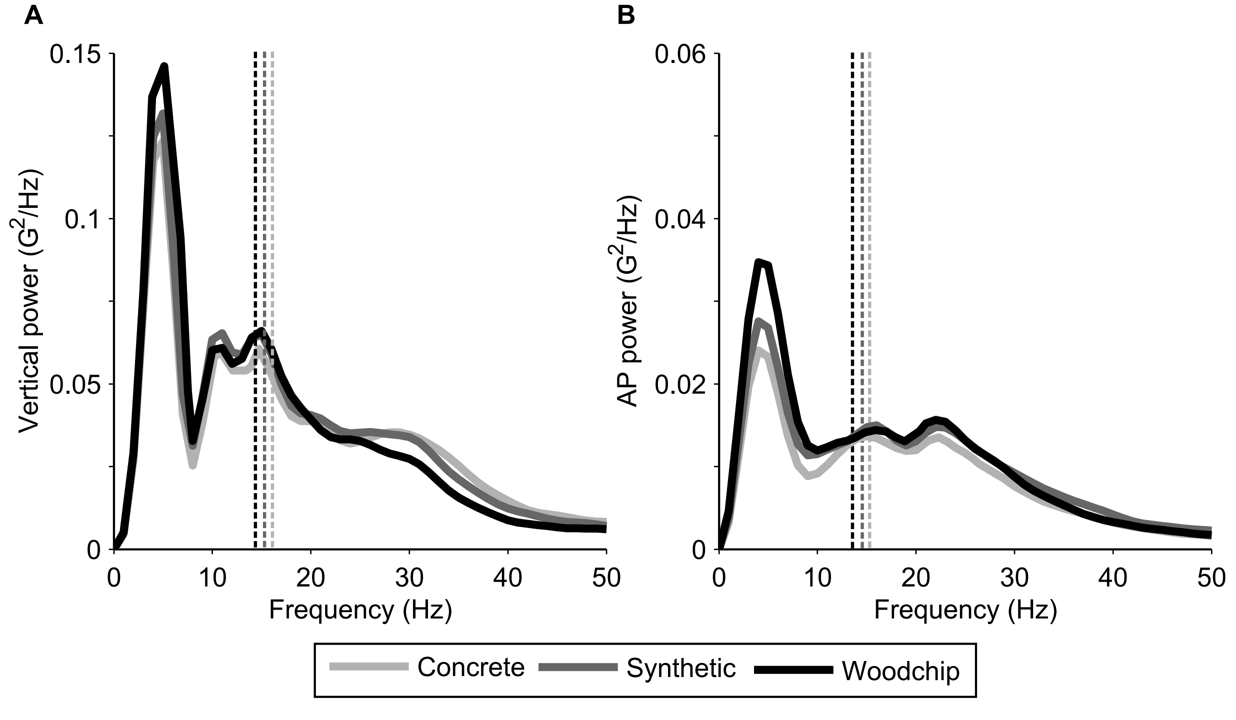

A
B
Vertical power (G2/Hz)
0.15
0.1
0.05
0
0
10
20
30
40
50
Frequency (Hz)
AP power (G2/Hz)
0.06
0.04
0.02
0
0
10
20
30
40
50
Frequency (Hz)
Concrete
Synthetic
Woodchip

Fig. 1. Regression coefficients (95% confidence intervals) regarding GEE results for surface effects on accelerometry-derived parameters for repeated measures ($n = 28$). VT: vertical; ML: mediolateral; AP: anteroposterior; a.u: arbitrary units**.** */**/*** Regression coefficient significantly different from reference category concrete road surface ($p < 0.05$)/ ($p < 0.01$)/ ($p < 0.001$).

Fig. 2. Group mean ($n = 28$) power spectra of A) vertical and B) AP trunk acceleration signals compared between concrete (light grey), synthetic track (dark grey), and woodchips (black). Vertical dashed lines indicate the median frequency for each surface respectively.