Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

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JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2020.1824340

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SPORTS MEDICINE AND BIOMECHANICS

Fatigue-related changes in vertical impact properties during normal and silent running

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ABSTRACT
Running while minimizing sound volume can reduce vertical impact loading, potentially reducing injury risks. Fatigue can increase the vertical loading rate during running, but it is unknown whether fatigue influences silent running similarly. This study aimed to explore the differences in vertical impact properties during normal and silent running following a fatiguing task. Seventeen participants performed overground running (normal and silent) before and after a fatiguing running protocol. Running footfall sounds were collected using four microphones surrounding a force platform on the track. Peak impact sound, vertical impact peak force (IPF), instantaneous (VILR), and average vertical loading rate (VALR) were compared from Pre- to Post-fatigue. Peak impact sounds were significantly greater for fatigued runners during normal running when compared to silent running ($p < 0.005$), without changes in force parameters. Moreover, peak impact sounds, IPF, VILR, and VALR from normal running were greater when compared to silent running ($p < 0.001$), both fresh or fatigued. Our results suggest that fatigue may not compromise silent running technique, which may be relevant to reduce early vertical impact loading. Therefore, runners seeking to modify running style towards the reduction of impact loading may benefit from including silent running drills in their training sessions.

ARTICLE HISTORY
Accepted 12 September 2020

KEYWORDS
Running fatigue; injuries; sound; ground reaction forces; running technique; foot strike pattern

Introduction

Muscular fatigue is defined as the muscle's inability to produce maximal force and/or maintain performance (Enoka, 2012; Oliveira, Caputo et al., 2013). Fatigue is a continuous process that can lead to reduced proprioception, muscle responsiveness to stimuli, and efficiency of movement control (Derrick et al., 2002; Enoka, 2012; Oliveira, Caputo et al., 2013). All these previous fatigue-related effects are relevant for runners, with previous studies associating fatigue with reduced performance and increased risks of sustaining running-related injuries (Clansey et al., 2012; Derrick et al., 2002; Oliveira, Caputo et al., 2013). Fatigue reduces the capacity to generate propulsion and increases foot contact time during running (Rabita et al., 2011). Moreover, fatigue reduces the effectiveness of lower limb muscles to absorb impacts loads at early initial contact (Clansey et al., 2012), leading to increased peak forces and vertical loading rates (Jafarnezhadgero et al., 2019). Therefore, fatigue might modify running vertical impact properties and potentialize well known running-related injury risk factors, such as increases in loading rates.

There have been interventions aiming to reduce running-related injury incidence. Some interventions proposed reducing impact loading by modifying the foot strike pattern and cadence (Yong et al., 2018), while other interventions proposed the use of bio-feedback based on vertical tibial acceleration (Bowser et al., 2018). A similar prevalence of running-related injuries has been reported for rearfoot strike (RFS) and non-RFS runners, varying only in nature and location. RFS runners present with predominantly stress fractures on the lower leg, medial tibial stress syndrome, patellofemoral pain, and lower back pain. On the other hand, non-RFS runners present with predominantly stress fractures of the metatarsals and Achilles tendinopathy (Stearne, Alderson, Green, Donnelly, & Rubenson, 2014, Daoud et al., 2012). Despite similar injury prevalence, approximately 89% of all runners are RFS (Futrell et al., 2018), thus highlighting that methods to reduce loading for this type of runners is highly relevant.

Transitioning from RFS to non-RFS running can reduce the vertical loading rate by 50% (Futrell et al., 2018), potentially contributing to reducing the incidence of patellofemoral pain and anterior compartment syndromes in runners (Rice et al., 2016). Moreover, auditory gait retraining has been shown to significantly reduce loading rates (Ching et al., 2018) and running-related injury risks by 62% (Chan et al., 2018). Recently, silent running has been proposed as a gait re-training alternative to reduce impact loading (Pirscoveanu et al., 2020; Tate & Milner, 2017). Running impact sounds have been used by running coaches as a feedback tool to minimize harmful impact forces (Phan et al., 2016). There is a positive linear relationship between the impact sound and vertical ground reaction forces (vGRF) during running (Pirscoveanu et al., 2020; Tate & Milner, 2017). Furthermore, running silently may reduce peak vertical force and loading rate (Phan et al., 2016; Tate & Milner, 2017), as well as, induce a change from RFS to predominantly non-RFS (Phan et al., 2016; Pirscoveanu et al., 2020). Therefore, silent running is a relevant method to attenuate vertical impact loading during running.

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Although silent running may potentially reduce injury incidence, it is unknown whether changing running style towards reducing sound volume would increase the metabolic cost when compared to normal running (Derrick et al., 2002). It is known that fatigue can increase the vertical loading rate during running, but it remains to be shown whether fatigue influences the runner's ability to perform silent running. Therefore, this study aimed to investigate the effect of running-induced fatigue on the vertical impact properties of normal and silent running. It was hypothesized that fatigued runners would present increased vertical impact properties (peak sounds and loading rates) especially during silent running, as it may be a more metabolically demanding locomotor task. Furthermore, the relationship between impact sound and vGRF parameters were quantified during fresh and fatigued running. We also hypothesized that greater fatigue-related changes in vertical impact properties would be associated with greater changes in peak sound amplitudes.

Methods

Participants

Seventeen healthy recreational runners, right foot dominant (age: 25 ± 8.2 years, height: 179.8 ± 8.2 cm, weight 81.2 ± 14.4 kg) agreed to participate in the study. The runners had at least 3 years of running experience (7 ± 4.5 years) and a minimum self-reported weekly running distance of 5 km (14.6 ± 8 km). Participants were injury-free for a minimum of 6 months before the test, as well as avoided performing any strenuous exercises 24 hours before participating in this study. Additionally, participants were asked to avoid consuming any product containing caffeine and alcohol for at least 12 hours before the test. Participants were informed about the experimental procedure and provided verbal and written informed consent to participate in this study. The procedures applied in this study were in accordance with the ethical committee of Northern Jutland practices.

Experimental design

In a single session, participants performed overground running in two different conditions, a fatigue running protocol and a knee extension maximum voluntary isometric contraction (MIVC) protocol. Figure 1 illustrates the timeline of the experimental protocols. The MIVC protocol was conducted at the start of the experiment and immediately after the fatiguing running protocol (Christina et al., 2001). The MIVC protocol took approximately 5 minutes between finishing the fatigue protocol and starting the Post-fatigue running test. Furthermore, all experimental tasks took place in the same location, minimizing the time in resting-state between such tasks. Furthermore, 4 participants performed a third MIVC at the end of the protocol, immediately after the Post-test. These participants presented a considerable reduction (~13%) in isometric torque from Pre- (325.5 ± 31.5 Nm) to Post-fatigue (283.5 ± 29.5 Nm). More importantly, there was only a marginal reduction (~1%) from Post-fatigue to the third MIVC performed at the end of the protocol (287.5 ± 27.5 Nm). Therefore, the MIVC was not recovered at the end of the protocol.

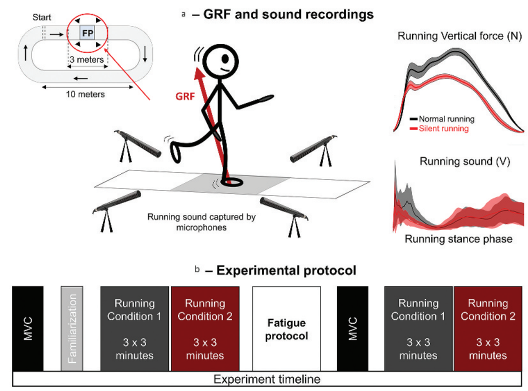

Figure 1. Illustration of running track and experimental setup used for the acquisition of overground running impact sounds (a). In (b), Overview of the experimental protocol used in this study. MVC: maximum voluntary contraction.

Participants were asked to run normally and silently on an indoor running track. For the silent condition, participants were instructed to run "with the lowest impact sound possible" (Phan et al., 2016) during the entire running trial. Prior to data recording, all participants were provided with a warm-up session combined with a 10-minute familiarization period to the running track and normal running condition. The warm-up consisted of run-throughs, walking lounges, running with high knees, and leg swings (Phan et al., 2016). In addition, a minimum 10-minute familiarization period was conducted specifically for silent running. Silent running was defined as running with the lowest impact sound by minimizing landing noises and participants were instructed to run as they normally do, but with the lowest impact sound possible at the pre-established speed (Phan et al., 2016; Pirscoveanu et al., 2020; Tate & Milner, 2017). Participants were considered familiarized when achieving a comfortable and constant running pace at a consistently low impact sound, as well as easily hitting the embedded force platform with the right foot.

The running conditions (normal and silent) were randomized for each participant prior to testing. Following the familiarization, participants were asked to perform a 3-minute running trial at their self-selected pace. The average pace across all steps reaching the force platform was calculated and established as the running speed to be executed during both normal and silent running trials. Three blocks of three minutes per runner were collected for each running condition (Figure 1(b) *illustrates the experimental design)*, allowing for the acquisition of at least 15 steps onto the force platform per block. Furthermore, faulty steps (maximum 5 steps/trial) onto the force platform were noted if participants changed their running pattern before hitting the force plate (e.g., stride shortening or small jumps). Any instructions during the test were provided while the participants were returning to the starting position, minimizing potential influences on data acquisition. All participants wore standard running shoes (Nike Air Pegasus) containing two optical markers for motion capture. Additionally, participants wore a headband containing four optical markers. The two running conditions were repeated after inducing fatigue (Figure 1(b)).

Treadmill running fatigue protocol

Prior to the fatiguing protocol, participants were introduced to the fatigue procedure and the Borg's rated perceived exertion (RPE) scale (Borg, 1990). The participant's heart rate (HR) was continuously measured during running using a heart rate monitor (Suunto Ambit 3; Suunto. Oy, Vantaa, Finland). The fatiguing protocol was conducted using a motorized treadmill (Woodway Pro XL, Waukesha, WI, USA) set with at 1°-degree inclination grade. Similar fatigue protocol has been previously applied in the literature (Dierks et al., 2010; Hajiloo et al., 2020; Amir Ali Jafarnezhadgero, Sorkhe, & Oliveira, 2019; Koblbauer et al., 2014; Medicine, A. C. of S, 2009). The protocol started with participants walking at 6 km/h for two minutes. Subsequently, the treadmill speed was increased 1 km/h every 2 minutes until participants reached 13 on the Borg RPE-scale (intensity defined as "somewhat hard"). Participants were asked to rate their perceived exertion every minute during this task. Subsequently, participants ran at the speed representing 13 on the Borg scale until volitional fatigue (Xia et al., 2017), which was confirmed when participants reached either 90% of their maximum heart rate or 17 on the Borg RPE-scale (Xia et al., 2017). An age-predicted equation (i.e., 208 – (0.7 age)) was used to estimate their maximum heart rate (Tanaka et al., 2001). At the end of the fatigue protocol, the participants were verbally encouraged by a researcher.

Data acquisition – running kinetics and kinematics

Running data were captured at an indoor motion capture laboratory, using a 24-metre obround running track (*see* Figure 1). The track contained a floor embedded force plate (AMTI Optima Gen 5, Advanced Mechanical Technology, Inc., Watertown, USA), sampled at 1000 Hz. An eight-camera motion-capture Qualisys system (Qualisys 1.0, Qualisys Oqus, Sweden) sampled at 200 Hz recorded three-dimensional foot and head position data. The running speed was measured between two pre-defined places along the running track, −1.5 m and +1.5 m from the centre of the force platform. Running speed was computed manually immediately after each running trial by dividing the distance (e.g., 6 m) by the time spent between these two points. Time was measured using a stopwatch. Moreover, running speed was computed offline using the four reflexive markers positioned on the participant's head through a headband containing four equidistant markers (16-mm diameter). A pilot study from our research group revealed that there are no differences in the speed computed from the centre-of-mass displacement and the head marker displacement ($n = 7$; 2 ± 0.6% difference between conditions). The participant's foot displacement was captured by two optical markers positioned on the foot's second metatarsal head and calcaneus correspondent positions on the shoe.

Data acquisition – sounds of footfalls

Four shotgun microphones (Røde, NTG2, Silverwater, NSW, Australia) and a sound card (Focusrite, Scarlet 18i8, High Wycombe, UK) captured running impact sounds with a sample rate of 44.1 kHz. The data acquisition was controlled via a customized Matlab Simulink script. The microphones were positioned at each corner facing directly towards the centre of the force plate and placed 10 cm from the corner of the force plate and 15 cm above the ground (*see* Figure 1(a) for illustration) (Pirscoveanu et al., 2020). A digital sound level metre (HoldPeak HP 824, Zhuhai, China) was used to record a consistent level of 250 Hz, which served as a reference for subsequent sound calibration for each microphone (Pirscoveanu et al., 2020). This procedure was used to convert the captured running sounds from voltages to decibels.

Data acquisition – knee extensor isometric torque

All participants were familiarized with performing knee extensor MIVC on an isokinetic dynamometer (CSMI, Humac Norm, Stoughton, MA, USA) with their dominant leg. Participants were comfortably seated in an upright sitting position, with the knee aligned with the dynamometer's axis of rotation. The leg performing the MIVC was secured at the ankle to the dynamometer, and the rest of the body was restrained with straps crossing over the chest, waist, and thigh to minimize compensatory movements during maximal efforts. During familiarization, participants performed three to five 4-second 90% submaximal contractions at 90° knee angle (0° = full extension). After a 5-minute rest interval, participants were asked to perform three 4-second MIVC interspaced by 60-second rest periods (Meldrum et al., 2007). Visual feedback regarding the generated knee extensor torque was displayed to participants, and verbal encouragement was provided throughout the protocol (Meldrum et al., 2007). The MIVC with the highest torque was used for further analysis. The MIVC measurement was conducted before and immediately after the fatigue protocol, although no familiarization was provided Post-fatigue.

Data analysis

After removing faulty steps (e.g., stride shortening or small jumps), an average of 45 ± 5 steps per participant was analysed for each condition to extract impact sound, kinetics, and kinematic data. The kinetic, kinematic, and sound data were synchronized and continuously recorded throughout the 3-minute blocks. All data processing was conducted using customized scripts on MATLAB (R2017b, The MathWorks, Natick, MA). Running initial contact and toe-off events for every step were defined when the vertical ground reaction force exceeded 20 N (Oliveira, Silva et al., 2013). The sound data were band-pass filtered using a range between 10 Hz to 20 kHz (second-order Butterworth). Furthermore, a low-pass filter (second-order Butterworth, 200 Hz cut-off frequency) was applied to create a linear envelope of the continuous sound data. The sound data from each microphone (e.g., sound in the following formula) were converted and normalized to decibels (dB) using the following formula (Pirscoveanu et al., 2020):

$$\text{Sound} = V_1 * c / V_2 \tag{1}$$

where V_1 is the recorded sounds, c is the constant decibel level recorded by the sound level, and V_2 is the 250 Hz stable tone. Subsequently, the data from all four microphones were averaged to represent data from each participant. The peak impact sound amplitude was extracted from the first 20% of the stance phase from the mean of all microphone recordings.

The force data were low-pass filtered (fourth-order Butterworth, 50 Hz cut-off frequency) and normalized to body weight (BW). The step time, vGRF impact peak force, vGRF active peak, instantaneous vertical loading rate (VILR), and average vertical loading rate (VALR) were extracted from each step. If no impact peak was present, the vertical force magnitude at 13% of the stance phase was used to define the impact peak (Willy et al., 2008). The vertical loading rate was calculated as the slope between 20–80% of the impact peak (Milner et al., 2006), where VALR and VILR were calculated using the following formulas (Kobayashi et al., 2016):

$$\mathrm{VALR} = (F_{80\%} - F_{20\%})/(t_{80\%} - t_{20\%}) \tag{2}$$

$$\mathrm{VILR} = \Delta F_{max}/\Delta t \tag{3}$$

where $F_{20\%}$ and $F_{80\%}$ are the force occurring at $t_{20\%}$, respectively at $t_{80\%}$ time to impact peak, ΔF_{max} is the maximum vertical force change and Δt is calculated between $t_{20\%}$ and $t_{80\%}$ (Kobayashi et al., 2016). Due to issues with the acquisition of ground reaction forces, the vGRF active peak was computed for only 16 participants.

The kinematic data were low-pass filtered (fourth-order Butterworth, 10 Hz cut-off frequency) (Oliveira, Silva et al., 2013). The foot contact angle at initial contact was offset by the angle between two vectors at 30% of the stance phase, instant in which participants presented the foot fully in contact with the force plate. Positive angles indicated RFS, whereas negative angles indicated non-RFS (midfoot or forefoot strike) (Phan et al., 2016). The running speed for each step was calculated from the position data of the head markers as an average position of the head markers, computed and calculated 1 metre before and after the origin of the force plate.

Statistical analysis

The Shapiro-Wilks test was conducted to verify the normal distribution and the variables violating normality ($p < 0.05$) were log-transformed prior to statistical testing (Changyong et al., 2014). IBM SPSS Statistics 25.0 (SPSS, Inc., Chicago, IL, USA) was used for all statistical tests. To assess the effect of the fatigue protocol on MIVC measurements, a paired samples t-test was conducted. A Pearson chi-square test was performed to determine if the participants altered their foot strike pattern when instructed to run silently. To assess the effect of fatigue (fatigued *vs* non-fatigued) and running conditions (normal *vs* silent) on peak sound, impact peak force, VALR, and VILR, a two-way repeated measure analysis of variances (ANOVA) was conducted. Significant main effects and interactions were analysed, and Bonferroni corrected for multiple analyses. Lastly, the delta differences (%change) between Pre- and Post-fatigue for the impact sound, vGRF impact peak force, VILR, and VALR were calculated. These %changes were used to calculate Pearson correlations between impact sound and the force parameters (impact peak force, VILR, and VALR). Correlations were classified as weak ($r < 0.3$), moderate ($r > 0.3$ and <0.6) and strong ($r > 0.6$) (Akoglu, 2018). An alpha level of $p < 0.05$ was selected for all statistical tests.

Results

The results of the present study are based on the analysis of 45 ± 5 steps per each running condition (normal and silent) and fatiguing condition (Pre- and Post-) per participant (3207 steps in total). Fatiguing running lasted 26:49 ± 5:48 min at a - 3.33 ± 0.36 m/s average. All participants reached above their calculated 90% maximum heart rate (188.5 ± 10.3 bpm) and 17 on the Borg RPE-scale at volitional fatigue. The fatigue running protocol significantly reduced the knee extensor MIVC (17 ± 8%, $p < 0.005$, effect size: 1.02, 95% confidence interval (CI): Pre- 301.32–381.22; Post- 248.44–312.55, Figure 2(a)). No statistical differences were found in either running conditions or fatigue for running active peak ($p > 0.05$, Table 1) and foot contact time ($p > 0.05$, Table 1). Similarly, running speed showed no statistical differences in either running conditions or fatigue ($p > 0.05$, Figure 2(b), Table 2).

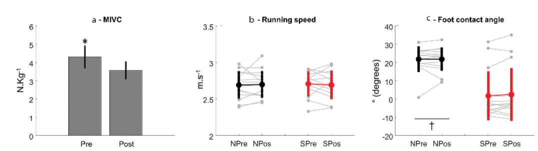

Figure 2. Mean (SD) maximal knee extensor isometric voluntary contraction (MIVC) before (Pre) and after fatiguing running (Post). In (b) and (c), running speed and foot contact angle data displayed from single participants, where small grey circles are individual data points and traces connect a participant for normal running Pre- (NPre) and Post-fatigue, as well as for silent running Pre- (SPre) and Post-fatigue (SPost). The large circles indicate average values, whereas the thick vertical lines indicate ±1 standard deviation for normal (in black) and silent running (in red). * denotes significant difference in relation to Post-Fatigue ($p < 0.005$). † denotes significant difference in relation to silent running ($p < 0.001$).

Table 1. Step time(s) and running speed(m/s) of the participants during normal running Pre- (NPre) and Post-fatigue (NPos) and during silent running Pre- (SPre) and Post-fatigue (SPos).

Parameters	NPre	NPos	SPre	SPos
Foot contact time (s)	0.29 ± 0.02	0.29 ± 0.03	0.29 ± 0.02	0.29 ± 0.02
Active Peak (xBW)	2.36 ± 0.19	2.35 ± 0.23	2.33 ± 0.19	2.34 ± 0.28

Table 2. Border values of 95% confidence of calculated parameters for during normal running Pre- (NPre) and Post-fatigue (NPos) and during silent running Pre- (SPre) and Post-fatigue (SPos).

95% Confidence intervals	NPre	SPre	NPos	SPos
Running speed (s)	8.90–9.89	8.97–9.96	8.91–9.87	8.81–9.85
Foot contact angle (°)	18.99–25.88	−5.60–7.05	18.95–25.19	−6.00–7.88
Peak Sound (dB)	66.28–100.23	32.74–54.63	78.28–117.40	38.02–65.43
Peak Force (xBW)	1.40–1.60	0.82–0.95	1.49–1.62	0.85–0.99
VALR ($Nkg^{-1}s^{-1}$)	51.01–67.69	25.22–34.68	51.01–67.69	26.10–36.42
VILR ($Nkg^{-1}s^{-1}$)	61.28–82.19	31.91–41.54	68.44–85.55	33.19–44.11

Foot strike pattern

The foot contact angles were significantly greater during normal running for both Pre- and Post-fatigue ($F(1,16) = 58.8$, $p < 0.0001$, $\eta p2 = 0.77$, Figure 2(c), Table 2). No significant differences were seen for both running conditions while the runner was fatigued. The chi-square test demonstrated a significant change in the foot strike pattern from RFS during normal running to non-RFS during silent running (Pearson Chi-square = 38.62, $p < 0.000$). During normal running in both fatiguing conditions, all participants used RFS, whereas during silent running 14 out of 17 adopted a non-RFS technique during both fatigue conditions (74.33%). Consequently, no significant difference was observed before and after fatigue (Pearson Chi-square = 0.000, $p = 1.000$).

Normal vs silent running

There was a greater peak impact sound during normal running when compared to silent running ($F(1,16) = 49.5$, $p < 0.0001$, $\eta p^2 = 0.76$, Figure 3(a), Table 2). Similarly, participants presented greater impact peak force ($F(1,16) = 201$, $p < 0.0001$, $\eta p2 = 0.92$, Figure 3(b), Table 2), VALR $F(1,16) = 130$, $p < 0.0001$, $\eta p2 = 0.89$, Figure 3(c), Table 2) and VILR $F(1,16) = 125.8$, $p < 0.0001$, $\eta p2 = 0.89$, Figure 3(d), Table 2) during normal running when compared to silent running.

Pre- vs post-fatigued running

Fatigued participants presented increased peak sounds during normal running when compared to running fresh ($F(1,16) = 11.1$, $p < 0.005$, $\eta p^2 = 0.41$). The impact peak force, VALR, and VILR increased from Pre- to Post-fatigue during normal running (4.9 ± 11%, 10.0 ± 23%, and 10.59 ± 24% respectively). However, these changes did not reach statistical difference ($p = 0.09$, Figure 3(b), 3(c) and 3(d)). Similar non-significant increases were found for impact peak force following fatigue during silent running (4.6 ± 14%), but there was a lower influence of fatigue in VALR (4.6 ± 15%) and VILR (5.8 ± 17%) during silent running. No condition *vs* fatigue interactions were found for any variable.

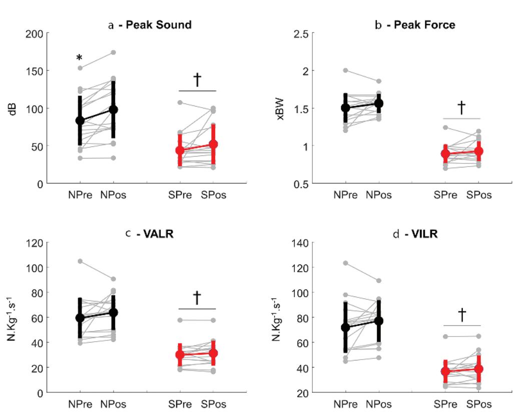

Figure 3. Averaged peak sounds (*panel a*), vertical impact peak force (*panel b*), vertical average loading rate (VALR, *panel c*), and vertical instantaneous loading rate (VILR, *panel d*). Data points and traces connect a participant for normal running Pre- (NPre) and Post-fatigue, as well as for silent running Pre- (SPre) and Post-fatigue (SPost). The large circles indicate the average values, whereas the thick vertical lines indicate ±1 standard deviation for normal (*in black*) and silent running (*in red*). * denotes significant difference in relation to Post-Fatigue ($p < 0.005$). † denotes a significant difference in relation to normal running ($p < 0.001$).

The relationship between sound and vGRF parameters

There were significantly strong correlations between the % change in peak sound and impact peak force for both normal ($r = 0.92$, $p < 0.001$) and silent running ($r = 0.82$, $p < 0.001$, Figure 4(a)). Similarly, strong correlations were found between %change in peak sound and VALR for both normal ($r = 0.93$, $p < 0.001$) and silent running ($r = 0.75$, $p < 0.001$, Figure 4(b)). Finally, strong correlations were found between %change in peak sound and VILR for both normal ($r = 0.92$, $p < 0.001$) and silent running ($r = 0.78$, $p < 0.001$, Figure 4(c)).

Discussion

The main findings of this study were that fatigued runners will produce greater peak impact sounds when compared to running fresh under normal running conditions. However, runners were able to maintain reduced footfall sound volumes and loading rates when running silently while fatigued. Moreover, the effects of fatigue on peak sounds were highly associated with the effects of fatigue on force parameters, regardless of the running condition. These results suggest that fatigue may have a marginal influence on a runner's strategy to increase shock absorption and achieve silent running. Therefore, the inclusion of silent running as part of routine running training may assist runners in modifying their running style towards reducing vertical impact loading.

Changes in running vertical impact properties during silent running

As expected, the sounds of footfalls were reduced during silent running. Several studies have established a connection between running stress fractures/muscle strains and higher peak impact forces and/or vertical loading rate (Milner et al., 2006; Rice et al., 2016). Therefore, reducing running impact sound may lead to reduced vertical forces during early initial contact. There is a relevant relationship between instantaneous impact forces and injury occurrence in running. Previous studies have shown that vertical loading rate is a strong predictor of running-related injuries (Bowser et al., 2018; Davis et al., 2016; Milner et al., 2006). Moreover, the use of sound feedback

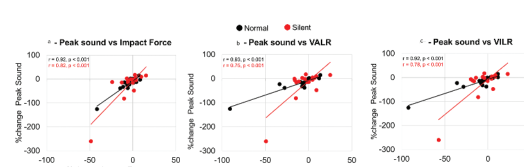

Figure 4. Pearson correlation coefficients from the association between peak sound and impact peak force (a), vertical average loading rate (VALR, b), and vertical instantaneous loading rate (VILR, c). The values are represented as a % change from Pre- to Post-fatigue conditions for both normal (*black dots and trendlines)* and silent running (*red dots and trendlines*).

to achieve silent running can reduce the loading rate, possibly reducing running-related injury risks through reductions in vertical loading (Tate & Milner, 2017). The reduction in peak vertical impact force and loading rate during silent running demonstrated in our results, corroborate these previous studies. More importantly, our results demonstrated the possibility of maintaining a running style that reduces footfall sound volume in fatigued conditions.

Fatigue-related effects on MIVC

In the present study, the knee extensor torque has been reduced by 17 ± 8% following the fatiguing treadmill running. Fatigue-related deficits in force output following running have been associated with running intensity and duration (Millet & Lepers, 2004). Previous studies have reported knee extensor force reduction ranging from 15% to 41% (Bonnacci et al., 2018; Jensen et al., 2016; Kuhman et al., 2016; Martin et al., 2010; Nummela et al., 2008). Our results corroborate those from Nummela and co-workers (Nummela et al., 2008), who found an average 15% decreased in knee extensor torque and a 16% decreased in maximal sprint velocity following a 5-km running time-trial. A previous study applying similar fatiguing protocol has induced changes in running kinematics (e.g., knee flexion, ankle inversion/eversion) and mechanical parameters such as leg impact acceleration and impact attenuation (Derrick et al., 2002). Such modifications in running impact properties induce increases in running metabolic costs towards the end of the fatiguing protocol (Derrick et al., 2002). It is noteworthy that changes in isometric knee extension torque might not entirely represent muscle activation in dynamic actions such as running, as the fatigue may have the greatest effect on fast eccentric contractions following fatiguing running (Oliveira, Caputo et al., 2013; A. S. Oliveira et al., 2009).

Fatigue-related effects on running vertical impact properties

The fatiguing running protocol induced increases in peak sounds, but only for normal running. The lack of change in peak sounds following fatigue for the silent condition does not corroborate our initial hypothesis. We hypothesized that runners would not be able to maintain lower sound amplitudes following a running-induced fatigue protocol. Sounds of footfalls are not directly correlated with running impact peaks, but the vertical loading rate can be weakly predicted from peak sounds during silent running (Phan et al., 2016; Pirscoveanu et al., 2020). However, no previous study has described the effects of fatigue on silent running. Subsequently, our results might not be comparable to those from previous studies investigating impact loading during running (Ng et al., 2017; Phan et al., 2016; Pirscoveanu et al., 2020; Tate & Milner, 2017).

Despite increases in peak sound following running-related fatigue, our results demonstrated only trends for significant changes in vGRF parameters. Abt and colleagues (Abt et al., 2011) showed that a brief fatiguing running workout does not significantly alter running kinematics and shock absorption properties. Moreover, Clansey and co-workers (Clansey et al., 2012) reported greater VILR and VALR following 20 minutes of running at their corresponding lactate threshold intensity, suggesting that fatigue influences vertical loading during running. However, fatigued running may influence the vertical loading rate without significant changes in leg stiffness and heel vibrational magnitude (Dickinson et al., 1985; Rabita et al., 2011). It is noteworthy that both VALR and VILR presented ~10% and ~5% increases on average following fatigue during normal (effect size: VALR – 0.21; VILR – 0,21) and silent running (effect size: VALR – 0.11; VILR – 0.15) in our study, respectively. Therefore, there is a trend for increases in these parameters, especially for normal running.

Previous studies have demonstrated greater mechanical loading through measurements of running peak forces or tibial/sacral acceleration following a fatiguing task (Christina et al., 2001; Clansey et al., 2012; Derrick et al., 2002). However, some studies have found no change in such parameters during fatigued running (Luo et al., 2019). It is plausible that the applied fatiguing protocol was not sufficient to induce changes in running vertical impact properties to impair silent running technique. Therefore, further studies applying more intense fatiguing protocols may be relevant to advance our understanding of vertical impact properties during silent running. Moreover, these studies may contribute to determining which combination of running intensity/duration elicits more evident changes in vertical impact loading properties during silent running.

The inability to attenuate vertical impact loading using eccentric muscle work during running may be responsible for the fatigue-related increases in peak forces, loading rates, and segment acceleration (Oliveira, Caputo et al., 2013; A. S. Oliveira et al., 2009). Indeed, it has been proposed that soft landing attenuates the effects of fatigue on vGRF parameters, as soft landing may maximize impact absorption through increased hip and knee ranges of motion (Luo et al., 2019). Our results corroborate such findings, as the peak sounds and peak vertical forces were significantly lower during both Pre- and Post-fatigue while running silently. Such findings suggest that evaluating the sounds of running footfalls is a sensitive and cheaper alternative to describe fatigue-related changes in vertical impact properties during normal running. Furthermore, it has recently been shown that vGRF is not directly related to the actual loading on internal structures such as tibial bone load (Matijevich et al., 2019). Future studies investigating the relationship between tibial bone loading and impact sound are necessary to increase our understanding of this matter.

Fatigue-related effects on foot strike patterns

The results of the present study suggested that running while fatigued does not affect foot strike patterns and has a very limited effect on foot contact angle. Likewise, Murray et al. (2019) analysed foot strike patterns of recreational runners over a 12 km race and reported no significant changes in foot strike patterns when compared to pre-race. Likely, the fatigue induced in this study was not sufficient to influence neuromuscular control of running and its impact loading properties. Interestingly, most RFS runners changed their landing technique to a non-RFS strike pattern during silent running in our study (13 out of 17). According to Pirscoveanu et al. (2020), the use of multi-directional microphones allows dissociating impact sounds from different foot strike patterns. However, the reported peak sounds in this study were calculated by averaging the peak sounds from all four microphones, excluding the potential influence of the direction of sound propagation on the results.

The relationship between sound and force parameters

It was expected that fatigue could influence all dependent variables in this study, and the extend of such influence on vGRF parameters could be related to the influence on footfall sounds. Indeed, our results showed strong and significant correlations between the %change in vertical impact peak, VALR, and VILR with peak sounds (Figure 4). Therefore, sounds of footfalls may represent the influence of fatigue on the loading rate, which has been classified as a risk factor for running-related injuries (Davis et al., 2016; Tate & Milner, 2017). However, these results might be overestimated by the presence of outliers. The removal of one outlier reduced the Pearson correlation coefficient, especially for silent running. The correlations were reduced for peak sound *vs* impact force (normal: $r = 0.74$, $p = 0.002$, silent $r = 0.53$, $p = 0.4$), peak sound *vs* vertical loading rate (normal: $r = 0.81$, $p < 0.01$; silent $r = 0.33$, $p = 0.22$), as well as peak sound *vs* vertical instantaneous loading rate (normal: $r = 0.77$, $p = 0.001$; silent $r = 0.31$, $p = 0.26$). Nonetheless, correlations were moderate-to-strong across all comparisons. However, no significant sound correlations with vertical load rate and instantaneous loading rate were found without the outliers during silent running. Although previous studies have not shown a strong relationship between footfall sounds and impact forces (Phan et al., 2016), multi-directional sound recordings allowed capturing sensitive impact properties at initial contact (Pirscoveanu et al., 2020). Such information should be explored in future studies, as sound recordings may be implementable in different scenarios to deepen our understanding of running vertical impact properties in outdoor settings. Furthermore, multi-directional sound recordings present superior accuracy when compared to a single microphone to identify individual footsteps during walking (Pirscoveanu et al., 2020; Riwurohi et al., 2018). This fact suggests that multi-directional sound recordings may provide a superior representation of sound propagation from running footfalls.

Limitations

This study was conducted indoors to minimize the acquisition of sound artefacts expected in an outdoor setup or from treadmill running (e.g., treadmill engine noise, wind). Therefore, extrapolating the results from the present study to outdoor conditions must be done with caution. Moreover, the footfall sounds from this study were acquired from the impact contact between a specific combination of a shoe model sole and the aluminium surface of the force plate. Different surfaces and/or combination of shoe materials and surfaces may influence sound propagation and potentially influence expected outcomes from this experimental design. For instance, the vertical loading rate can be reduced by increased contact time, which can be achieved by running on softer surfaces and/or by running using shoes with softer heel cushioning. Future investigations should examine whether the impact sound is dependent on different shoe properties and different surfaces, to confirm the potential transferability of the present results to a wider range of running shoes and surfaces. Moreover, runners were not instructed on how to perform silent running in this study, which may augment inter-subject variability on the investigated running parameters. All runners were RFS during normal running, whereas 76% were non-RFS during silent running. However, future studies exploring groups of RFS and non-RFS runners could establish whether fatigue influences differently silent running depending on the runner's foot strike pattern. Finally, experienced runners are more resistant to fatigue-related changes in running kinematics when compared to runners with less experience (Maas et al., 2017). Therefore, our results might not be entirely applicable to highly trained runners. Likewise, our results might not be applicable for females with pronated feet, as a previous study applying similar fatiguing running protocol induced substantial reductions in loading rate (A. A. Jafarnezhadgero et al., 2019). Future studies are necessary to elucidate the effects of contraction type, gender, and foot alignment following fatiguing running.

In summary, fatigued runners generate greater peak sounds during normal running compared to fresh runners. However, runners were able to maintain similar levels of footfall sound volumes and foot strike pattern following the fatiguing protocol when running silently. This finding suggests that fatigue influences landing properties related to sound propagation in normal running conditions, but not in adapted running techniques, such as silent running. Therefore, fatigue may have a marginal influence on a runner's technique to sustain shock absorption and achieve silent running. It is suggested that runners aiming to reduce early vertical impact loading can add periods of silent running bouts to their training routines. This may help runners to self-educate towards reducing loading rates and potentially reducing injury risks, as vertical loading rate has been linked to running-related injuries.

Acknowledgments

This project was fully funded by Kulturministeriets Forskningsudvalg under Grant number: FPK 2018 – 0048. The funders had no contribution to the study design, data collection, and analysis, manuscript writing, or publishing decisions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Kulturministeriet (DK) [FPK 2018-048].

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