The relationship between impact sound and vGRF during fatigued and non-fatigued running

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Studies have suggested that the impact sound during running contains properties, which is directly related to the running technique. Identification of these specific properties could contribute to valuable information on both performance and injury risk. The aim of present study was therefore, to investigate the relationship between impact sound and vGRF parameters, during both fatigued and non-fatigued running. Eighteen participants completed trials of over ground running during normal and quiet conditions, which was performed pre and post, separated by a treadmill fatigue protocol. During the run, vGRF measurements was collected, simultaneously, four shotgun microphones captured the impact sound. Kinematics were captured to determine the foot strike pattern of the participants. Simple linear regressions revealed a significant linear relationship between impact sound and vGRF parameters of impact peak, IVLR and AVLR, demonstrating that increase of impact sound results in increase of vGRF parameters. A Chi-square test demonstrated that participants (83.33%) changed their foot strike pattern significantly during the quiet condition. A two-way repeated measures ANOVA revealed an effect of running conditions, as both the vGRF parameters and impact sound was significantly reduced during the quiet condition. Impact sound significantly increased, when running in a fatigue state, however, the same tendencies was not observed for any vGRF parameters. Thus, indicating properties of the impact sound is a beneficial alternative measurement method to assess vGRF, and can be used to alter the running mechanics, hence the possibility of reducing the prevalence of overuse injuries.

Keywords

Running, fatigue, injuries, sound, ground reaction force, running technique, foot strike pattern

Introduction

Running is one of the most popular physical activities around the world, as it is an efficient way to achieve and upheld physical fitness and thereby decrease all-cause and cardiovascular mortality (Lee et al., 2014). Running does, however, induce a relatively high risk of injury. A majority of injuries are located in the lower extremities, where incidence rates vary between 19.4% and 79.3% (Van Gent, 2007). Overuse injuries are the most common running-related injury, which is a result of repetitive microtrauma, caused by shock waves propagating through the lower extremities, created at the foot impact during running (Dickinson et al., 1985; Hreljac et al., 2000). Risk factors originating from running can be assigned to multiple factors, where the vertical ground reaction force (vGRF) and loading rate (VLR) are commonly used to predict and investigate overuse injuries. Greater impact forces have been reported to increase the risk of stress fractures (Davis et al., 2016; Milner et al., 2006), indicating lowering the impact forces having a potential beneficial effect on overuse injuries.

Foot strike pattern (FSP) has been suggested as a risk factor for running-related injuries, as alterations of the FSP have been associated with changes in biomechanical characteristics (Daoud et al., 2012; Lieberman et al., 2010). Non-rearfoot strike (non-RFS) runners have shown to reduce impact forces and loading rates, compared to rearfoot strike (RFS) runners (Daoud et al. 2012; Almeida et al., 2015). Though FSP is highly influential in the area exposed to the risk of injuries. RFS is often associated with increased loads on the knee and hip, whereas non-RFS are exposed to greater loads on the ankle and Achilles tendon (Rooney & Derrick, 2013; Daoud et al. 2012; Anderson et al., 2017). A study by Cheung & Davies (2011), investigated the influence of FSP on the running kinetics, using an audio-feedback device to assist the runners to change their FSP from RFS to non-RFS. This resulted in a reduction of vGRF and VLR, leading to reduced perceived patellofemoral pain (Cheung & Davies, 2011). This insinuates that an audio-feedback tool is efficient to alter the running technique, resulting in a reduction in running kinetics and injury risk.

Running coaches have similarly employed the impact sound as an auditory feedback tool, with the purpose of changing the runners FSP to decrease the impact forces (Phan et al., 2016). This suggests, that there are properties in the impact sound, which can potentially be used to determine the FSP and injury risks. Studies investigating drop landings have established a positive linear relationship between the impact sound and vGRF parameters, and when instructed to reduce the impact sound, both parameters decreased, which could be applicable during running (McNair et al., 2000; Wernli et al., 2016). Tate et al. (2017) investigated the running sound intensity and vGRF parameters and showed a reduction of peak vGRF and VLR when subjects had visual feedback of their impact sound. Similarly, a study by Phan et al. (2016) investigated the relationship between running sound and vGRF parameters, on two different running conditions; normal and quiet running. They showed that the vGRF, VLR and impact sound decreased during the quiet condition. Furthermore, the quiet condition resulted in participants changing their FSP from RFS to predominantly non-RFS. In conjunction, this insinuates that the impact sound during running contains properties, which is directly related to the running technique and mechanics. Identification of these specific properties could contribute to valuable information on both performance and injury risk.

Only a few studies have investigated the relationship between the impact sound and vGRF parameters, however, the factor of fatigue has not been considered. Fatigue has been heavily investigated in relation to performance and relation to the risk of injuries. Fatigue naturally occurs during running and imposes greater peak forces on the runner, which potentially increases the risk of overuse injuries (Derrick et al., 2002; Mizrahi et al., 2000; Voloshin et al., 1998; Clansey et al., 2012). Increased levels of fatigue are related to delayed muscle response, proprioception deficiency, changes in movement characteristics (Enoka, 2012; Moreau et al., 2008; Derrick et al., 2002). Studies further argue that fatigue decreases the effectivity of the muscle's capability of absorbing ground impacts during running (Voloshin et al., 1998; Clansey et al., 2012). Additionally, fatigue is inevitable during distance running (Derrick et al., 2002), and it could, therefore, be interesting to investigate the effect of fatigue on vGRF parameters together with properties of the impact sound. A potential establishment of a relationship between the impact sound and vGRF can possibly be an essential application for running coaches and athletes in the matter of injury prevention. This can potentially improve the accessibility and knowledge regarding running-related injuries. The aim of present study was, therefore, to investigate the relationship between impact sound and vGRF parameters, during both fatigued and non-fatigued running. It was hypothesized that parameters of impact sound during running would have a positive linear relationship with vGRF parameters. It was further hypothesized that parameters of the impact sound and vGRF would increase during fatigue running. Additionally, it was hypothesized when participants were informed to run quietly, they would alter their FSP, resulting in changed vGRF and impact sound parameters.

Method

Participants

Eighteen healthy male and female recreational runners were recruited to participate in present study (26 ± 2 years, 178.6 ± 8.6 cm, 80.5 ± 15.1 kg). Participants were required not to have any injuries in the lower extremities, hindering their ability to run, at a minimum 6 months prior to the test, as well as not having performed any strenuous exercises 24 hours prior to participating. Furthermore, participants were required to be active runners, running a minimum of 5 km a week (15 ± 8 km) with at least 3 years (7 ± 4.5 years) experience. Additionally, the participants were asked not to consume any form of caffeine and alcohol at least 5 hours prior to the test. Prior to testing, participants were informed about the experiment and signed a letter of consent of participation.

Experimental design

The protocol consisted of two familiarization periods, two running sessions, separated by a fatigue and maximal voluntary isometric contraction (MVIC) protocol, as depicted in

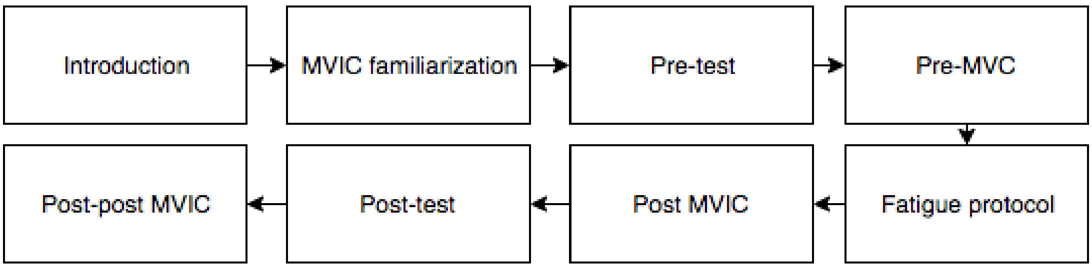


Figure 1 shows the protocol with the order of the different steps the participants had to complete.

Maximum voluntary isometric contraction familiarization and protocol

Initially, the participants were introduced to the knee extensor maximum voluntary isometric contraction (MVIC), performed in an isokinetic dynamometer on their dominant leg. After initial adjustments of the dynamometer and position of the participant, they were asked to perform three MVIC's trials at a knee joint angle of 90°, for a duration of 4 seconds with 60 seconds rest between each trial (Chen et al., 2009; Meldrum et al., 2009). They were instructed not to press maximum in the first two trials, and then go all out in the last. After completion of the pre-test and immediately after the fatigue protocol, participants were escorted back to the isokinetic dynamometer and instructed to complete three MVIC, at the same angle and seating position as performed during the familiarization. Before the MVIC examination, the participants performed submaximal contractions, to optimize the strapping and position. During MVIC measurements, visual feedback was displayed on a laptop to the participants and verbal encouragement was provided by the same researcher during each MVIC (Gandevia, 2001).

Protocol familiarization

After MVIC familiarization, participants were provided with a 10-minute familiarization period in the laboratory, acting as a warm-up, to get familiar to the selected running pattern, condition and speed. During the warm-up, the participants were instructed to run under two different conditions: Normal and quiet running. During the normal and quiet condition, the participants were instructed to run as they normally would and "to run with as quiet an impact sound as possible", respectively (McNair et al., 2000; Phan et al., 2016). Additionally, the participants were asked to run at a pace which they felt comfortable, which had to be maintained during all trials. The participants ran with an average of 9.6 (± 1) km/h during all trials.

Pre- and post-test

The pre- and post-test consisted of the two running conditions, performed in the familiarization protocol, which was verbally informed immediately before testing commenced. Conditions were randomized for each participant prior to the test. The running course was designed as an obround with a force plate centered in the middle of the straight path (Figure 2). The participants were instructed to run continuously around the course, hitting with the right foot on the force plate. The running speed was measured between two marked points (A and B) on the track during the trials using a stopwatch (Figure 2). The participants were instructed to either increase or decrease their speed if they differed more than 10 percent from their self-selected speed. Furthermore, if they deviated from their regular running movement pattern immediately before hitting the force plate, e.g. stride shortening or small jumps, it was noted by a researcher and counted as a faulty step. Any instructions during the test were provided while the participants were returning to the starting position, as to not influence the sound recording and the running flow. A total of three trials with a duration of three minutes each had to be completed of each condition. Based on pilot-tests it was expected that participants would hit the force plate at least 15 times each trial.

during the fatigue protocol using a heart rate monitoring watch (Suunto Ambit 3; Suunto. Oy, Vantaa, Finland) and continuously asked to rate their perceived exertion. The treadmill was set with a constant grade of 1 degree during the run. Initially, the participants were instructed to walk at 6 km/h on the treadmill for two minutes. Throughout the test, the speed was increased with 1 km/h every second minute until the participants reached 13 (somewhat hard) on the Borg RPE-scale. The participants were subsequently instructed to run until volitional fatigue (Steib et al., 2013; Xia et al., 2017). At the point of volitional fatigue, the participants had to reach either 90% of their HRmax or 17 on the Borg RPE-scale (Brown et al., 2014; Xia et al., 2017). If either of these criterions was not met, the participants were instructed to keep running. An age-predicted equation (i.e., 208-(0.7*age) was used to estimate the HRmax of the participants (Tanaka et al., 2001). At the end of the fatigue protocol, the participants were verbally encouraged by a researcher.

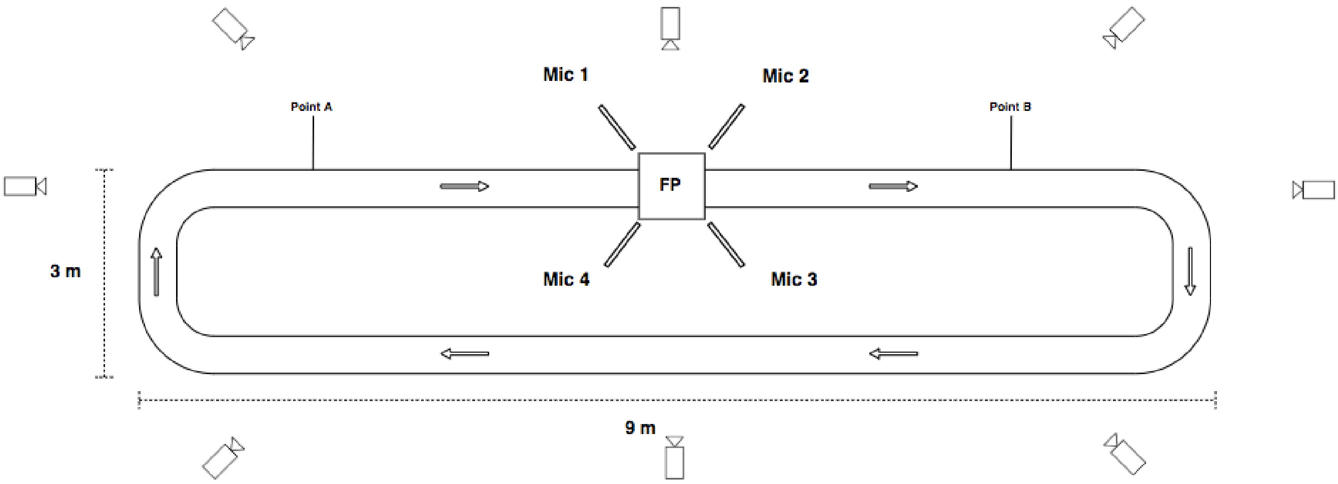


Figure 2 depicts the laboratory running course (9x3m) and direction of running. Point A and B denotes the area from which running velocity was calculated. The force plate (FP) was placed in the middle of the course with microphones at each corner. Cameras were positioned in an octagon surrounding the force plate.

Fatigue protocol

Subsequently after the pre-MVIC, the participants were set to perform a fatigue protocol on a motorized treadmill (Woodway Pro XL, Waukesha, WI, USA). The fatigue protocol was inspired by Koblbauer et al. (2014) and selected based on the evaluation of a pilot test (See Appendix B "Selection of fatigue protocol" for further information). Before initiating the protocol the participants were provided a brief introduction to the protocol and Borg's rated perceived exertion (RPE) scale. The participants' heart rate (HR) was monitored

Instrumentation

The impact sound was collected through four dual powered directional condenser microphones (Røde, NTG2, Silverwater, NSW, Australia). The sound was captured at a sample rate of 44.1 kHz through a laptop with a custom MatLab script. The laptop was connected to an amplifier (Focusrite, Scarlet18i8, High Wycombe, UK), which received the four microphones as input. The microphones were positioned at each corner facing directly towards the center of the force plate and placed 10 from the corner of the force plate and 15 cm above the ground.

Kinematic and kinetic measurements were collected through Qualisys motion capture system (Oqus 300 series, Qualisys, Göteborg, Sweden). Kinematic data were collected from 8 cameras with a sampling frequency of 200 Hz positioned in an octagon around the laboratory facing the force plate (Figure 2). The cameras were used to record two markers attached to the right shoe of the participants, placed at estimations of anatomical landmarks on the heel and toe. Additionally, the cameras were tracking four head markers strapped to a headband, to estimate the speed of the participants.

A 50.8 cm by 46.4 cm force plate (AMTI Optima OPT464508-HF-1000 9862M, Waterton, MA) connected to the Qualisys system, was used to measure ground reaction forces (GRF) (F_x, F_y, F_z), with a sampling frequency of 1000 Hz. A trigger device was used to automatically synchronize the cameras, sound and force measurements during all trials.

MVIC of the participants were collected as a measure of the degree of fatigue and was performed pre-and post of the fatigue protocol on an isokinetic dynamometer (CSMI, Humac Norm, Stoughton, MA, USA). During the collection of MVIC, participants were seated in an upright sitting position, with the knee aligned with the dynamometer's axis of rotation. The leg performing the MVIC 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, during trials. The highest MVIC of the three trials was noted and used for further analysis.

Data analysis

A customized MATLAB script was used to analyze data of impact sound, kinetics, and kinematics. Hereafter, the onset and end of each step were found as a location index in the vGRF data. Initial contact (IC) was determined as the point when forces exceed 20N (Kowalski & Li, 2016). These indexes were further used to find corresponding indexes in sound and marker data in their original sample frequency. All faulty steps were discarded from the analysis.

A first-order Butterworth low pass filter with a cutoff frequency of 200 Hz was applied to the sound data. A total of 45 ± 5 steps were analyzed from each trial. The following parameters were derived from the sound recordings: Peak impact sound, the average sound of the step and average sound impulse of the steps. A lacrosse ball was used to normalize the sound. The ball was dropped on to the force plate from a height of 75 cm, before initiating the test for each participant. The impact sound is reported as a percentage of the peak amplitude of the ball dropping.

The force data were filtered using a fourth order Butterworth low pass filter with a cutoff frequency of 50 Hz. The stance phase was extracted for each step, and the following parameters were calculated: Step time, vGRF impact peaks, instantaneous vertical loading rate (IVLR) and average vertical loading rate (AVLR). If no impact peak was present, the force at 13% of the stance phase was used as the location for the impact peak (Willy, Pohl & Davis, 2008). The vertical loading rate was calculated as the slope between 20-80% of the impact peak (Milner et al., 2006). All vGRF parameters were normalized to body weight.

Initially, all kinematic data were filtered using a fourth order Butterworth low pass filter with a cutoff frequency of 10 Hz (Sinclair et al., 2012). The FSP was determined from the angle of the foot at IC. The angle was measured from the toe and heel markers and was calculated with regard to an offset, collected during a standing position before initiating the running. The FSP was deemed RFS when the toe markers were higher than the heel markers at IC, resolving in a positive angle, and non-RFS when toe markers were below the heel at IC, resolving in a negative angle. The speed of the participants was calculated from the kinematic data of the head markers. An average position of the head markers was computed and calculated from 1 meter before and after the origin of the force plate.

Statistical analysis

To determine if the data was normally distributed a Shapiro Wilks test was conducted. Variables violating normality ($p < 0.05$) were log transformed prior to statistical testing. A paired samples t-test was conducted on the MVIC measurements, to investigate the effect of the fatigue protocol. A two-way repeated measure analysis of variances (ANOVA) was conducted to test the effect of fatigue (fatigued vs. non-fatigued) and running conditions (normal vs. quiet) on all sound and vGRF parameters. Significant main effects and interactions were analyzed, and Bonferroni corrected for multiple analysis. Additionally, several simple linear regression analyses were conducted between the impact sound and vGRF impact peak, IVLR, and AVLR, to investigate the relationship of the sound and vGRF parameters. Lastly, a chi-square test was performed to determine if the participants altered their FSP when instructed to run quietly. All statistical test was performed in SPSS (Version 25, IBM Corporation). Results are presented as mean +/- standard deviation (SD), unless stated otherwise. An alpha level of $p < 0.05$ was selected for all statistical tests.

Results

The results of present study are based on the analysis of 45 ± 5 steps in each of the four conditions per participant (3207 steps in total). Running velocity calculated from the head markers showed no effect of either conditions or fatigue ($p > 0.05$). The same tendency was observed for step time ($p > 0.05$) (see table 1).

Table 1. Step time and velocity for each condition before and after fatigue, including standard deviations. PN = pre-normal, PQ = pre-quiet, PoN = post-normal and PoQ = post-quiet.

Parameters	PN	PQ	PoN	PoQ
Step time (s)	0.29 ± 0	0.29 ± 0	0.29 ± 0	0.29 ± 0
Velocity (km/h)	9.5 ± 1	9.5 ± 1	9.3 ± 1	9.3 ± 1

Foot strike pattern

The chi-square test demonstrated a significant difference in the FSP utilized between the normal and quiet condition (Pearson Chi-square = 40.78, $p < 0.001$). During the pre-test normal condition, 2 participants utilized non-RFS (11.1%), and the remaining 16 participants used RFS (88.9%), whereas 15 out of 18 adopted a non-RFS technique during the quiet condition (83.33%). Both the participants utilizing non-RFS maintained their running technique when instructed to run quiet, whereas 3 participants utilizing RFS during the normal condition, maintained their running technique during the quiet condition. The same tendency was observed during the post-test.

Fatigue protocol

During the fatigue protocol, the participants ran with an average of 26:49 ± 5:48 minutes with a mean speed of 12 ± 1.3 km/h. All participants reached above their calculated 90% HR_{max} (188.5 ± 10.3 bpm) and 17 on the Borg RPE-scale at volitional fatigue. Additionally, the paired t-test showed a significant difference between MVIC scores pre-fatigue (M=333.5 Nm ± 83.8) and post-fatigue (M=276 Nm ± 66), $t(17) = 7.19$, $p < 0.01$, $d = 1.69$, with an average declination of 16.89% torque (Figure 3).

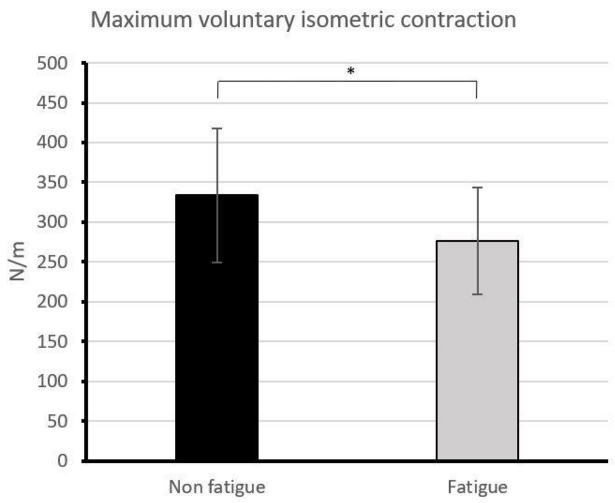


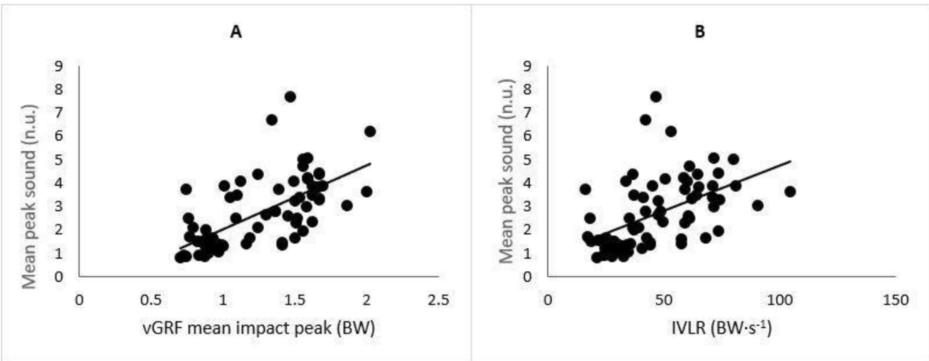
Figure 3. MVIC (N/m) before and after fatigue protocol with standard deviations. * denotes a significant difference ($p < 0.05$).

Effect of fatigue and conditions

Results regarding IVLR ($F_{1,17} = 3.249$, $p > 0.05$, $\eta^2 = 0.168$) and AVLR ($F_{1,17} = 3.021$, $p > 0.05$, $\eta^2 = 0.151$) showed no effect of fatigue. Neither did vGRF impact peak ($F_{1,17} = 3.973$, $p = 0.063$, $\eta^2 = 0.189$), though it should be noted that a tendency was observed. Sound impact peak ($F_{1,17} = 14.250$, $p < 0.05$, $\eta^2 = 0.456$), sound mean ($F_{1,17} = 14.601$, $p < 0.001$, $\eta^2 = 0.462$) and sound impulse ($F_{1,17} = 14.309$, $p < 0.001$, $\eta^2 = 0.457$) all reveal to increase significantly when running in a fatigued state. Results regarding the running conditions demonstrates vGRF impact peak ($F_{1,17} = 225.84$, $p < 0.001$, $\eta^2 = 0.930$), IVLR ($F_{1,17} = 130.17$, $p < 0.001$, $\eta^2 = 0.884$), and AVLR ($F_{1,17} = 113.73$, $p < 0.001$, $\eta^2 = 0.870$) to be significantly decreased when participants were asked to run quietly.

*Table 2. Result presented for both vGRF and sound parameters as an effect of condition and fatigue. All values are presented with standard deviations. * denotes p<0.05, ** denotes p<0.001.*

		Conditions		*p*	
		Normal	Quiet	Fatigue	Conditions
vGRF impact peak (BW)	Pre-fatigue	1.51 (± 0.19)	0.91 (± 0.13)	p=0.063	p<0.001**
	Post-fatigue	1.59 (± 0.17)	0.92 (± 0.13)		
IVLR ($BW \cdot s^{-1}$)	Pre-fatigue	72.04 (± 19.8)	38.21 (± 10.6)	p>0.05	p<0.001**
	Post-fatigue	78.00 (± 16.4)	39.59 (± 12.2)		
AVLR ($BW \cdot s^{-1}$)	Pre-fatigue	59.07 (± 15.9)	30.40 (± 9.1)	p>0.05	p<0.001**
	Post-fatigue	63.24 (± 13.8)	31.65 (± 10.4)		
Sound impact peak (n.u.)	Pre-fatigue	3.14 (±1.3)	1.67 (± 1)	p<0.05*	p<0.001**
	Post-fatigue	3.92 (± 1.5)	2.00 (± 1.1)		
Sound impulse (V)	Pre-fatigue	7.72 (± 2.4)	4.59 (± 1.9)	p<0.001**	p<0.001**
	Post-fatigue	8.87 (± 2.7)	5.16 (± 1.8)		
Sound mean (n.u.)	Pre-fatigue	0.66 (± 0.3)	0.41 (± 0.2)	p<0.001**	p<0.001**
	Post-fatigue	0.78(± 0.3)	0.54 (± 0.2)		



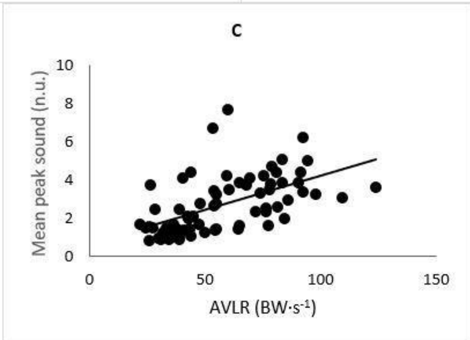


Figure 4. The relationship between mean peak sound and (a) vGRF mean impact peak, (b) IVLR and (c) AVLR.

The same tendency was observed for all three sound parameters, as the sound impact peak ($F_{1,17}$ = 63.30, p <0.001, η^2= 0.788), mean ($F_{1,17}$ = 65.75, p <0.001, η^2= 0.795) and impulse ($F_{1,17}$ = 77.34, p <0.001, η^2= 0.820) significantly decreased during the quiet condition. Across all parameters, no interaction between conditions and fatigue were found.

The relationship between sound and vGRF parameters

Simple linear regressions were calculated to investigate the relationship between the impact sound and the vGRF impact peak, IVLR and AVLR. The regression between impact sound peaks and vGRF impact peaks reveals a significant positive linear relationship ($F(1, 70)$

= 70.665, $p < 0.001$, $r^2 = 0.502$) (Figure 4a). The same tendency is revealed for IVLR ($F(1, 70) = 70.665$, $p < 0.001$, $r^2 = 0.413$) (Figure 4b) and for ALVR ($F(1, 70) = 36.473$, $p < 0.001$, $r^2 = 0.343$) (Figure 4c).

Discussion

The purpose of this study was to investigate the relationship between the impact sound and vGRF parameters, during fatigued and non-fatigued running. The results of present study revealed a significant positive linear relationship between the impact sound and vGRF parameters (mean vGRF impact peak, AVLR, and IVLR), and thereby confirming the hypothesis regarding the impact sound and vGRF parameters having a positive linear relationship. The sound parameters showed a significant effect of fatigue, whereas the same tendency was not observed for the vGRF parameters, and thereby rejecting the second hypothesis regarding fatigue. However, significant differences were present in both sound and vGRF parameters, together with altered FSP, between the normal and quiet condition, and thereby accepting the hypothesis regarding FSP and the effect of conditions. Neither the running velocity and step time revealed any significant differences, thus not influencing the results of present study.

The effect of fatigue

The results of MVIC displays a significant effect of the fatigue protocol, as the participants decreased their force generation capability with 16.89%. The degree of fatigue is highly dependent on the intensity and duration of the run, as previous studies have reported force reduction ranging from 15-41% of the knee extensors (Nummela et al., 2008; Martin et al., 2010). The degree of force reduction is similar to the findings of Nummela et al. (2008), who found a 15% decrease of knee extensors after a 5 km running time-trial, together with a decrease of 16.3% in maximal sprint velocity. Additionally, the running biomechanics have been proven to be altered after 15 minutes of exhaustive running, and present fatigue protocol lasted on average 26:49 ± 5:48 minutes on the treadmill (Derrick et al., 2002). The results indicate that the fatigue protocol was effective, as the runners of present study were not getting cardiovascular fatigued before neuromuscular fatigue was induced.

Results of present study revealed no significant effect of fatigue in vGRF parameters, although mean values indicate to increase during the fatiguing run. This is not consistent with previous findings of Clansey et al. (2012), who found significant increases in both IVLR and AVLR after 20 minutes of lactate threshold running. The inconsistency could be due to differences in the training level of the runners and fatigue protocol implemented between present study and that of Clansey et al. (2012). However, a tendency towards a significant increase in the vGRF impact peak was observed ($p = 0.63$), together with mean values of IVLR and AVLR increasing after the fatigue run, which indicates trends towards the results reported by Clansey et al., (2012). Although, the results demonstrate that the degree of fatigue induced in present study was not sufficient to elicit significant differences in running mechanics.

Contrary, all sound parameters display a significant effect of fatigue, which indicates that the impact sound increases when runners are fatigued. This questions the relationship between impact sound and vGRF parameters, which shows conflicting effects of fatigue, as several studies have demonstrated fatigue to induce greater mechanical force on the runner, thereby increasing risk of injuries (Hreljac et al., 2000; Derrick et al., 2002; Mizrahi et al., 2000; Voloshin et al., 1998; Clansey et al., 2012). This could potentially question the impact sounds ability as a predictor for fatigue and thereby injury risk. However, present study did reveal a significant relationship between vGRF parameters and impact sound. Furthermore, all vGRF parameters increases due to fatigue, although not significant, with vGRF impact peak trending towards being significant. It could, therefore, be argued that the sound parameters potentially are more sensitive to alterations in running mechanics than vGRF, hence being a good indicator of possible running-related injuries. Furthermore, a study by Matijevich et al. (2019) shows, that the vGRF is not directly related to the actual loading on internal structures and overuse injuries. It could, therefore, be discussed, if the impact sound reflects the actual loading of the bone to a higher degree than vGRF, and thereby is a more sensitive predictor of running fatigue and overuse injury risk. However, future studies investigating the relationship between tibial bone loading and impact sound should be conducted, to confirm this statement.

Foot strike pattern and conditions

The majority (88.9%) of participants in present study were characterized as habitual RFS runners. When asked to run quietly 83.33% of habitual RFS runners adopted a non-RFS pattern. None of the habitual non-RFS runner's altered FSP when asked to run quietly. This illustrates that the perception of a quiet running technique, could potentially be used to actively change running mechanics, as previously showed by Tate et al. (2017) and Phan et al., (2016). Furthermore, results from the quiet condition display a significant drop in both vGRF and sound parameters. This suggests that reduction of impact sound will lead to a reduction of impact forces, which is consistent with previous studies (Wernli et al., 2016; Phan et al., 2016; Tate et al., 2017). Several studies have established a connection between runners who formerly have suffered from stress fractures and muscle strains have higher vGRF impact forces and vertical loading rate (Ferber et al., 2002; Milner et al., 2006; Davis et al., 2016). A reduction of the impact sound could, therefore, be an effective method to prevent compressive forces applied on the lower extremity joints during running, thereby reducing running-related injuries, or as a method of rehabilitation. However, further investigations are needed to decisively conclude if quiet running can efficiently lower the prevalence of running-related injuries.

Furthermore, using the impact sound as a feedback tool, allows the runner to experiment with different running techniques without the presence of a running coach, in the attempt to decrease the impact sound. It is noteworthy that there is not a clear linkage between FSP and impact sound, as habitual RFS runners who did not change to non-RFS when instructed to run quietly, also accomplished a lower impact sound and vGRF parameters. This suggests, that a reduction of the aforementioned parameters may be a result of multiple factors and not solely by changing the FSP. It was observed that the participants utilizing RFS pattern lowered their center of mass when instructed to run quiet, however, future research should be conducted to quantify this topic.

The relationship between sound and vGRF parameters

The results from the multiple simple linear regressions revealed significant relationships between all three vGRF parameters and the impact sound. Furthermore, the vGRF impact peak demonstrated a strong correlation (r^2=0.52), whereas the IVLR (r^2 = 0.413) and AVLR (r^2=0.343) revealed a moderate correlation to the impact sound. The results of present study are consistent with Wernli et al. (2016), who found a significant positive linear relationship between the impact sound and vGRF impact peak during drop landings. However, this is not confirmed by Phan et al. (2017), as they only found a significant relationship between the vertical loading rate and impact sound, together with an insignificant correlation (r^2 = 0.189), and no significant relationship between the impact sound and vGRF impact peak. Phan et al. (2016) argue that the lack of relationship is due to running is a more complex motor task, however, present study contradicts this argument. The contradicting findings of Phan et al. (2016) could be due to the difference in the participants training level, as they included novice runners. Additionally, they instructed the participants to run barefooted, which possibly elicits different sound waves than shod running, however, further investigation of the topic is required. The relationship between impact sound and vGRF parameters could have a clinical significance, because of the inherent connection between running overuse injuries and higher vGRF parameters (Davis et al., 2016). An establishment of a relationship between impact sound and vGRF parameters could potentially provide a simple cost-effective feedback tool to reduce the prevalence of overuse injury. Additionally, the impact sound may prove to be beneficial as an alternative measurement method to assess ground reaction forces, as force assessment equipment is costly and non-practical.

Limitations

Findings of present study may not be directly transferable to regular running activities, as the experiment was conducted in a laboratory setting aiming at reducing noise from the environment. The participants were provided with shoes fitting their size, however, the properties of the shoe differed from different shoe-sizes and models. It is unknown whether different shoe properties elicit different impact sound, thus present study is limited to the shoes included in the protocol. Furthermore, it is limited to the aluminum surface of the force plate, as different surfaces may influence the impact sound differently. For instance, the vertical loading rate can be reduced by increasing the contact time, which can be achieved by running on softer surfaces and implementing shoes with softer midsole cushioning. This, in conjunction with the findings of present study, could possibly also reduce the impact sound. Future investigations should aim to examine if the impact sound is dependent on different shoe properties and different surfaces, to investigate if the results are transferable to running conditions differently than the setup included in present study.

The results of this study are also limited to the type of runner included, in conjunction with the self-selected speed. The impact sound may be influenced by the speed and the experience of the runner, as it has been reported that experienced runners are more resistant to kinematic alterations with fatigue compared to runners with less experience (Maas et al., 2017). Future research should aim to examine how the speed and different training levels of the runner influences the impact sound.

Future research and product development should be carried out, to investigate if smart device microphones, i.e. MEMS microphones, can reliably measure the impact sound in an outdoor environment with different surfaces and shoe properties. This is essential for running coaches and athletes to use the impact sound, not relying on having expensive sound equipment available. This could further progress into the development of a smart device application available for the average runner to self-regulate and monitor their impact sound, with the aim of altering their running mechanics and reducing the risk of injuries.

Conclusion

Present study demonstrated significant linear relationships between impact sound and vGRF impact peak, AVLR, and IVLR. Furthermore, the participants were able to lower both sound and vGRF parameters when instructed to run quietly. The perception of quiet running also resulted in alterations toward a non-RFS pattern. The impact of fatigue resulted in significant increases in maximum impact sound, however, the same tendencies could not be concluded for vGRF parameters. It is unclear if the impact sound function as a more sensitive indicator than vGRF parameters to identify fatigue and injury risk, which should be a topic for future research. Furthermore, it is required to investigate if the results of present study are applicable to different shoes, surfaces, and environments, and if running speed and the ability of the runner also affects the relationship between the impact sound and vGRF parameters.

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Conflict of interest

The authors declare no conflicts of interest regarding the results of present study.

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