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Acute effect of running retraining interventions on low & high-frequency components of the impact signals.

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ABSTRACT

Running-related injuries (RRIs) have been linked to high-frequency components of impact-related variables. The influence of running retraining interventions on low- (LoF) and high-frequency (HiF) components of impact-related variables remains unexplored. This study investigated the effects of different retraining strategies on LoF and HiF components of impact-related variables. Twenty-six habitual rearfoot runners completed four overground running conditions: no instructions (CON), forefoot strike (FOR), increased cadence by 10% (CAD), and a combination of both (CADFOR). Three-dimensional kinematics were recorded, while ground reaction forces were processed to separate LoF and HiF signals (10 Hz as cutoff value). Compared to CON, HiF impact peak was reduced in FOR ($P < 0.001$, $d = 2.0$), CAD ($P = 0.006$, $d = 0.6$), and CADFOR ($P < 0.001$, $d = 2.3$). HiF instantaneous vertical loading rate was significantly reduced only in FOR ($P < 0.001$; $d = 0.6$) and CADFOR ($P < 0.001$; $d = 0.7$). Notably, adopting a forefoot strike pattern reduced HiF components of impact-related variables nearly three times more than cadence increase alone. The combination of forefoot strike and increased cadence produced the largest reduction in HiF impact components, suggesting it may be the most effective retraining strategy for potentially lowering RRI risk.

Key words: Running, Impact, Biomechanics, Injury.

Introduction

Running is among the most widely practised physical activities worldwide, due to its accessibility, affordability, and its well-established physical and mental health benefits²⁶. However, these advantages are limited by the high incidence of running-related injuries (RRIs)²⁶. For decades, impact-related biomechanical parameters have been considered potential risk factors for overuse injuries⁷. This assumption largely stems from animal studies showing that repetitive impacts can cause early cartilage damage in the knees of rats and guinea pigs^{22,25}. Despite this, evidence supporting a direct relationship between impact-related parameters and RRIs in humans remains limited⁷.

Traditionally, impact-related parameters have been assessed using time-domain analysis⁷. During running, the vertical ground reaction force (vGRF) typically presents two distinct components: a passive peak, often referred to as the impact peak, and an active peak, associated with the propulsion phase of movement¹⁹. However, time-domain analysis may not always be optimal for capturing impact characteristics²⁴. Factors such as footstrike pattern, running speed, and footwear can alter the timing and amplitude of the impact peak, potentially leading to its overlap with the active peak and compromising the accuracy of analysis^{9,24}.

As a result, frequency-domain analysis has emerged as a promising alternative for isolating impact forces during running²⁴. The low-frequency component of impact-related variables (below 10 Hz) reflects voluntary lower-limb motion and the vertical acceleration of the centre of mass during the stance phase, whereas the high-frequency component (above 10 Hz) captures the rapid deceleration of the foot and leg at initial ground contact⁸. A recent randomised controlled trial involving over 800 recreational runners demonstrated that time-domain impact variables were not associated with the risk of RRIs¹⁸. In contrast, after decomposing the signal into high- and low-frequency components through frequency-domain analysis, the high-frequency components of these same variables were found to be significantly associated with RRI risk¹⁷. These findings highlight the need for targeted interventions aimed at reducing the high-frequency components of impact-related variables as a potential strategy for injury prevention.

Running retraining, which typically involves transitioning to a forefoot strike pattern or increasing running cadence, has shown promising effects on impact-related variables in time-domain analyses⁵. Adopting a forefoot strike pattern has been associated with reductions six months after intervention in both the average vertical loading rate (AVLR) and the instantaneous vertical loading rate (IVLR) by 49.7% and 41.7%, respectively⁶. Similarly, increasing running cadence by 7.5% has been reported to reduce AVLR six months after intervention by approximately 16%⁶. However, despite their efficacy in time-domain analysis, the effects of these retraining strategies on low- and high-frequency components of impact-related variables remain unknown.

The aim of the present study was to investigate the effects of running retraining interventions on impact-related parameters of high- and low-frequency signals. Specifically, the research objective was to examine the influence of adopting a forefoot strike pattern or increasing running cadence by 10% or combining both on the high- and low-frequency components of impact forces during running. We hypothesised that both interventions will result in a reduction in AVLR and the magnitude of the impact peak in the high-frequency signals⁵.

Materials and methods

Participants

The required sample size was calculated using a repeated measures ANOVA (within factors) in G*Power software (version 3.1.9.2, Germany). Based on a pooled standardized mean difference ($d \approx 0.7$) reported in a meta-analysis comparing vertical loading rate between rearfoot and forefoot striking runners, we assumed a medium effect size for our repeated-measures design ($f = 0.25$) for the a priori power calculation¹. For our study, a total of 24 participants per condition was estimated to be necessary to detect a difference in AVLRL with an effect size of $f = 0.25$, a statistical power of 0.80, and an alpha level of 0.05. Healthy recreational runners were recruited for this repeated measures experimental study between September 2024 and November 2024 using social media platforms, flyers, and online advertisements at popular local running competitions and running shoe stores, and via athletics federations. Eligibility criteria included age between 18 and 55 years, running with a rearfoot strike pattern, running at least 10 km per week for at least one year, no RRLs in the last three months prior to testing, having a European shoe size between 38 and 46 (approximately US men's sizes 6 to 12). Exclusion criteria included a history of orthopaedic surgery or chronic medical conditions that could affect running biomechanics or performance. This study was approved by the local ethics committee (N°2024/231).

Experimental protocol

Biomechanical variables were collected on an indoor 27.5 m straight running track. Participants performed, with standardised running footwear (®Kalenji, Jogflow 100.1), five continuous running sessions of five minutes each, consisting of repeated back-and-forth runs at a speed of 10 km/h ($\pm 5\%$). The first session consisted of a running speed and running footwear familiarisation. Then, the second session was considered as the “control” condition. The control condition needed to be completed first in order to accurately determine the cadence adjustment required for the subsequent retraining conditions. Finally, the last three conditions were performed in a random order: “cadence”, “forefoot” and “forefoot and cadence”. According to the literature, a minimum of 30 steps per condition was collected on the force plates to ensure sufficient data²⁰. The running speed was verified in real-time using four time gates positioned every six meters on the running track. The experimental setup is illustrated in Figure 1.

Conditions description:

The control condition (CON) involved participants running “as usual”. Runners with a non-rearfoot strike pattern were excluded from the analysis at this point. The cadence condition (CAD) consisted of running with a 10% higher running step rate compared to the step rate measured during the control condition using a metronome. The forefoot condition (FOR) consisted of running with a non-rearfoot strike pattern. The experimenter advised the runners to land on the ball of their foot. Finally, the cadence and forefoot condition (CADFOR) consisted of combining a non-rearfoot strike pattern with a 10% higher running step rate compared to the step rate measured during the control condition using a metronome. A period of self-determined recovery was allowed between the trials to minimise fatigue.

Data collection:

Three-dimensional kinematic data were collected using an optical motion capture system (Qualisys AB, Gothenburg, Sweden) equipped with nine cameras operating at 200 Hz. Five markers were placed on the following landmarks: left and right calcaneus, left and right heads of the fifth metatarsals, and pelvis (midpoint between the left and right posterior superior iliac spines).

The ground reaction force (GRF) data were simultaneously captured using two consecutive force plates (Kistler, Kistler Group, Switzerland) at a sampling rate of 1000 Hz.

Data processing

The stance phase was defined between the instant when the vertical GRF increased above 20 N and the instant when it fell below 20 N. The signal present in the vertical GRF was further analysed using the script provided by Blackmore et al. (2016). The vertical GRF signal was decomposed, for each stance phase, into high and low-frequency components (10 Hz as cutoff value) using the Discrete Fourier Transform ^{3,9,24}. Both high and low-frequency components were then recomposed into the time-domain using the Inverse Fourier Transform to form the two new signals (the high and low-frequency signals, respectively – Figure 2). The impact peak, average and instantaneous vertical loading rate and time-to-impact peak of the high-frequency signal were extracted. Likewise, active peak and time to active peak of the low-frequency signal were also extracted. Impact peak was defined as the maximal value of the high-frequency signal, and time-to-impact peak was defined as the time from initial contact to impact peak. Instantaneous vertical loading rate was the maximal slope of the high-frequency signal during the same period. Average vertical loading rate was calculated as the average slope in the high-frequency signal between 20 and 80% of the period between initial contact and impact peak ³. Active peak was the highest value observed in the low-frequency signal, while time to active peak was defined as the time between initial contact and active peak. Force characteristics were normalised by the participant's body weight.

Each foot was considered as the segment between the heel and the head of the fifth metatarsal. The footstrike angle at initial contact was calculated for both feet using the method described by previous authors ². The footstrike angle was defined by subtracting the foot angle in a standing position from the foot angle at footstrike. A positive footstrike angle indicated dorsiflexion. The cadence was calculated from the total number of left and right foot strikes per passage within the 3D camera capture volume (approximately eight meters in the middle of the track). The running speed was estimated from the derivative of the pelvis marker position.

Kinematic variables were calculated for each gait cycle occurring within the 3D camera capture volume during the five-minute recording and then averaged per subject. Spatio-temporal variables were calculated for each passage within the 3D camera capture volume during the same period and also averaged per subject. Kinetic data were analysed for each gait cycle performed on one or both of the two force plates. Trials were considered valid when the participant's foot landed entirely on a single force plate or partially across both. In the latter case, the vertical ground reaction force components from the two plates were summed point-by-point to obtain a single continuous vertical GRF signal for that stance phase. Data from both limbs were averaged.

Statistical analysis

Statistical analysis was performed using JASP software. The significance level was set at 5%. Initially, a descriptive analysis of the sample was conducted by calculating the mean, standard deviation, minimum, and maximum of the individual variables (age, height, weight, running experience, and training habits) of the participants.

Before analysing the main outcome variables, a repeated-measures ANOVA was performed to compare the running speed, foot strike angle, and cadence across the four conditions (control, cadence, forefoot, and forefoot + cadence). Mauchly's test of sphericity was systematically conducted, and Greenhouse–Geisser corrections were applied to the p-values when necessary.

Subsequently, a repeated-measures ANOVA was conducted to compare the impact-related parameters in the high-frequency signal (impact peak, time-to-impact peak, instantaneous and average vertical loading rate) and low-frequency signal (active peak, time to active peak) across the four conditions. Partial eta squared (η^2) was used to estimate effect sizes, with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively¹¹. When significant differences were observed, a post-hoc analysis was performed with a Bonferroni correction. The mean difference and its 95% confidence interval (95% CI) were calculated for each post-hoc analysis. Cohen's d effect size and its 95% CI were also computed, with effect sizes interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$)¹¹.

Results

Sample description

Data were collected for 26 runners (24 males, 2 females, age = 22.7 ± 2.5 years; mass = 70.4 ± 8.7 kg, height = 1.74 ± 0.06 m, personal best in 5.000 metres race = 21.3 ± 3.7 minutes, volume per week = 23.5 ± 20.0 km, running experience = 5.7 ± 4.4 years).

Effect of conditions on running speed, cadence and footstrike angle

Repeated measures ANOVA highlighted a significant difference in footstrike angle between conditions ($P < 0.001$; $\eta^2 = 0.948$). Post-hoc analysis indicated that footstrike angle was significantly smaller in FOR condition compared to CON ($P < 0.001$; d [95%CI] = 6.2 [4.5 – 7.9]) and CAD ($P < 0.001$; d [95%CI] = 5.6 [4.1 – 7.1]) conditions. Similarly, footstrike angle was significantly smaller in CADFOR compared to CON ($P < 0.001$; d [95%CI] = 6.3 [4.7 – 8.0]) and CAD ($P < 0.001$; d [95%CI] = 5.8 [4.3 – 7.2]).

Repeated measures ANOVA highlighted no significant difference in running speed between conditions ($P = 0.129$; $\eta^2: 0.948$).

Repeated measures ANOVA highlighted a significant difference in cadence between conditions ($P < 0.001$; $\eta^2 = 0.879$). Post-hoc analysis indicated that cadence was significantly higher in CAD condition compared to CON ($P < 0.001$; d [95%CI] = 2.0 [1.1 – 3.0]) and FOR ($P < 0.001$; d [95%CI] = 1.4 [0.7 – 2.1]) conditions. Similarly, cadence was significantly higher in CADFOR compared to CON ($P < 0.001$; d [95%CI] = 2.2 [1.3 – 3.2]) and FOR ($P < 0.001$; d [95%CI] = 1.6 [0.89 – 2.3]). All mean, standard deviations, p-values and effect sizes for the footstrike angle, running speed and running cadence for each condition are available in Table 1.

Effect of running retraining on low- and high-frequency components of impact-related parameters

Effect of running retraining on high-frequency components of impact-related parameters

Repeated measures ANOVA highlighted a significant difference in impact peak between conditions ($P < 0.001$; $\eta^2 = 0.773$). Post-hoc analysis indicated that impact peak was significantly smaller in FOR condition compared to CON ($P < 0.001$; d [95%CI] = 2.0 [1.1 – 3.0]) and CAD ($P < 0.001$; d [95%CI] = 1.4 [0.6 – 2.2]) conditions. Similarly, impact peak was significantly smaller in CADFOR compared to CON ($P < 0.001$; d [95%CI] = 2.3 [1.2 – 3.4]) and CAD ($P < 0.001$; d [95%CI] = 1.7 [0.8 – 2.5]) conditions. Finally, impact peak was significantly smaller in CAD compared to CON ($P = 0.006$; d [95%CI] = 0.6 [0.06 – 1.1]) condition.

Repeated measures ANOVA highlighted a significant difference in time-to-impact peak between conditions ($P = 0.049$; $\eta^2 = 0.132$). Post-hoc analysis indicated that time-to-impact peak was significantly higher in CADFOR condition compared to CON ($P = 0.024$; $d [95\%CI] = 0.6 [4.2 \times 10^{-5} - 1.2]$) condition.

Repeated measures ANOVA highlighted a significant difference in AVLR between conditions ($P < 0.001$; $\eta^2 = 0.743$). Post-hoc analysis indicated that AVLR was significantly smaller in FOR condition compared to CON ($P < 0.001$; $d [95\%CI] = 2.0 [1.0 - 2.9]$) and CAD ($P < 0.001$; $d [95\%CI] = 1.4 [0.6 - 2.2]$) conditions. Similarly, AVLR was significantly smaller in CADFOR compared to CON ($P < 0.001$; $d [95\%CI] = 2.2 [1.2 - 3.3]$) and CAD ($P < 0.001$; $d [95\%CI] = 1.7 [0.8 - 2.5]$) conditions. Finally, AVLR was significantly smaller in CAD compared to CON ($P = 0.029$; $d [95\%CI] = 0.5 [0.01 - 1.1]$) condition.

Repeated measures ANOVA highlighted a significant difference in IVLR between conditions ($P < 0.001$; $\eta^2 = 0.427$). Post-hoc analysis indicated that IVLR was significantly smaller in FOR condition compared to CON ($P < 0.001$; $d [95\%CI] = 0.6 [0.2 - 1.03]$) and CAD ($P = 0.003$; $d [95\%CI] = 0.4 [0.05 - 0.7]$) conditions. Similarly, IVLR was significantly smaller in CADFOR compared to CON ($P < 0.001$; $d [95\%CI] = 0.7 [0.2 - 1.1]$) and CAD ($P < 0.001$; $d [95\%CI] = 0.5 [0.1 - 0.9]$) conditions. All mean, standard deviations, p-values and effect sizes for the impact peak, time-to-impact peak, AVLR and IVLR for each condition are available in Table 2. Individual responses of the impact peak, time-to-impact peak, AVLR and IVLR across running retraining interventions are shown in Figure 3.

Effect of running retraining on low-frequency components of impact-related parameters

Repeated measures ANOVA highlighted a significant difference in active peak between conditions ($P < 0.001$; $\eta^2 = 0.501$). Post-hoc analysis indicated that active peak was significantly smaller in CAD condition compared to CON ($P < 0.001$; $d [95\%CI] = 0.3 [0.06 - 0.7]$), FOR ($P < 0.001$; $d [95\%CI] = 0.8 [0.3 - 1.2]$) and CADFOR ($P < 0.001$; $d [95\%CI] = 0.6 [0.2 - 0.9]$) conditions. Conversely, active peak was significantly higher in FOR compared to CON ($P < 0.001$; $d [95\%CI] = 0.4 [0.09 - 0.7]$) condition.

Repeated measures ANOVA highlighted a significant difference in time to active peak between conditions ($P < 0.001$; $\eta^2 = 0.435$). Post-hoc analysis indicated that time to active peak was significantly smaller in CAD condition compared to CON ($P < 0.001$; $d [95\%CI] = 0.6 [0.2 - 1.0]$) and FOR ($P = 0.004$; $d [95\%CI] = 0.3 [0.04 - 0.7]$) conditions. Similarly, time to active peak was significantly smaller in CADFOR condition compared to CON ($P < 0.001$; $d [95\%CI] = 0.6 [0.2 - 1.0]$) and FOR ($P = 0.004$; $d [95\%CI] = 0.3 [0.03 - 0.7]$) conditions. Finally, time to active peak was significantly smaller in FOR condition compared to CON ($P = 0.049$; $d [95\%CI] = 0.2 [0.03 - 0.6]$) condition. All mean, standard deviations, p-values and effect sizes for the active peak and time to active peak for each condition are available in Table 2. Individual responses of the active peak and time to active peak across running retraining interventions are shown in Figure 3.

Discussion

The research objective of this study was to examine the influence of adopting a forefoot strike pattern or increasing running cadence by 10% on the high- and low-frequency components of

impact forces during running. Our results confirm the hypothesis that adopting a forefoot strike pattern or increasing the running cadence decreases the impact peak and the AVLR measured in the high-frequency signal compared to the control condition. Increasing the running cadence by 10% reduces the impact peak and AVLR measured in the high-frequency signal by 20% and 15%, respectively. Interestingly, adopting a forefoot strike pattern reduces the impact-related parameters measured in the high-frequency signal by nearly three times more than increasing running cadence by 10% alone (impact peak: -53%, AVLR: -57%). In addition, adopting a forefoot strike pattern also reduces the IVLR measured in the high-frequency signal whereas increasing running cadence alone does not affect the IVLR measured in the high-frequency signal. Finally, combining a 10% increase in running cadence and a forefoot strike pattern is the most efficient running retraining to reduce high-frequency components of impact-related parameters. Indeed, a combination of a 10% greater running cadence and forefoot strike pattern reduces the high-frequency components of the impact peak by 61%, the AVLR by 64% and the IVLR by 43%. The reduction in impact-related variables associated with forefoot striking may be attributed to changes in the point of initial contact and ankle stiffness¹⁶. Rearfoot strike typically results in impact beneath the ankle joint, producing a plantarflexion moment. Therefore, the ankle transfers little translational energy into rotational energy, resulting in higher effective mass and increased impact forces¹⁶. In contrast, forefoot strike initiates contact at the anterior portion of the foot, creating a dorsiflexion moment at the ankle, which is controlled by the triceps surae and the Achilles tendon¹⁶. This mechanism allows a portion of the translational kinetic energy to be converted into rotational kinetic energy around the ankle, reducing effective mass due to lower ankle stiffness¹⁶. On the other hand, increasing the running cadence reduces the centre of mass vertical displacement and stride length, thereby reducing vertical impact forces¹⁰. Previous studies have shown that adopting a forefoot strike pattern reduces the high-frequency components of impact-related loading. Gruber et al. (2017) reported lower maximum power, a reduction in the frequency at which peak power occurs, and a decrease in the weighted mean pseudo-frequency in forefoot compared with rearfoot strike. Similarly, Gruber et al. (2014) found lower peak tibial acceleration and reduced signal power in the higher frequency range (9–20 Hz) in forefoot strike runners. Accordingly, the reductions in high-frequency impact peak and loading rates observed in the present study would be expected to coincide with lower maximum power and a shift toward lower dominant frequencies. Finally, our findings are consistent with previous studies that conducted conventional time-domain analyses without separating the signal into low- and high-frequency components. Such studies report that transitioning to a forefoot strike pattern can acutely reduce AVLR by 31–47% and IVLR by 17–47%, while increasing cadence by 10% yields an approximate 8% reduction in AVLR but no measurable change in IVLR^{4,13,15,23,29}. Interestingly, adopting a forefoot strike pattern increased the active peak measured in the low-frequency signal, whereas a 10% increase in cadence reduced it compared with the control condition. These findings are consistent with a previous study showing that forefoot striking is associated with a greater ankle plantarflexor moment during mid-stance, which enhances the vertical ground reaction force before the propulsion phase²⁷. This increase in plantarflexor demand indicates an increased requirement to support body weight vertically during mid-stance, which likely explains the greater active peak observed with forefoot striking..

Conversely, increasing running cadence reduces step length and consequently decreases the mechanical demand needed to support body weight during mid-stance, which may explain the lower active peak observed in the present study.

Recent results from a randomised controlled trial involving over 800 runners suggest that higher AVLR measured in the high-frequency signal is associated with increased risk of RRIs¹⁷. Our findings indicate that a running retraining intervention combining a forefoot strike pattern and a 10% higher cadence may reduce the high-frequency components of the AVLR by 64%. Therefore, adopting a forefoot strike pattern and increasing running cadence may reduce the risk of RRIs by lowering the high-frequency component of the AVLR. However, injury development is not solely determined by the magnitude or frequency content of the impact forces, but also by how the body responds to and attenuates the vibrations induced by these impacts²¹. Different running strategies may modify both the mechanical input and the body's capacity to dissipate high-frequency vibrations, thereby influencing the mechanical load experienced by tissues²¹. Prospective studies are needed to explore if an intervention targeting an impact reduction of the high-frequency signal could reduce the risk of RRIs.

Several limitations should be considered before generalising the results of this study. First, the study sample was predominantly male ($n = 24$), and sex-specific responses to running retraining may differ. Caution is therefore warranted when generalising the findings to female runners²⁸. Second, the protocol was conducted in a laboratory on a 27.5-metre straight runway, requiring participants to turn frequently, which may have introduced biomechanical variability and reduced gait stability compared to treadmill running¹⁴. Third, a standardised running shoe was used to control for cushioning effects. Since participants were unfamiliar with the model, this may have influenced their natural running biomechanics¹². Finally, it was not possible to impose a precise foot strike angle during the running protocol. Although mean foot strike angle values were similar between the cadence and control conditions, unintentional shifts toward a more anterior foot strike cannot be entirely excluded. Therefore, the effects attributed to cadence retraining may partially reflect concurrent modifications in foot strike pattern.

Conclusion

In conclusion, adopting a forefoot strike pattern reduces high-frequency components of impact-related parameters nearly three times more than increasing running cadence by 10% alone. However, combining a forefoot strike pattern with a 10% increase in running cadence appears to be the most effective running retraining strategy for reducing high-frequency components of impact-related parameters. This combined approach may contribute to lowering the incidence of RRIs, although prospective interventional studies are required to confirm this potential benefit.

Declaration of conflicting interests

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Legends

Table 1. Comparison of footstrike angle, running speed and running cadence between running conditions to ensure protocol validity.

Table 2. Comparison of impact-related parameters of low- and high-frequency components of impact-related parameters between conditions.

Figure 1. Illustration of the experimental setup.

Figure 2. Example of curves from one participant showing an identified impact peak on the vertical ground reaction force (GRF) signal. The blue line represents the participant's vertical GRF signal, while the red and green lines correspond to the reconstructed high-frequency (HiF) and low-frequency (LoF) components, respectively.

Figure 3. Individual responses of impact-related parameters across running retraining interventions (CON = Control; CAD = Cadence +10%; FOR = Forefoot strike pattern; CADFOR = Cadence +10% and Forefoot strike pattern). Facets display individual data points per condition, grouped by subject. Metrics include impact peak, time to impact peak (time to IP), average vertical loading rate (AVLR) and instantaneous vertical loading rate (IVLR) of the HiF and active peak, time to active peak (Time to AP) of the LoF, BW = Body weight.