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# Immediate effect of visual, auditory and combined feedback on foot strike pattern

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## ABSTRACT

**Background:** A growing body of literature supports the promising effect of real-time feedback to re-train runners. However, no studies have comprehensively assessed the effects of foot strike and cadence modification using different forms of real-time feedback provided via wearable devices.

**Research question:** The purpose of the present study was to determine if a change could be made in foot strike pattern and plantar loads using real-time visual, auditory and combined feedback provided using wearable devices.

**Methods:** Visual, auditory and combined feedback were provided using wearable devices as fifteen recreational runners ran on a treadmill at self-selected speed and increased cadence. Plantar loads and location of initial contact were measured with a flexible insole system. Repeated measures ANOVAs with Bonferroni adjusted pairwise comparisons were used to assess statistical significance.

**Results and significance:** A significant effect of condition was noted on location of center of pressure ( $p < 0.01$ ). Bonferroni-adjusted post-hoc comparisons showed that feedback conditions differed from baseline as well as the new cadence conditions, however did not differ from each other. A significant interaction effect (region  $\times$  feedback) was found for plantar loads (maximum force  $P < 0.001$ ). Significant effects of feedback were noted at the heel ( $P < 0.001$ ), medial midfoot ( $P < 0.001$ ), lateral midfoot ( $P < 0.001$ ), medial forefoot ( $P = 0.003$ ), central forefoot ( $P = 0.003$ ), and great toe ( $P = 0.004$ ) but not at the lateral forefoot ( $P = 0.6$ ) or lateral toes ( $P = 0.507$ ).

**Significance:** The unique findings of our study showed that an anterior shift of the center of pressure, particularly when foot strike modification was combined with 10% increased cadence. We found lower heel and midfoot loads along with higher forefoot and great toe loads when foot strike modification using real-time feedback was combined with increased cadence. Our findings also suggest that auditory feedback might be more effective than visual feedback in foot-strike modification.

## 1. Introduction

Running is a popular activity associated with substantial health benefits [1]. However increasing evidence has revealed a high incidence (5–70%) of running-related injuries [2,3]. High levels of different aspects of vertical loading have been linked with the development of running injuries [3,4]. Consequently, several recent studies have proposed interventions such modifying cadence or foot strike pattern [4–7] to reduce vertical loads and attendant injury risk.

Objective evidence in support of this hypothesis comes from studies reporting reduced vertical loading with cadence retraining. A number

of individual studies as well as a recent systematic review have noted that a 10% increase in cadence is accompanied by significantly decreased vertical loading [8–10]. Similarly, a small but growing number of studies have explicitly focused on foot strike pattern re-training, and have also reported significantly lower loading with mid- or forefoot strike patterns. Cheung and Davis (2011) found a 10–35% reduction in vertical loading parameters accompanied by symptomatic relief following an 8-week intervention that targeted foot strike patterns in runners with patellofemoral pain [11]. Similar reductions in vertical loading were reported in runners with chronic exertional compartment syndrome after 6 weeks of forefoot strike training [12]. Interestingly,

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**Fig. 1.** Visual feedback instrumentation: sock (a), ankle (b), and display on a tablet (c). Bright colors (orange, red, or yellow) indicate high pressure, while blue indicates/ low pressure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

one recent study noted that increasing cadence resulted in a transition from a heel strike to a mid-foot or forefoot strike pattern [13]. However, this change in foot strike pattern with cadence retraining was only noted in a small sub-group (18–30%) of the study sample. Taken together, these studies provide robust evidence that a 10% increase in cadence is accompanied by reduced vertical loading. However, it is not known whether adding footstrike re-training will confer additional benefits. No studies have assessed whether combining the two approaches i.e. simultaneously altering both foot strike pattern and increasing cadence during running, will provide greater decreases in vertical loading compared to cadence re-training alone.

Recent advances in technology have made it feasible to use real-time feedback training to modify running techniques. Most studies have used a metronome to change cadence [8–10]. Both auditory and real-time visual feedback have been used to change foot strike patterns [14–17]. Auditory feedback about footstrike pattern, such as a warning beep to discourage participants from landing on the heel, has been shown to facilitate a forefoot strike pattern [11]. While visual feedback has been used to train runners to adjust impact loading by decreasing vertical ground reaction forces [15,16], only one study has used visual feedback to change foot strike pattern. Diebal et al. (2011) used video and instructions to facilitate the use of a forefoot strike pattern [12]. Taken together, these studies suggest that both auditory and visual feedback can be used to alter foot strike pattern. However, the combined effect of the two feedback mechanisms has not been examined. Simultaneous use of both auditory and visual feedback may provide even greater re-training effects. Additionally, most previous studies have used lab-based systems to provide visual feedback i.e. real-time feedback has been provided using a computer monitor in front of a treadmill. While a number of wearable devices have been developed for running re-training, there is no objective evidence examining their efficacy.

Several studies have quantified vertical loading during running using a force plate, a recent systematic review highlighted the utility of insole-based systems that can quantify loads at the foot-shoe interface [18]. In addition to the magnitude and timing of loads, these systems can also provide valuable insights about the distribution of loads at the foot-shoe interface. Using this approach, Wellenkotter et al. (2014) showed that increasing cadence by 5% decreased both heel and metatarsal loads [19]. Use of a forefoot strike pattern resulted in a 33–38% increase in forefoot loads [20,21]. However, no studies have assessed plantar loads while simultaneously altering both foot strike pattern and

cadence during running.

The purpose of the present study was to determine if a change could be made in foot strike pattern and plantar loads using cadence and foot-strike modification using real-time visual, auditory and combined feedback. The findings of this study will address important gaps in the running re-training literature and provide several novel insights. First, we will assess the effects of simultaneously changing both foot strike pattern and cadence. Second, we will clarify the role of visual versus auditory versus combined feedback in altering foot strike pattern. Third, we will use wearable devices to provide real-time feedback. These data have direct clinical relevance in the development and implementation of evidence based running re-training strategies.

## 2. Methods

### 2.1. Subjects

All study procedures were approved by the Institutional Review Board. A total of 15 recreational runners who were habitual rearfoot strikers [males = 4, females = 11, mean age = 25.67 ( $\pm$  3.99) years, mean weight = 61.95 ( $\pm$  7.81) kg, mean height = 1.69 ( $\pm$  0.07) m, and mean BMI = 21.83 ( $\pm$  2.95)] volunteered for the study. They all ran at least twice a week for at least 30 min per session. Prior to participation, all participants provided Informed Consent.

### 2.2. Instrumentation

#### 2.2.1. Plantar loads

Flexible, instrumented, appropriately-sized insoles were placed in the shoes of the participant (Pedar<sup>®</sup>-X; Novel Inc., St. Paul, MN). The insoles were approximately 2 mm in thickness. Each insole was composed of 99 capacitive sensors, and was sampled at 100 Hz, using a telemetry-based system.

#### 2.2.2. Visual feedback for foot contact

Participants donned socks (Sensoria<sup>®</sup>, Sensoria Inc., Redmond, WA 98052) (see Fig. 1). Each sock is a smart garment made with conductance yarn and had sensors located at the center of the heel, the medial ball of the foot, and the lateral ball of the foot. The sensors connected to a magnetic cuff/anklet at the proximal cuff (approximately 3 cm above the ankle joint). The magnetic cuffs connected via Bluetooth to the Sensoria app on a tablet (iPad Mini,

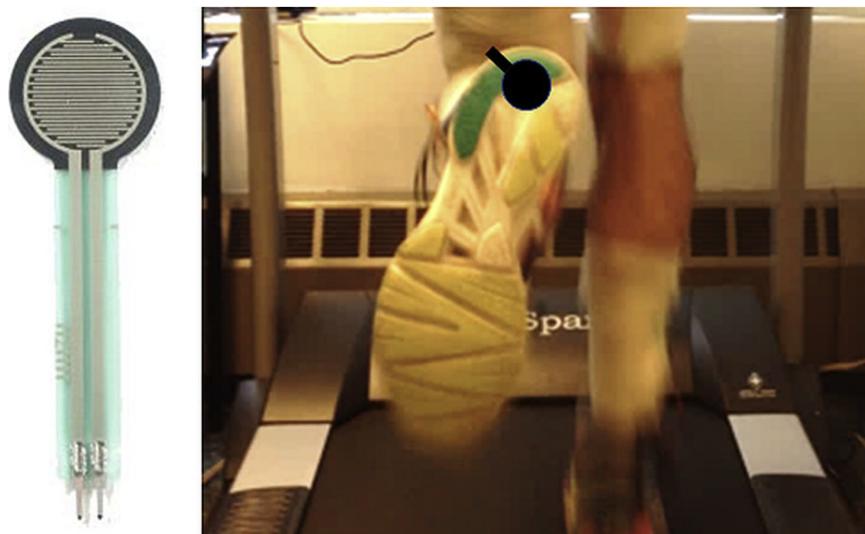


Fig. 2. Auditory feedback instrumentation. Foot switch (left) and its placement on the heel (right).

MD528LL/A, Apple Inc., Cupertino, CA).

### 2.2.3. Auditory feedback for foot contact

A custom-made auditory feedback device was built (see Fig. 2) and consisted of foot switches (MA-153 event switches; Motion Lab Systems Inc., Baton Rouge, LA) connected to a microcontroller (Arduino UNO; Atmel Corporation, San Jose, CA), buzzers (GP-1405; Challenge Electronics, Deer Park, NY), and a 9-volt battery. Each foot switch was placed at the middle of the heel cushion of the participant's shoe, while the microcontroller was placed at the middle of participant's arm and secured with pre-wrap.

### 2.3. Data acquisition

After the participant warmed up by walking at a comfortable fast pace on the treadmill for 3 min, they started running at their self-selected speed (ranged between 5–10 mph) and their self-selected cadence for 5 min. This was the baseline condition (BASELINE). Next, the cadence was increased by 10% using a metronome set at 10% above their baseline cadence (NEW CADENCE). Then, while running at the same speed with the new cadence, three feedback conditions were presented with the order counterbalanced (VISUAL, AUDITORY, COMBINED). Each feedback condition lasted 5 min. The participants were allowed to rest between conditions in order to set up the instrumentation for feedback and to re-calibrate the flexible instrumented insoles.

For each feedback condition, the participant was asked to “try not to land on your heel”. Foot strike visual feedback (VISUAL) was provided by means of the display on the iPad Mini (Fig. 1). Foot strike auditory feedback (AUDITORY) was provided by means of a single beep when the participant landed on the event switches on their heels (Fig. 2). During the COMBINED condition, participants received feedback from both the app on the iPad Mini and the beep from the custom-built device.

### 2.4. Data analysis

Consistent with the literature, plantar pressure loading data from the last 30 s of each condition were analyzed [19–21]. First, data were inspected visually to ensure consistency. Next, for each condition, the center of pressure location at initial contact was calculated and expressed as a percentage of the insole length. Lastly, the foot was subdivided into the following regions of interest: heel; medial and lateral midfoot; medial, central, and lateral forefoot; great toe; and lesser toes.

The maximum force was calculated in each region using Novel Projects software (Novel Inc., St. Paul, MN).

### 2.5. Statistical analysis

Assumptions related to normality and variance homogeneity were examined. A repeated measures one-way ANOVA was used to determine if statistically significant differences existed between conditions. First, the location of center of pressure at initial contact was analyzed. Bonferroni-adjusted post-hoc comparisons were used to determine the statistical significance of pair-wise comparisons.

Next, a two-way fixed effects ANOVA was used to examine the effect of plantar regions and feedback conditions on maximum force. Interaction effects were assessed first. If the interaction effect (Region x Feedback conditions) was significant, a one-way ANOVA was used to examine the effect of feedback conditions at each foot region (simple main effects). To control for type 1 error, Bonferroni-adjusted comparisons were used for post-hoc testing. All analyses were done using the SPSS software, version 23 (SPSS Inc, Chicago, IL).

### 3. Results

Representative data are presented in Fig. 3. Mean (SD) center of pressure location at initial contact along the long axis of the insole, expressed as a percentage of insole length, is summarized in Table 1. Bonferroni-adjusted post-hoc comparisons showed that feedback conditions differed from baseline as well as the new cadence conditions, however did not differ from each other.

A significant interaction effect (region x feedback) was found for maximum force ( $P < 0.001$ ). Subsequently, simple main effects (the effect of feedback at each region) were evaluated. A significant effect of feedback (Table 2) was found at the heel ( $P < 0.001$ ), medial midfoot ( $P < 0.001$ ), lateral midfoot ( $P < 0.001$ ), medial forefoot ( $P = 0.003$ ), central forefoot ( $P = 0.003$ ), and great toe ( $P = 0.004$ ) but not at the lateral forefoot ( $P = 0.6$ ) or lateral toes ( $P = 0.507$ ). Significant Bonferroni-adjusted post hoc interactions are indicated in Fig. 4.

### 4. Discussion

The chief objective of this study was to examine the effect of simultaneously altering both, cadence and foot strike pattern, using real-time visual, auditory, and combined feedback during running. We used wearable devices to provide real-time feedback and facilitate foot strike

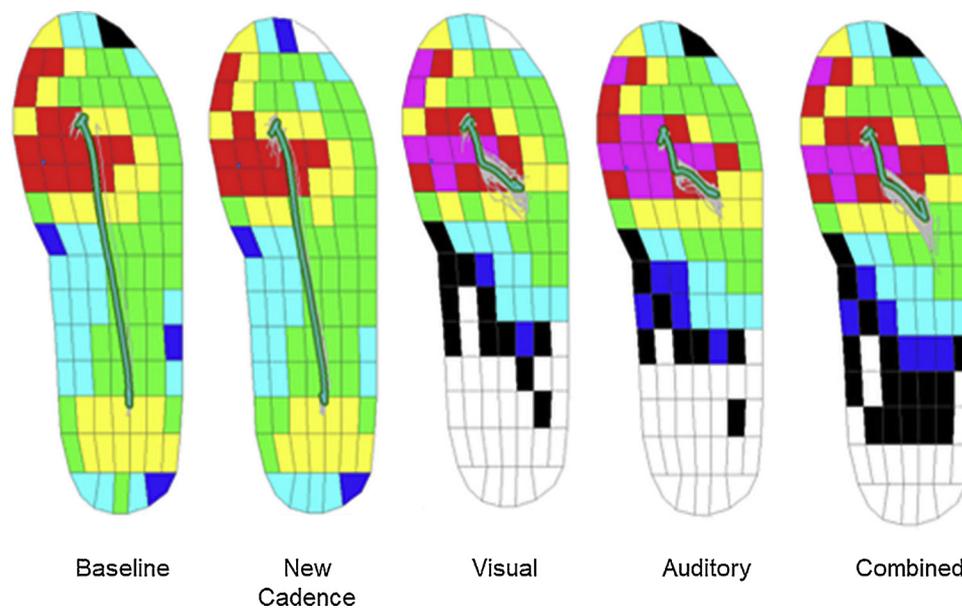


Fig. 3. Representative plantar loading and center of pressure for each condition from a single subject. Each image represents 30 s of data.

Table 1

Center of pressure location at initial contact along the long axis of the insole expressed as a percentage of insole length.

Condition	Mean $\pm$ SD
Baseline	21.45 $\pm$ 3.38
New Cadence	27.47 $\pm$ 5.02
Visual	58.76 $\pm$ 4.27 <sup>a,b</sup>
Auditory	66.80 $\pm$ 1.36 <sup>a,b</sup>
Combined	66.96 $\pm$ 1.45 <sup>a,b</sup>

<sup>a</sup> Indicates statistically significant difference from baseline condition ( $p < 0.01$ ).

<sup>b</sup> Indicates statistically significant difference from new cadence condition ( $p < 0.01$ ).

Table 2

Significant interaction of conditions and region was found  $F = 17.836$ ,  $p < 0.001$ . A significant effect of conditions was found at each region. Significant Bonferroni-adjusted post hoc comparisons are indicated in Fig. 4 and described in the text.

Region	P Value
Heel	$p < 0.001$
Medial Mid Foot	$p < 0.001$
Lateral Mid Foot	$p < 0.001$
Medial Fore Foot	$p = 0.003$
Middle Fore Foot	$p = 0.003$
Lateral Fore Foot	$p = 0.6$
Big toe	$p = 0.004$
Lateral toes	$p = 0.507$

modification during running. For visual feedback, a novel smart garment and app was used, and a custom-built device using event switches and a buzzer was used to provide auditory feedback. The key findings of our study noted significant differences in location as well as magnitude of loading, discussed in detail below.

The results of our study indicate that simultaneously altering cadence and foot strike changes the location of loading during running retraining (Table 1, Fig. 1). During the baseline condition, the center of pressure showed a characteristic pattern, moving proximal to distal from initial contact to toe off, similar to the pattern described by

Kernozek et al. (2016) [21]. With a 10% increase in cadence, a modest anterior shift of the center of pressure was noted at initial contact. These changes are consistent with less foot inclination at initial contact (a more plantarflexed ankle) that has been reported when runners increase their cadence by 10% [8,13,22].

The anterior shift of the center of pressure was significantly more pronounced when foot strike modification was combined with increased cadence (Fig. 3). The anterior shift of the center of pressure has important implications for musculoskeletal loading, since it reduces the demand on the knee extensors but increases the demand on the ankle plantarflexors [23]. Several studies have showed that midfoot or forefoot striking during running necessitates increased activation of the gastrocnemius muscle and decreased activation of the tibialis anterior [24–26]. The increased demand on the calf muscle complex is supported by recent data showing increased Achilles tendon stress during forefoot striking [27]. Taken together these findings support the beneficial effects of a forefoot strike pattern in individuals with anterior knee pain [11] but not in individuals with calf strain or Achilles tendon-related symptoms [28].

While previous studies have assessed the individual effects of cadence re-training and foot-strike pattern modification on plantar loads [19,21], our approach is unique in that we assessed the effect of simultaneously altering both foot strike pattern and cadence on plantar loads sustained during running. When cadence was increased by 10%, we found trends towards **lower** plantar loads. The reduction was most evident at the heel (11% decrease in maximum force), and less dramatic reductions were noted at the midfoot and forefoot (2–5% reduction in maximum force). Consistent with the work of Wellenkotter et al. (2014), we did not find evidence for increased metatarsal loading with increased cadence [19]. Taken together, our results suggested that a 5–10% increase in cadence does **not** significantly increase the maximum force sustained at the metatarsal heads.

When foot strike modification was combined with increased cadence, significant **reductions** in heel (80% decrease in maximum force) and midfoot (40% decrease in maximum force) loads were noted. Additionally, significant **increases** in forefoot (10–36% increase in maximum force) and great toe (30% increase in maximum force) loads were found. Higher forefoot loads have important clinical implications as a potential mechanism contributing to the risk of metatarsal stress fractures [29]. The unique findings of our study suggest that running with a 10% increased cadence might slightly decrease forefoot loads,

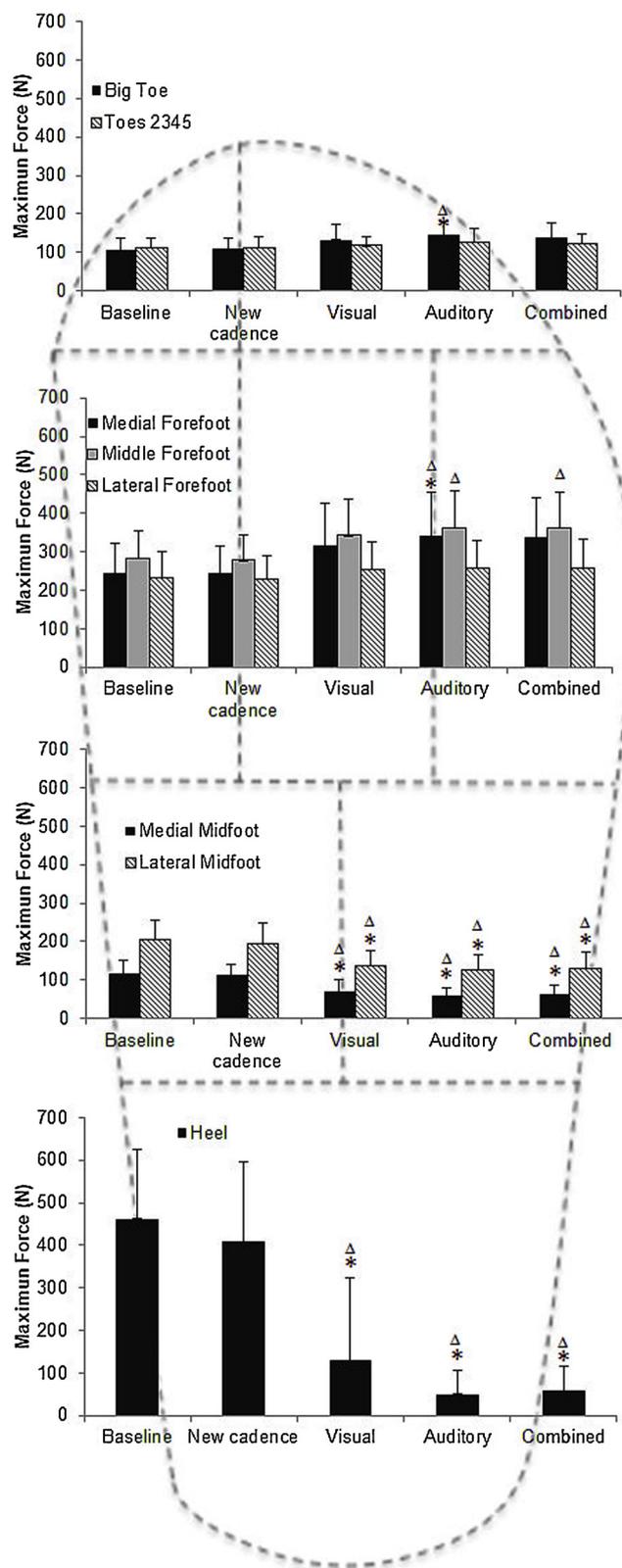


Fig. 4. Schematic depiction of maximum force in the regions of interest across the five conditions. Error bars indicate standard deviation. Significant Bonferroni-adjusted pair-wise comparisons compared to the Baseline Condition are indicated by \*; significant Bonferroni-adjusted pair-wise comparisons compared to the New Cadence condition are indicated by Δ.

but a forefoot strike pattern may be expected to worsen symptoms in an individual at risk for metatarsal stress reaction due to the substantially increased forefoot loads accompanying this pattern. Overall, greater changes were noted on the medial aspect of the foot compared to the lateral. The reduction in loading at the medial midfoot combined with increased loading at the medial forefoot and great toe might indicate increased demands on the flexor hallucis longus, tibialis posterior, peroneus longus, and intrinsic muscles of the foot. Future studies are needed to evaluate this hypothesis using musculoskeletal models with/ or electromyography to evaluate the individual and combined roles of these muscles.

The effect of feedback varied by foot region. At the heel, medial midfoot, and lateral midfoot, all feedback conditions resulted in significantly lower maximum force compared to the baseline and new cadence conditions. The effects of feedback were more variable at the forefoot and great toe. Auditory, but not visual feedback, resulted in a significant increase in maximum force at the medial forefoot, central forefoot, and great toe. Our results were in agreement with a growing body of literature suggesting that auditory feedback may be more effective than visual feedback in running re-training [14,30].

In addition to our findings, our methods are also novel, in that we used wearable devices for real-time feedback training. Most previous studies have used a computer monitor with real-time graphs for displaying visual feedback [11,15,30]. While these methods allow the researcher full control of the experimental set-up, they are not portable. Consequently, opportunities for running re-training are limited to the lab setting. Recent advances in wearable technology have made a variety of options available for running re-training, however objective evidence evaluating wearable devices is lacking in the scientific literature. The devices used for visual and auditory feedback in the current study can be used not only in lab or clinic settings but also in outdoor training and habitual running environments. Wearable devices have enormous potential for running-retraining and our preliminary positive findings provide support for their feasibility and utility.

The chief limitations of our study were its relatively small and homogenous sample of injury-free recreational runners who were all habitual rearfoot strikers. Nevertheless, the lack of confounding factors, such as previous injury status or current level of pain allowed us to evaluate the effect of feedback conditions on plantar loads with confidence. Future studies should focus on subgroups at higher risk of running-related injuries and on the long-term effects of foot strike modification using feedback.

In summary, we examined the effect of altering foot strike pattern using real-time visual, auditory, and combined feedback. Additionally, we assessed the effect of simultaneously altering both foot strike pattern and cadence on plantar loads sustained during running. We used wearable devices to provide real-time visual and auditory feedback. The key findings of our study showed that the anterior shift of the center of pressure was significantly more pronounced when foot strike modification was combined with increased cadence. We found significant reductions in heel and midfoot loads along with significant increases in forefoot and great toe loads when foot strike modification using feedback was combined with increased cadence. Last but not least, our results suggest that auditory feedback might be more effective than visual feedback in foot-strike modification. With rapid growth in apps and smart garments available for tracking movement, runners and their health providers face a plethora of choices when choosing how to train (or retrain) running technique. The findings of our study contribute to the literature by providing objective data to help guide decision making and avoid increased injury risk.

**Declaration of Competing Interest**

Nothing to disclose.

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