StrikeGuide: Modulating Foot Strikes During Running Using Ambient Auditory Feedback

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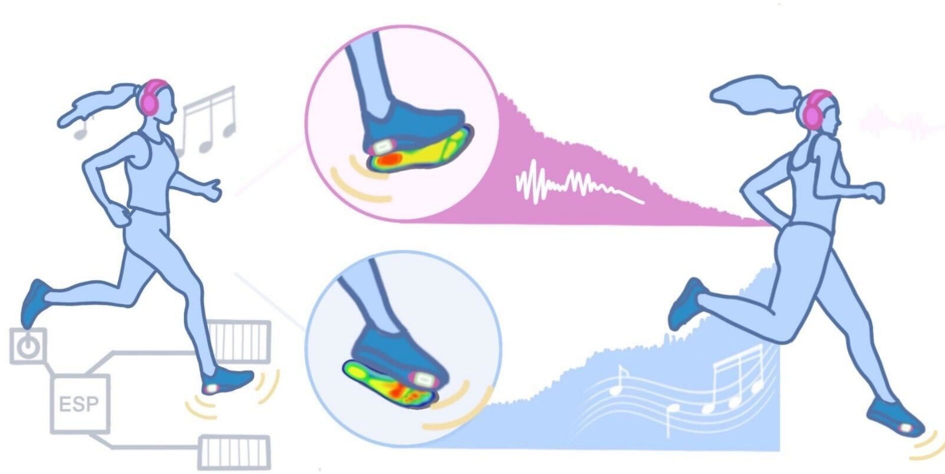

Figure 1: This work presents *StrikeGuide*, a sensor-based running system that adapts a user's running style using adaptive auditory feedback. *StrikeGuide* has been designed through engaging with interviews and surveys, with the motivation to improve the running practices of runners while reducing the risk of injuries. *StrikeGuide* utilizes two force-sensitive resistors at the front and back of the runners' shoes, thus estimating foot strike patterns and creating awareness about them using auditory feedback.

Abstract

Running is a popular physical activity to increase fitness and foster a healthy lifestyle. However, an erroneous running technique increases the risk of injury. Providing feedback on their technique to runners can potentially contribute to their well-being and satisfaction. This work investigates how to support runners in correcting their running technique in real-time. Informed by interviews ($N = 14$) with runners and validation questionnaires ($N = 78$), we designed and implemented *StrikeGuide*, a sensor-based system that detects the runner's foot strike and provides real-time auditory feedback. Our system helps the user avoid excessive force on the foot while running. The preliminary evaluation ($N = 7$) of *StrikeGuide* showed a significant reduction of excessive foot strikes when using ambient auditory feedback. We discuss how future running systems can support gait awareness in real time to enhance the running experience.

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CCS Concepts

• **Human-centered computing → Ubiquitous and mobile computing**; *Human computer interaction (HCI).*

Keywords

Feedback, HCI for Sports, Physical Activity, Running, Sensors

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1 Introduction

Almost 50 million people in the United States are running or jogging on a regular basis [47].Running is an attractive sport because it improves overall health, cardiovascular fitness, and stamina without depending on another person or cost-intensive equipment apart from running shoes. It further counterbalances the daily work routine and other stressful factors in everyday life. Advances in technologies in the fitness market have further strengthened the trend. Apps and fitness trackers enable the user to record different parameters, such as location, number of steps, running pace, and distance, which generate a training history over time. Yet, despite the fact that recreational runners are often unaware of what a healthy and correct running style looks like, most commercial systems that support running ignore the notion of running form.

Consumer apps rarely provide a genuine understanding of the running technique as they are usually not designed to provide detailed insights and parameters for measuring a healthy running strike, such as the Foot Strike Types (FSTs). The FST is, among others, a crucial factor during running to avoid injuries [2, 12]. Disadvantageous foot strikes can cause high orthopedic strain on the joints or increase the risk of twisting the ankle because of the flat surface [7, 57] or causing stress-induced fractures [61]. Runners can reduce the risk of injuries by adopting a proper running technique [48]. Studies show that runners are often unaware of their strike type [22], and such awareness may offer benefits [8]. Runners require concentration to run with proper technique and find an adequate pace for the current training state. Constantly focusing on the surroundings and paying attention to the FST can impact concentration, thus letting runners slip in their running technique. Consequently, runners easily fall back into bad running behaviors without noticing, causing joint pain over the long term. This raises the need for a feedback system. For example, introducing an external focus of attention [60] to direct the attention back to the proper technique can positively influence runners to acquire the correct technique. At the same time, current feedback mechanisms require runners to perceive feedback that can be challenging while running (e.g., perceiving haptic feedback while being under vigor running [23]). Real-time feedback, for example, from some commercially available wearable systems, can effectively reduce severe injuries for recreational runners [53]. While the benefits of providing form feedback during running are clear, it remains a challenge for HCI for sports to understand how such feedback should be delivered, customized for the individual user and integrated into everyday running practice.

In order to explore the research challenge of how interactive systems can effectively support running form, we utilized a user-centered approach and conducted interviews with runners ($N = 14$) to understand contemporary running behaviors, running metrics, and desired feedback to make users more aware of the FST. Using the interviews, we summarized design factors for a sensor-based feedback system in a running context, emphasizing the FST as a relevant factor to consider during running sessions. Then, a follow-up questionnaire ($N = 78$) revealed auditory stimuli as a suitable feedback mechanism for notifying users about their FST behavior. The insights from the interviews influenced the design and implementation of *StrikeGuide*, a running system using auditory feedback to modulate runner FSTs. Inspired by previous work [23], we used force-sensitive resistors (FSRs) to detect and classify the FST of runners. *StrikeGuide* then gives the user real-time feedback when not running with the desired FST. We opted for auditory real-time feedback because the user then notices immediately when to adapt the movement and focus more on the running technique again [24]. We evaluated *StrikeGuide* in a within-subject study ($N = 7$) to observe the changes in the running technique using *StrikeGuide*. Our results show that the FST was modulated successfully using *StrikeGuide*, indicating that our approach will facilitate more awareness of one's running technique. Our work sets the boundaries for integrating real-time feedback to change suboptimal running habits.

2 Related Work

Here, we discuss past research that influenced our work, reviewing technologies for running and focusing on in-situ feedback during running.

2.1 Runner Support Technologies

Running has long been a popular form of exercise, and its popularity has only grown with technology integration. Various research studies in the field of HCI looked at different aspects of running, from motivation to performance analysis. Knaving et al. [25] investigated motivation technologies for advanced amateur runners. While many studies focus on motivating non-runners, Knaving and colleagues sought to understand what drives committed runners, especially those participating in organized races. Their findings suggest that while flow theory can be useful for understanding in-race support, various other factors must be considered when designing for this domain. As a consequence, these studies introduce design requirements for runners with insights into the lived experience of technology while running. Lastly, Tholander and Nylander [51] conducted interviews with elite and recreational athletes to understand the experiential aspects of endurance sports and the role of wearable sports technology. They concluded that while technology plays an instrumental role in measuring performance, it also plays an experiential role, enhancing the overall sports experience.

Another strain of work explored how technology can support the social aspect of running. Curmi et al. [10] embedded an online crowd inside a relay baton. This digital relay baton connects long-distance runners with online spectators. As the runner progresses, the baton broadcasts live location data to an online social network and, in return, communicates back remote crowd support through haptic and audible cheers. Their work provides insights into designing real-time techno-mediated social support for runners. Mueller [36] explores the social dynamics of jogging by introducing "Jogging over a Distance," a system that uses spatialized audio to simulate the experience of jogging with a partner even when the participants are geographically separated. This innovative approach addresses the common challenge of finding compatible jogging partners in one's vicinity and harnesses technology to maintain motivation and social connections among joggers. Mueller and Muirhead further studied technology support for social running in "Jogging with a Quadcopter" [35]. They introduce a quadcopter as a robotic jogging companion, demonstrating how flying robotic systems can enhance the jogging experience. Through analysis of user interactions with the quadcopter, they present design dimensions and tactics for future robotic systems that support physical exertion activities.

Finally, HCI investigated how runners can use interactive tools to explore data about running. McGookin and Brewster [32] investigated how map data can support enjoyable, undirected running practice. While running is a strong theme in the HCI for sports [37] landscape, limited attention is devoted to evaluating the design and implementation of adaptive running interfaces which take the current user state and performance into account and that contribute to the physical well-being of runners. Our work addresses that gap.

2.2 Systems for In-Run Feedback

Recent advances in wearable technologies offer opportunities for providing runners with real-time feedback during their runs. Mencarini et al. [33] provided a comprehensive literature review on wearable systems in sports, analyzing the different research perspectives, types of sports and athletes, roles of wearables, their *wearability*, and types of feedback. Their review identifies multiple opportunities for future research, emphasizing the potential of wearable technologies in reshaping the sports domain. Colley et al. [9] addressed shoes as a platform for wearable displays. They presented a sports shoe display prototype integrated with LEDs to indicate the wearer's running pace relative to a preset target pace. Initial findings from their study suggested that the ambient, peripheral visibility of the shoe display was appreciated by regular runners and seemed fitting for the running activity. Woźniak et al. [59] investigated how shoe-worn sensors can be leveraged to provide insights into runners' techniques. They developed *GraFeet*, an augmented running shoe that visualizes kinesiological data about a runner's feet and gait. Their results indicated that *GraFeet* was perceived as more user-friendly and produced more insights with less confusion than a standard sensor dashboard. Phanpho et al. [40] showed that feedback during running can change the running behavior. Their study evaluated the impact of visual, auditory, and combined feedback on the foot strike performance. Their results suggest that auditory feedback might be more effective than visual feedback in foot-strike modification. The work by Hassan et al. [23], known as *FootStriker*, utilized Electrical Muscle Stimulation (EMS) combined with an insole equipped with force-sensing resistors. The device detects heel striking and actuates the calf muscles to control the foot angle before landing, thereby promoting mid or forefoot running. However, it is worth noting that while this approach showed potential in reducing heel striking, the underlying assumption that forefoot strike is universally beneficial can be challenged [30, 56]. Moreover, the electrical muscle stimulation feedback method could be considered invasive and potentially kinesiologically harmful. Therefore, we have considered a less invasive feedback modality by providing auditory feedback. Sigrist et al. [46] have shown that auditory alarms that notify a user through sound modulation when a certain threshold is exceeded are sufficient to inform users about bad behavior and result in observable changes in, e.g., breathing rhythm [55] or adapted gait patterns [4, 18]. Past work in kinesiology has shown that auditory feedback can be effective [40]. Yet, it remains a question if and how such feedback affects the running experience. In contrast, our work addresses fostering a desired strike pattern without invasive measures. Our approach is interestingly different from past work as our design goal is to inform the runner in real time about their gait pattern and allow the runner to autonomously adjust (or not) their running technique.

Music is often employed as a tool to motivate and pace runners. The *DJogger* system [6] builds a model of a runner's pace and dynamically adjusts the musical soundtrack based on this information. Rushton and Kantan [42] built a system that detects temporal asymmetry in the running style and notifies runners through gait sonification. Another study by Bauer and Kratschmar [5] synthesized sports science and psychology findings to provide requirements for designing a music-controlled running application, highlighting music's potential role in increasing casual runners' motivation and controlling training. These works inspire this paper as we explore the use of sound in fostering improved running techniques.

While the systems above assume that running technique can and should be modified through feedback, the broader literature on running biomechanics raises important nuances. Research on self-optimization suggests that experienced runners naturally converge on a gait that is metabolically efficient for their individual physique [15], with preferred stride parameters lying within approximately 3% of the mathematically derived optimum. This view is supported by a recent systematic review and meta-analysis by Moore [34], which found low- to moderate-certainty evidence that gait retraining interventions do not improve running economy or performance, noting that technique modification may in fact increase metabolic demands in runners who have already self-optimized. Moore explicitly states that nudging runners to change their gait patterns for the purpose of improving running economy should be approached with caution. These findings suggest that universal prescriptions for "correct" running form are difficult to justify, and that the value of feedback systems may lie less in enforcing a target gait pattern and more in raising awareness and supporting autonomous, informed decision-making. This directly informs the design philosophy of the system presented here: rather than prescribing a particular technique, our system provides runners with real-time insight into their gait.

3 Study Methodology

Running is an activity that requires special considerations when designing for it. It includes the whole body in the movement, which impedes, e.g., deciphering information on a smartphone display or smartwatch on the wrist. Additionally, the activity imposes risks of injury when done incorrectly. Therefore, developing effective feedback loops for running is essential for supporting runners, minimizing injuries, and, in general, enhancing the overall training experience. We followed a user-centered approach to learn about this context's design requirements. All steps in our process are shown in Figure 2. We begin by conducting semi-structured interviews with recreational runners at different levels of running experience to better understand runners, gain comprehensive insights, and observe behaviors. We used the insights to identify design factors that serve as guidelines for real-time feedback systems and support their development and evaluation. We then conducted an online survey to comprehend runners' perceptions of technologies for providing real-time feedback during running. We then applied these insights in the prototype *StrikeGuide*, a wearable real-time feedback system for running. Lastly, we evaluated the prototype in a proof-of-concept study.

The interviews and questionnaire aim to answer the following research questions:

RQ1: What are the design factors for sensor-based feedback for running form?

RQ2: What metrics are important for assessing running technique and performance from a runner's perspective?

RQ3: How can user interfaces support runners in becoming more aware of their running form?

Based on the findings, we developed *StrikeGuide* as a system to promote gait pattern awareness. We pose the following research question to evaluate the feasibility of *StrikeGuide*:

RQ4: How can a system be designed to support runners in achieving their desired running form?

4 Design Considerations & Process

We began by conducting interviews with runners from a local running group. The interviews focused on the running motivation of the participants, which assistive devices they use while running, including particular sensing modalities, and what metrics are interesting for them **(RQ1 & RQ2)**. Based on the interview findings, we conducted a survey to classify assistive technologies and to validate the feasibility of the supporting interface designs **(RQ3)**.

4.1 Interviews

In order to gain a deeper understanding of the topic of running, we conducted semi-structured interviews with runners. Such interviews enable in-depth exploration of a particular topic area and allow for tailored interaction with individual participants, including asking further questions or making necessary adjustments during the interview process [38]. Furthermore, interviews provide initial insights about the running practices of runners, their concerns regarding injuries, and how they avoid them. Then, we investigate which obstacles runners are facing and how they are using assistive running technologies to cope with these challenges. Finally, we combine the interview results into one affinity diagram.

4.1.1 Interview Procedure. The interview was conducted using a semi-structured approach. At the beginning of the interview, we first discussed the general conditions of the interview. We also clarified the goals of our research project and the reasons for conducting the interviews. It was important to emphasize that the participants' personal opinions were the focus and that they were free to ask questions at any time to establish trust and reduce the fear of providing incorrect answers. During the introduction, we took care not to provide any information that could bias the participants. After clarifying the demographic data, we asked the participants to talk freely about their running experience, how they got into the sport, and their motivation. This created a comfortable atmosphere for discussion and led to a natural conversation. We also asked about the participants' level of running experience, the average distance they cover per week, and how they would describe a typical run in terms of distance, duration, terrain, type of run, and other factors.

The third phase focused on identifying the key metrics and measurements known to the participants or regularly reflected upon. We also explored whether participants desired additional metrics or information that is currently unavailable. To gain insight into the injury experience, we introduced a hypothetical scenario in the fourth part where participants were asked to imagine that they experienced discomfort while running. We first discussed the participants' experiences with potential health issues to better contextualize this scenario. Subsequently, we explored the specific measures they would take in such a situation and whether they believed receiving information in advance could help prevent a similar scenario.

The fifth part of the interview addressed the use of technology during running, such as fitness trackers and real-time feedback, to elicit potential interactions with potential devices [14]. It also explored what benefits participants hoped to gain, what type of feedback they used, whether they listened to music or received auditory cues during the run, and whether they wanted other feedback forms. The sixth part briefly discussed whether participants interact with their environment using technology or with other runners during their runs. This included activities such as talking to other runners and adjusting music playback or input on their smartwatches. Finally, we showed the participants images of fictional feedback technologies. The aim was to collect different opinions on the feedback modalities to get new inspiration and conceptual ideas and requirements regarding other technologies. The images were created in advance with generative artificial intelligence[1] by generating an image for each modality based on a specific prompt (see Figure 3). We have used AI-generated pictures of devices that resemble existing technologies, as well as those that are utopian, to provide a basis for understanding and developing AI. The pictures serve as a source of priming and inspiration since the creation of low-fidelity speculative prototypes is a method used in this process. Feedback on fictional technologies helped to gain a general understanding of user needs and define design factors.

4.1.2 Participants. To recruit participants with running experience for the interviews and establish contact, an author actively participated in running events and distributed flyers to participants. Additionally, attempts were made to find participants through other online channels. The challenge involved acquiring runners with varying levels of experience to obtain a representative and diverse picture in the interviews. All interviews were conducted in German and audio-recorded with the participant's consent. We conducted a total of 14 interviews with runners, including six female and eight male participants. The participants' ages ranged from 22 to 57 years old ($M = 39\,y$, $SD = 11.88$) and ran between 12 and 70 kilometers per week ($M = 41.42\,km/week$, $SD = 19.85$ or $M = 25.74\,mi/week$,

[1] We generated the pictures with Midjourney. We used the following prompt: "Device that helps runners improve their running technique through [visual/auditory/haptic] feedback"

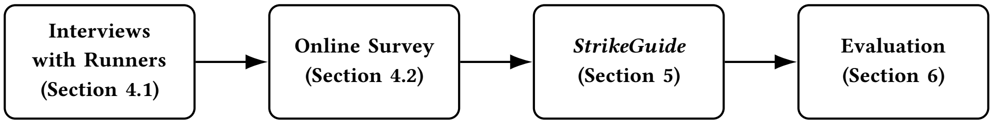


Figure 2: Our design process considers the characteristics of the running context. We used insights from expert interviews (Section 4.1) to gain an understanding of the requirements for feedback in the running context. We conducted an online survey (Section 4.2) about participants' perceptions of technologies and feedback for running. We used these insights to design and implement the prototype *StrikeGuide* (Section 5). We evaluated the prototype in a proof-of-concept study (Section 6).

Figure 3: AI-generated pictures presented to the participants at the end of the interview. The pictures were shown at the end of the interviews to stimulate additional ideas for a running system fostering desired and enjoyable running styles.

SD = 12.33). More details about the participants can be found in Table 1.

Table 1: Interview participants, including running experience and weekly training.

ID	Age	Gender	Years of Running Experience	Average km/week
R1	52	m	8	20
R2	50	m	20	45
R3	56	f	11	60
R4	36	m	5	70
R5	48	f	4	50
R6	35	m	13	40
R7	43	m	10	50
R8	42	f	8	40
R9	22	m	6	25
R10	30	f	5	50
R11	24	f	7	12
R12	27	f	1	13
R13	57	m	30	55
R14	31	m	16	50

4.1.3 Affinity Maps. The evaluation of the interview was conducted using an affinity map to analyze the data qualitatively. Affinity maps are a widely adopted technique in user research for exploring and structuring information, gaining insights, and determine thematic areas [29, 45]. Therefore, we manually transcribed and collected the statements from the audio recordings of the interview as notes. In preparation for the collaborative analysis, the notes sheets were distributed on digital Miro boards using digital post-it notes. Using labels, each post-it note could still be associated with a participant. Three researchers of this research project met and collaboratively organized the resulting notes into categories. This allows for independent classification, reducing biases in the mapping. The goal was to obtain an overview of the different thematic areas by assigning the interview statements to clusters. Subsequently, we determined the main thematic areas through collaborative work. Then, the individual statements on the post-it notes were assigned to the respective thematic areas, resulting in clusters within the thematic areas.

4.1.4 Results. The resulting thematic areas are MOTIVATION, METRICS, INJURIES, and DESIGN FACTORS, which reflect the interview structure and its intended scope. We discuss these more in the following.

Motivation. To better understand running, we asked runners why they chose to run and their motivation to run regularly. Some participants emphasized that it helps them to counteract the urge to exercise or that they want to feel better after work:

> *"To exercise, simply to stay fit, to stay in shape."* (R14)

Eight participants mentioned the balance to everyday life as a motivation, for example, to *"just clear my head"* (R10). One participant mentioned that it helps to *"just have one or two hours for yourself"* (R13). Balancing everyday life also plays an important role:

> *"To create a balance besides studying or in school time and now in the job."* (R14)

Three runners stated that social contacts were relevant to their running sessions:

> *"... to exchange ideas with friends and colleagues."* (R13)

Finally, running played a competitive role for four runners, who, for example, wanted to *"challenge themselves"* (R7) or *"[...] improve their last best time."* (R6).

Running Metrics. Running metrics were an important aspect for runners. We distinguished between generally actively used metrics and desired metrics. We begin by presenting known metrics. Typical running metrics such as pace or distance were prominently mentioned throughout the interviews, next to cadence, stride length, and running speed. Asking about health-related metrics, participants mentioned heart rate and VO2 max values. Other metrics, such as ground contact time (GCT) and the FST, were desired but not used due to the lack of technology.

We continued by probing which metrics were considered relevant by runners and regularly used for further reflection. Here, it becomes apparent that the majority of the participants keep an eye on various key metrics during the run. The most frequently mentioned were heart rate and pace. Other data included the duration or distance. However, participants also mentioned that they do not track any data at the moment but rely on their own body feeling. Asking participants about which metrics they are currently using to monitor their health provoked the heartbeat as the most popular answer (i.e., nine participants).

When asking runners about a preferred future metric, they stated that running techniques and posture were relevant. Nine participants mentioned the FST most prominently when talking about the running technique:

> *"That I know from the start that I have to run more forefoot or more midfoot. It would definitely help me if I noticed that I'm too far forward or too far back (with my foot) today. I'm sure that could be optimized."* (R5)

Furthermore, several participants mentioned a general strain of the body during long running sessions. R13 mentioned, for example, a kind of index of the current state of the body. R14 also stated potential correlations between bodily stress and risk of injuries:

> *"It would of course be cool to get feedback on areas of your body that are particularly stressed, for example, joints or tendons. Or what is your level of strain there? The big question mark is always, of course, to what extent are these runs really healthy?"* (R14)

Experiences of Injury. Next, we asked in more detail what injuries and health problems the participants had already experienced with regard to running. The most frequently mentioned problem was knee problems, common when using the wrong FSTs [1]. Asking about this, one participant characterized the symptoms as "Runner's Knee":

> *"I had the classic runner's knee last year in particular because I just ran a bit more."* (R9)

But also complaints in connection with the Achilles tendon were mentioned by some participants:

> *"Achilles problems due to marathon training, I again underestimated and disregarded stretching."* (R9)

The participants also stated that they had problems with their shins and calf. Also, some runners had already twisted their ankles or complained about their verses. Single participants reported on a torn ligament (R7), shoulder as well as abdominal cramps (R12), and a torn muscle (R13) were also mentioned. We then asked about procedures when health problems occur during running or preventive measures to avoid injuries. On one hand, runners suggested breaks when being affected by injuries:

> *"Cure, don't overdo it, and don't start again too quickly."* (R2)

On the other hand, four runners suggested they would walk carefully and run more slowly:

> *"Then you try to run a bit slower and more carefully."* (R9)

Two participants mentioned stretching regularly to prevent pain. Two participants also mentioned an alternative program, such as swimming, cycling, walking, or adjusting the load by taking a different route. Three participants also stated that they seek medical help, such as going to medical gymnastics or starting physiotherapy.

Design Factors. At the end of the interviews, participants were presented with AI-generated design probes (see Figure 3). The runners were asked to freely ideate what a running metrics system could look like and how it would communicate with the runner. In this context, runners mentioned that real-time feedback should be presented in a clear and intuitive manner, allowing runners to easily grasp the information without any cognitive effort during running sessions. They particularly highlighted the relevance of form factors in terms of weight and size, as well as intuitive interaction. R5 highlighted that feedback should be quickly readable and easy to understand:

> *"[. . .] That I can see right away [whether I am] in the yellow, green, or red zone, immediately at a glance and preferably with colors and no data because that takes too long for me to see my level right away. [. . .] It should be quickly, easily recognizable, and available."* (R5)

The participants considered user-friendly interaction as important while running. Interestingly, runners considered current interaction with running technologies cumbersome. Thus, one runner stated that they prepare their running tracker before the run to minimize interaction:

> *"But apart from that, I have practically set my display in such a way that I can see the things I want to see at a glance. So interaction with the watch is just looking at it and nothing more."* (R07)

However, some runners state that they sometimes use music control. This is done either via the mobile phone, the smartwatch, or the headphones themselves. It is important to mention that the interaction is as short and intuitive as possible. The following quotes are to underline this point once again.

> *"I control the music via the AirPods and if it's something more complicated via the Watch"* (R14)

> *"If a song is stressing me out, I'll go on twice [via the AirPods control], I think that's actually quite cool. Before, I always continued [a song] via the watch, which actually annoyed me because it always takes a moment until the new song comes, but tapping twice via the AirPods I find good [. . .] Actually, I try to interact with the watch as little as possible."* (R11)

> *"Usability should be good so that when you want to set something, you can do it relatively quickly [...] that you don't have to click around so much"* (R14).

Furthermore, the adaptation of the real-time feedback to the **Running Context** plays a role. The aim is to ensure that the information provided is tailored to the specific requirements and goals of the activity in question. For example, Runner 12 stated that depending on the run, the requirements for the technology used change.

> *"Not during normal running. During intervals I then also have to stop the break if I haven't set this (in advance)"* (R12)

Participants stressed the importance of comfortable running hardware. The runners deemed several properties important, such as weight, battery life, material, and haptics. R5, in particular, noted in the concept ideas that they are reluctant to take more equipment with them to run:

> *"It would bother me because taking another device with me is out of the question. I always have my mobile phone in my pocket. If I have more with me [it is always] in my running backpack."* (R5).

In addition, five participants stated that weight played a decisive role in whether they would use the technology:

> *"On the one hand, it should be so inconspicuous in terms of weight that it has practically no influence on it [my walking behavior]."* (R7)

4.1.5 Discussion. Overall, runners already use technologies that help them quantify their running behavior. One important factor is the assessment of health-related running metrics, such as heart rate and pace. However, the interviews revealed that further running metrics and real-time feedback increase the running quality. In this context, participants mentioned that knee pain as a potential result of suboptimal FSTs is a non-negligible challenge. At the same time, real-time feedback about the running quality should be implicit and subtle, meaning that explicit interaction must be minimized or avoided. Participants prefer intuitive real-time feedback about their running performance to become more aware of suboptimal running behaviors (RQ3). Finally, participants suggested hardware requirements, pointing at already used technologies such as earphones (i.e., Apple AirPods) for providing real-time feedback. In the following, we will conduct a survey investigating technologies to provide running feedback.

4.2 Survey

Identifying the FST as an important factor to control during running, we conducted an online survey to obtain a representative recommendation for feedback technologies. The aim was to get a wider picture of how technologies are currently used and perceived when it comes to real-time feedback during running. In order to be able to evaluate the different technologies, the design factors from Section 4.1.4 were used in the questionnaire. We used an anonymous online survey in English using Qualtrics[2] to collect responses.

4.2.1 Survey Structure and Content. The survey consisted of a combination of closed and open questions. Closed-ended questions included Likert scales to ensure comparability and increase objectivity [50]. For each question item, we provided an open-ended text input field to get additional feedback and more detailed information from each participant. This allowed participants to provide elaborations or reasons for their decisions. This allowed participants to provide elaborations or reasons for their decisions. The survey consisted of three parts. The first part was an introduction to the topic, context, and a detailed description of the five types of devices[3]. Based on the interviews, we integrated running devices. The list of devices includes Smartphones, Smartwatches, Earphones, Augmented Reality glasses, and LED strips. The questions were answered on a five-point Likert scale (see Table 2).

Table 2: Questions in the online survey about the perception and feasibility of using different technologies for real-time feedback for running. The questions were inspired by the prior interviews concerning the possibility of making inputs, interpreting the feedback, understanding information, and including hardware constraints.

ID	Question
Q1	I can make inputs while running.
Q2	The presentation of information is understandable.
Q3	I have an overview of the necessary running information.
Q4	I am aware of my environment and understand what is happening around me.
Q5	The device does well in the factors of weight, haptics, or battery life.
Q6	The device does not disturb my running rhythm.
Q7	The device can adapt to my current running behavior and running context.

4.2.2 Participants. We utilized mailing lists and social platforms to acquire runners of all experience levels. Furthermore, postings were sent out in company-run groups. A total of 139 participants took part in the study, of whom 61 were excluded from the analysis due to incompleteness. Of the remaining 78 responses, 45 identified as female, 30 as male, and two as non-binary. One participant preferred not to disclose their gender. The age of the participants ranged from 18 to 74 years old ($M = 33.17\,y$, $SD = 14.04$).

4.2.3 Survey Results. We present the quantitative results of the questionnaire in the following. An overview of the survey results can be found in Figure 4 and Figure 5. We decided to conduct nonparametric statistical testing because the Likert items are nonparametric. To compare the Likert ratings between the device types, we conducted a Friedman test to assess the main effects with the effect size Kendall's W[4]. In case of a significant effect, we conducted post hoc analyses using Wilcoxon signed-rank tests with Bonferroni correction to test for statistical significance between the groups. The significance level was set at $\alpha = .05$. We report the p-values for each significant pairwise comparison if we find a significant main effect.

A Friedman test revealed a significant main effect for the Likert question Q1, $\chi^2(4) = 118.32$, $p =< .001$, $W = 0.39$. Bonferroni-corrected Wilcoxon signed-rank tests revealed a significant effect between smartphones and smartwatches, smartphones and AR glasses, smartphones and LED Strips, smartwatches and AR glasses,

[2]https://www.qualtrics.com

[3]Details on the device descriptions can be found in Appendix A.

[4]$W < 0.1$: Negligible effect. $W < 0.3$: Weak effect. $W < 0.5$: Moderate effect. $W \geq 0.5$: Strong effect.

smartwatches and LED strips, earphones and AR glasses, and earphones and LED stripes, $p < .001$.

Furthermore, Q2 reveals a significant main effect, $\chi^2(4) = 119.74$, $p < .001$, $W = 0.36$. Here, we found a significant effect between smartphones and earphones, smartphones and AR glasses, smartphones and LED strips, smartwatches and earphones, smartwatches and AR glasses, smartwatches and LED strips, and earphones and LED strips, $p < .001$. Additionally, we found a significant effect between AR glasses and LED strips, $p = 0.041$.

A further significant main effect was found for Q3, $\chi^2(4) = 140.09$, $p < .001$, 0.33. A post hoc test revealed a significant effect between smartphones and smartwatches, $p = .020$. We further found a significant effect between smartphones and earphones, smartphones and AR glasses, smartphones and LED strips, smartwatches and earphones, smartwatches and AR glasses, smartwatches and LED strips, and AR glasses and LED strips, $p.001$.

Q4 revealed a significant main effect, $\chi^2(4) = 38.80$, $p < .001$, $W = 0.33$. A post hoc test revealed a significant effect between smartphones and smartwatches, smartwatches and AR glasses, and earphones and AR glasses, $p < .001$. Furthermore, we found a significant effect between earphones and LED strips, $p = .005$, and AR glasses and LED strips, $p = .016$.

Q5 revealed a significant main effect, $\chi^2(4) = 129.27$, $p < .001$, $W = 0.30$. Here, post hoc tests revealed a significant effect between smartphones and smartwatches, smartphones and earphones, smartwatches and AR glasses, smartwatches and LED strips, earphones and AR glasses, earphones and LED strips, and AR glasses and LED strips, $p < .001$. We found a further significant between smartwatches and AR glasses, $p = 0.007$.

Q6 revealed a significant main effect, $\chi^2(4) = 111.57$, $p < .001$, $W = 0.33$. Post hoc tests revealed a significant effect between smartphones and smartwatches, smartphones and earphones, smartphones and LED strips, smartwatches and AR glasses, smartwatches and LED strips, earphones and AR glasses, and AR glasses and LED strips, $p < .001$. Furthermore, we found a significant effect between earphones and LED strips, $p = .018$.

Q7 revealed a significant main effect, $\chi^2(4) = 78.62$, $p < .001$, $W = 0.41$. Post hoc tests showed a significant effect between smartphones and smartwatches, smartwatches and earphones, smartwatches and AR glasses, and smartwatches and LED strips, $p < .001$. Furthermore, we found a significant effect between smartwatches and LED strips, $p = .002$.

4.2.4 Discussion. The survey results reveal that runners are positive towards all five device modalities. However, all five device modalities play out their own strengths and weaknesses. While smartphones and smartwatches are preferred for viewing and interpreting information, earphones excel in terms of non-intrusiveness and hardware capabilities. This feedback type has been shown to be efficient in previous work [40]. However, the interviews showed that direct interaction with devices during a run is not preferred. Simultaneously, the need for additional hardware should be reduced, while existing hardware should be easy to wear without adding more weight. Learning that earphones comply with these requirements, we focus on the auditory cues for reducing bad FSTs, as indicated in the interviews.

5 *StrikeGuide*

Based on the interviews and survey findings, we present the design considerations and prototypical technical implementation of our running prototype *StrikeGuide*.

5.1 Design Considerations for *StrikeGuide*

Our results reveal important insights for designing systems that promote awareness and enjoyment in amateur running. Injuries were a pivotal factor that a running system should consider [12]. The interviewees repeatedly mentioned that the FST is of great importance. At the same time, participants mentioned that they need frequent reminders not to fall back into bad running behaviors. Hence, we consider continuous reminders an important aspect of a supportive running system.

Furthermore, the system should integrate with already available feedback, such as auditory modalities. Although the participants descriptively preferred the smartphone and smartwatch, they mentioned a preference for hands-free feedback. Beyond that, research has shown that interactions with the smartphone or smartwatch significantly affect the runner's gait [44]. In this context, the interviews and the survey revealed that runners often listen to music while running, and they consider auditory feedback via earphones a suitable modality for non-intrusive feedback while letting runners focus on their running performance. As a consequence, we decided to explore a system that provides auditory feedback. Auditory feedback has been shown to successfully support athletes correct their technique through the sonification of movement [54, 58]. In the end, the prototype *StrikeGuide* consists of an ESP connected to the sensors as the tracking component, which records data that is interpreted in an app on the smartphone, which simultaneously works as the feedback component and generates the auditory feedback. The prototype's lightweight and wearability were convincing arguments for use while running, offering users a convenient and unobtrusive solution to monitor their performance.

Inspired by previous work [11], we integrate force-sensing resistors at the forefoot and backfoot to sense the initial pressure. Thanks to their thin form factor, force-sensing resistors are easy to put in a shoe without being disturbing. For the proof-of-concept evaluation in the current state, we used tape to attach the FSRs to the runner's foot. In future versions, it is conceivable to integrate them permanently into a shoe. Regarding the feedback, related research highlights the effectiveness of auditory feedback for real-time scenarios, as it allows for quick and intuitive interpretation without requiring visual attention, which is important for runners who need to maintain focus on their surroundings [16]. The interviews revealed that ambient auditory feedback is a desired way of being reminded when running with an excessive foot strike. The advantage is that some people are already listening to music from their smartphones while running, which allows us to integrate the pink noise as a modification to the music to provide feedback. Also, if they are already listening to music on headphones, there is no need to carry additional equipment to receive the feedback except for putting the sensors on the foot.

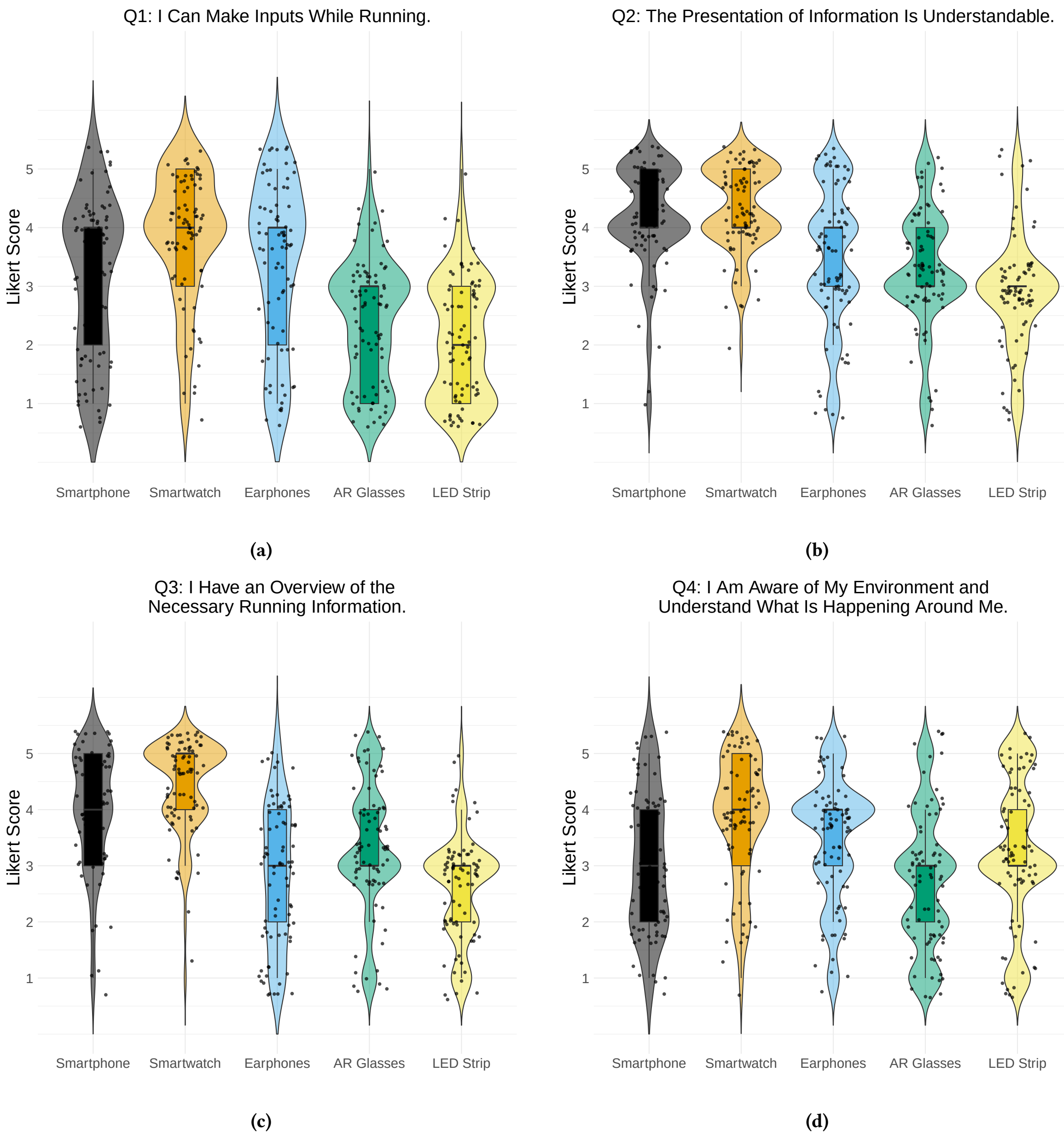
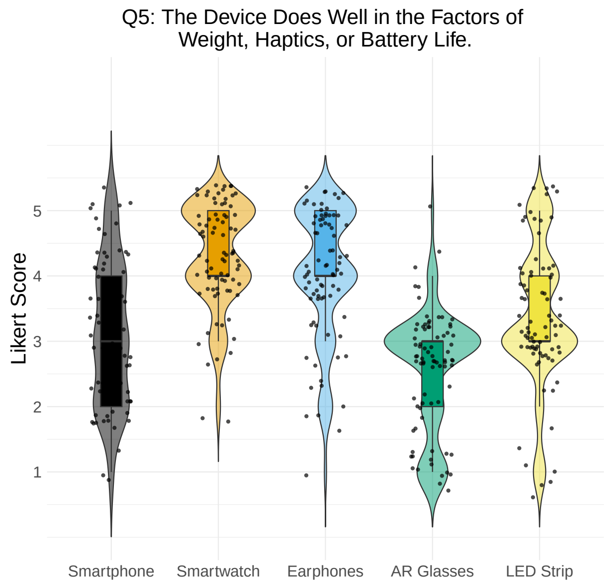


Figure 4: Results from the Likert questionnaire regarding the questioned output modalities for input, presentation, overview, and environmental awareness.

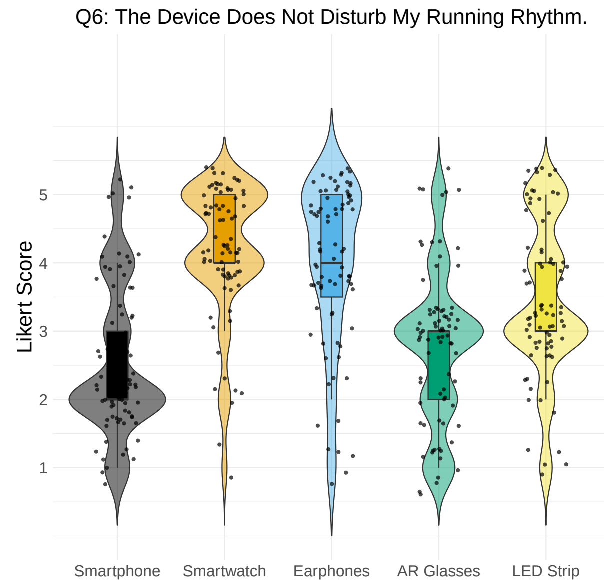
5.2 Tracking

The tracking component of the prototype consists of two force sensing resistor (FSR)[5] on the right foot with a size of 40 x 40 mm each. They are connected to an ESP32[6] with a built-in Wi-Fi module that is powered by a 5V rechargeable power bank. We record the runner's stride data with the FSRs. Therefore, we put one of the FSRs under the forefoot area and one under the heel area of the foot in the shoe insole. The ESP32 stores the data from both sensors in a Firebase database. The Firebase database allows real-time data synchronization between multiple devices so that we can constantly collect and analyze the data from the runner. An Android app retrieves the data from the database and processes it. Using this data, the app calculates individual strides and their FST. The app then stores each stride with its corresponding FST back into the Firebase database. We determine whether a stride is a forefoot strike or lateral foot strike by measuring the pressure on each sensor to see which part of the foot touches the ground first. When the

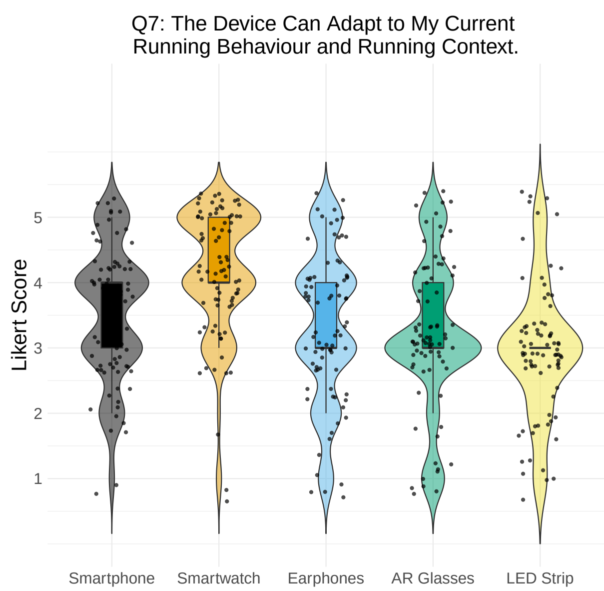
[5] Model RP-S40-ST, http://m.eleparts.co.kr/data/_gextends/good-pdf/201904/good-pdf-7495470-1.pdf
[6] https://www.espressif.com/en/products/socs/esp32



(a)



(b)



(c)

Figure 5: Results from the Likert questionnaire regarding the questioned output modalities for device ergonomics, intrusiveness, and adaptation to running behavior.

pressure of a sensor is at 0, it indicates that the foot is not in contact with the ground at the sensor's position on the foot. *StrikeGuide* classifies a stride as forefoot strike when the front part of the foot touches the ground first, i.e., the pressure value of the front sensor is bigger than zero before the heel sensor detects pressure, and as a lateral foot strike when the heel touches the ground first. Based on the analysis of the stride data, the user then receives real-time feedback. The Android app displays a live overview of the run with the runner ID, FST, total steps, and numbers of detected foot strikes. However, the current version of the Android app is solely meant for the experimenter to keep track during the study but can also be adapted to a training app for the runner, e.g., to create a history for post-hoc analysis over time.

5.3 Feedback

The feedback consists of a modification of music by adding pink noise to it. Previous work [28] found that pink noise with an exponential response curve was found to be the best-performing auditory distortion signal for altering running stride. In addition, its non-disruptive and non-irritating nature makes pink noise less likely to cause annoyance or irritation to the runner [28]. Because of those reasons, we chose pink noise as the feedback signal for the *StrikeGuide* system. The pink noise feedback is shown to work well with music since it is overlaid onto the runner's music, providing a seamless and integrated experience. The feedback component turns on the feedback when the system detects a lateral foot strike. Although our system is designed to mitigate lateral foot strikes, it can be adapted to foster other forms of running practices. As long as runners no longer hear the feedback, they can infer that they are running with the desired foot strike pattern, eliminating the need for continuous feedback interaction. This allows them to establish and detect the connection between their running behavior and the presence or absence of feedback without being explicitly told. The feedback serves as an external focus of attention [60] to notify the user to adjust the running style and not require lots of cognitive effort to process the feedback. Feedback through an external focus is shown to improve motivation and performance while reducing the risk of injury [52]. While runners need to have a general understanding of what constitutes an (excessive) lateral foot strike or forefoot strike, they do not necessarily need to know the details in order to interpret the feedback correctly. The system provides guidance and feedback to the runner in a simplistic but easy-to-understand way, indicating whether they have successfully implemented a good strike technique.

6 Evaluating *StrikeGuide*

To evaluate *StrikeGuide*, we conducted a proof-of-concept study in a controlled lab environment. The focus lies on our fourth research question if *StrikeGuide* effectively reduces the amount of excessive forefoot and lateral foot strikes with the provided feedback. We let the participants run on a treadmill while wearing our prototype.

6.1 Study Design

The evaluation of *StrikeGuide* is based on a within-subject design with three conditions: (A) 'No Feedback' as baseline, (B) 'Music Only', and (C) '*StrikeGuide*' (Music and auditory real-time feedback) using pink noise representing *StrikeGuide*. We gathered insights on how the running style changed between the conditions through the sensor data. We further examined usability aspects of *StrikeGuide* through custom and validated questionnaires as detailed in Section 6.2. During the study, participants were running a distance of 500 meters for each condition. We considered that this distance is also feasible for recreational runners, whom we chose as the target group for this study. Further, at this distance, it is already possible to observe changes in running kinematics [39]. Ethical approval for this study was obtained from the local ethics authority. *StrikeGuide* does not store user-identifiable data, thus assuring user privacy.

6.2 Procedure

The evaluation involved a series of steps to investigate if *StrikeGuide* can effectively reduce the amount of excessive strikes. Upon arrival, we welcomed the participants and introduced them to the study goals and the procedure. After they provided informed consent, we collected demographics, information about their running experience, technologies they use for running, and if they listen to music while running via a questionnaire to gain insights about their running routines. The participants brought their own running clothes and running shoes, which they are used to, and had the chance to change beforehand. Then, we equipped them with the sensors and showed them how to attach the prototype to their feet. As a precaution, the participants are secured with a harness and a rope while running on the treadmill. In case the participant stumbles, which creates tension on the rope, the rope construction will immediately stop the treadmill. To prepare the participants for the study, we performed a warm-up routine with them. This routine included a series of stretches and a 5-minute warm-up run on the treadmill designed to activate their muscles. We guided the participants through the warm-up process, ensuring their physical readiness for the running activity. The warm-up allowed the participants to familiarize themselves with the treadmill setup.

For the main part of the study, we provided information on the different foot strike types and emphasized the comprised problem of excessive forefoot and lateral foot strikes on the joints. We then introduced the three running conditions. Participants performed those conditions in a counterbalanced order. We tracked the running data for all conditions. Participants only received the pink noise feedback in condition (C) depending on their strike type. In addition to the running distance of 500 meters, we set the standard running speed to 5 km/h as slower running speeds are often associated with a higher frequency of lateral foot strikes [27], and the selected speed should not overly strain the participants resulting in fatigue so that they can complete all conditions. The experimenter observed the FST throughout the conditions to cross-validate with the tracked data. After finishing all conditions, we took off the sensors and the participants completed some custom and standardized questionnaires targeting their experience with the system (custom questions cf. Table 3), usability aspects (UMUX [19]), comfort with wearing the sensors (comfort rating scale [26]) and their self appraised performance [31]. They could also express their thoughts and ask questions about the *StrikeGuide* system. In total, the evaluation lasted approximately 60 min.

6.3 Participants

A total of seven people (four self-identified as female, three self-identified as male) with ages ranging from 16 to 59 ($M = 34.14\,y$, $SD = 17.13$) participated in the proof-of-concept study. We recruited recreational runners through personal contacts. We excluded very experienced and professional runners as we expect that they would have refined their running style to such an extent that it would not be detectable in this proof-of-concept evaluation. The participants self-rated their running experience and fitness level

Table 3: Custom questions about the perception of the feedback and *StrikeGuide* the system. All were rated on a visual analog scale (VAS) from 0 to 100, from strongly disagree to strongly agree.

	Custom questions regarding the system and its feedback.
Q1	The degradation of the music quality motivated me to change my running style.
Q2	It was easy to notice the lower music quality.
Q3	I noticed that I switched to a different foot strike type during the run to improve the music quality.
Q4	I did not have difficulty understanding the connection between the music quality and my foot strike type.
Q5	The *StrikeGuide* system is effective in improving a runner's foot strike type.
Q6	I would recommend the system to other runners who want to improve their foot strike type.
Q7	The system was disruptive or distracting during the run.
Q8	There were moments when I found the feedback loop demotivating or frustrating.
Q9	It is important for me to track my performance and progress when running.
Q10	It is important for me to improve my running performance.
Q11	It is important for me to minimize my risk of injury when running.
Q12	I would be willing to pay for access to the system if it were commercially available.
Q13	I knew what the foot strike type was before this study.

from 20 to 84[7] (M = 60.57, SD = 21.50). Five of the seven participants reported that they usually listen to music while running, and the other two preferred running without music. None of them regularly uses any technology to track their run. Each participant was reimbursed with $10 per hour.

6.4 Results

We present the results from the running and questionnaire data in the following.

6.4.1 Running Data. We analyze the running data by calculating the total force exhibited on the sensor. We begin by classifying the data into lateral foot strikes and forefoot strikes.

We count the number of lateral foot strikes and forefoot strikes. A step is initiated when either of the two sensors registers a pressure reading above zero and concludes when both sensors record zero pressure. Subsequently, we determine whether the initial pressure was detected by the front sensor or the lateral sensor. If the front sensor recorded the initial pressure, the step is categorized as a forefoot strike. If the lateral sensor registers the initial pressure, it is classified as a lateral foot strike. Inspired by Footstriker [11], each step is binary classified as either a forefoot strike or lateral foot strike.

[7]Visual Analog Scale (VAS) from 0 to 100; 'I have no experience' to 'I have a lot of experience'

We recorded a total of 7255 foot strikes (M = 1036.43, SD = 284.00, per participant) during the study. 3410 were lateral foot strikes (M = 115.00, SD = 58.27, per participant and per condition), and 3840 were forefoot strikes (M = 132.02, SD = 71.05, per participant and per condition).

We investigate the running data for significant differences between the conditions. We use the processed foot strike data for statistical analysis. We separate the analysis between data collected at the forefoot and lateral foot part of the right foot (i.e., the place where the sensor was placed).

A Shapiro-Wilk test revealed no deviation from normality for all measures in all conditions ($p < .05$). Hence, we applied a repeated measures ANOVA on the number of lateral foot strikes and forefoot strikes per condition. The repeated measures ANOVA revealed a significant main effect for the number of lateral foot strikes, $F(2, 12) = 6.46, p = .012$. A Bonferroni-corrected post-hoc test revealed a significant effect between the conditions 'No Feedback' and *StrikeGuide*, $p = .045$, as well as 'Music Only' and *StrikeGuide*, $p = .024$. Furthermore, we applied a repeated measures ANOVA on the number of forefoot strikes, revealing a significant main effect, $F(2, 12) = 13.55, p < .001$. Again, a Bonferroni-corrected pairwise comparison showed a significant effect between 'No Feedback' and *StrikeGuide*, $p = .009$, as well as 'Music Only' and *StrikeGuide*, $p = .007$.

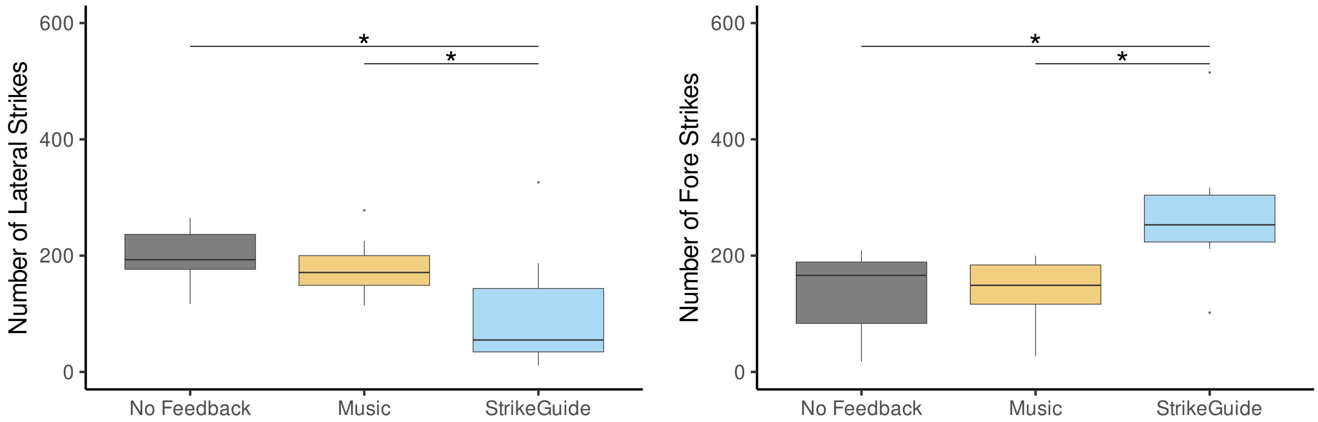
The average number of lateral foot strikes was $M = 200.14$ ($SD = 46.48$) during the 'No Feedback' condition, $M = 180.14$ ($SD = 51.63$) during the 'Music Only' condition, and $M = 106.86$ ($SD = 104.78$) during the *StrikeGuide* condition (see Figure 6a). The average number of forefoot strikes was $M = 134.00$ ($SD = 71.22$) during the 'No Feedback' condition, $M = 139.57$ ($SD = 55.48$) during the 'Music Only' condition, and $M = 275$ ($SD = 116.87$) during the *StrikeGuide* condition (see Figure 6b).

6.4.2 Questionnaires. Through the questionnaires, we gained more insights into the participants' impression of the system regarding the comfort, usability aspects, and the perception of the feedback. From their answers regarding the comfort when wearing the devices [26], we can see that they still noticed the devices on their body (Q2 "Attachment" $M = 13$, $SD = 7.12$) but did not perceive them as harmful (Q3 "Harm" $M = 1.57$, $SD = 2.44$) or felt insecure because of it (Q6 "Anxiety" $M = 4.14$, $SD = 5.30$). We did not observe any significant differences for either the UMUX or the self appraised performance score.

From the analysis of our custom questions, we can derive that the feedback was noticeable for the participants (Q1, Q2, Q3) and made them change their running style. This indicates that they started reflecting on how they were running. They perceived the system as effective in improving the foot strike type (Q5) and did not feel much distracted (Q7 $M = 25$, $SD = 20.8$).

7 Discussion

The quantitative and qualitative results from the interviews, survey, and prototype study provide insights into the special needs when designing a feedback system to foster awareness of one's running technique.



(a) (b)

Figure 6: Number of lateral- and forefoot strikes for each condition. (a): The overall number of lateral foot strikes is reduced when using *StrikeGuide*. (b): Similar, the overall number of forefoot strikes increased when using *StrikeGuide*.

7.1 Towards a Design for Healthy Running

The interviews showed that runners desired a healthy running form. Problems and injuries often come from incorrect training practices or overtraining, which may not manifest immediately and come at later stages. Where currently available applications and systems in related work are more performance-oriented [13], the runners highlighted desires for avoiding injuries. The comprehensible contextualization of healthy running-related information serves as valuable recommendations for the design of future systems. A crucial question arises regarding what information to present when to the user, especially since running bears potential health risks when practiced incorrectly over an extended period. Runners still use traditional metrics, such as distance or pace, but would like access to more metrics that allow them to become more aware of their running behavior and to acquire a healthy running style for running behavior that is hardly noticed, such as FST or GCT [22] **(RQ3)**. However, more specialized metrics are not available yet or need different technologies or a certain level of knowledge for proper interpretation [17], which is also influenced by the level of detail in the represented feedback.

Thus, runners require guidance in order to develop an awareness of how their bodies move and make informed decisions about technique and training. It is the responsibility of interaction designers to build a connection between sensor data and body awareness and *StrikeGuide* is an example of such a connection **(RQ3)**. In conclusion, we find that runners use sensors to monitor their performance during their running sessions **(RQ1 & RQ2)** while desiring further metrics related to body strains. Consequently, runners suggested that advanced metrics, such as FST or GCT, could help to avoid injuries or pain (i.e., knee pain) **(RQ2)**. Here, *StrikeGuide* goes beyond the state of the art by sensing foot strikes which is not implemented by commercially available fitness trackers, such as Garmin [20], Google Fitbit [21], or the Apple Watch [3].

Furthermore, we acknowledge that ongoing research in the kinesiology of running may lead to evolving understandings of optimal running form. This evolution suggests that the best running form is not universally fixed but rather the one that works best for each individual runner, taking into account their unique physiology, experience, and training goals. Consequently, interaction designers must create systems that not only deliver accurate sensor data but also empower runners with the autonomy and awareness necessary to make informed decisions about their own running form. Our system is designed with this flexibility in mind—it supports a wide range of gait patterns, and its future interactions can allow users to actively choose and customize their desired form.

7.2 Design Factors and Device Preferences for Sensor-Based Running Feedback

The interviews informed us about qualitative insights into which devices are used during running and which metrics are preferred by runners. It determines *When* and *How* to interact with the user, *Which information?* to provide *In which way?* so that it is beneficial. The feedback content, frequency, and modality affect the user’s perception and how the performance improves [24, 52]. Over time, through the feedback, the user can develop body awareness of how a good running technique should feel. In terms of understandability, the user needs to quickly understand the information communicated while running without having to spend lots of cognitive effort on it or getting confused by it. Generally, augmented feedback in a sports context should be easily and intuitively understandable to be beneficial [46]. Having holistic control of all running-related information comes with a trade-off with the ability to comprehend the information at a glance, which is the desired amount of time spent interacting with the information. Everything that goes beyond that should be retained for retrospective analysis after running or during a break. The same applies to long or complex interactions, which should be short and intuitive. Here, the survey findings show that, while each of the five device modalities has its advantages and disadvantages, earphones are a suitable feedback modality trading off information consumption and hardware requirements **(RQ2)**.

7.3 *StrikeGuide* Efficiently Reduces Lateral Foot Strikes

Our results show that the feedback from *StrikeGuide* significantly changed the FST **(RQ4)**. The average number of lateral foot almost halved in *StrikeGuide* condition, and the forefoot doubled, resulting in a significant effect. We built our prototype based on Hassan et al. and their FootStriker [23]. In contrast to their work, we used no active intervention (EMS) but pink noise as subtle auditory feedback to notify the user about the strike type. This approach could efficiently reduce the amount of lateral foot strikes. Our feedback can make users reflect on their running style and foster awareness of a striking pattern without invasive measures. Through practice and feedback related to the running technique, users can understand how correct strikes feel and consolidate the correct technique. However, these results must be interpreted in light of broader evidence on gait retraining. Moore [34] cautions that nudging runners to alter their gait patterns should be approached carefully, given that experienced runners tend to self-optimize toward a metabolically efficient form suited to their individual physique. Accordingly, the value of *StrikeGuide* lies not in prescribing a universally correct strike pattern, but in providing runners with the awareness and real-time information needed to make informed, autonomous decisions about their own technique.

7.4 New Forms of Interactive Feedback

Developing an inner understanding of how a correct strike feels is particularly relevant for novice runners as they still must develop awareness and consolidate the technique. Real-time feedback can prevent the development of harmful running practices and reduce the risk of injuries. In future versions, it is conceivable that the system can easily extend existing running routines. For example, the thin form factor of the sensors allows it to integrate them permanently into a shoe. As runners often listen to music during their training and thus wear earphones, this channel can then be extended with the pink noise as real-time feedback. As discussed in Section 7.2, we designed the system considering design factors for sensor-based feedback for running **(RQ1)**. With additional sensors in the shoes, *StrikeGuide* seamlessly integrates with existing applications without much additional effort required from the user.

8 Limitations

We recognize that our artifact-driven approach is prone to certain limitations.

Limited Participant Pool: One significant limitation of this study is the relatively small sample size in our case study, consisting of individuals covering only 500 meters of running per condition. While this was chosen to demonstrate the initial proof-of-concept for *StrikeGuide*, it may not represent the broader running population. Further, we conducted the study in a lab environment on a treadmill which might also limit the ecological validity. However, in this study, we did not evaluate the improvement of the FST on a quantitative level but the eligibility of the selected feedback in a controlled environment. While we acknowledge that running biomechanics can differ between treadmill and outdoor environments, the treadmill was intentionally chosen to provide full control over the experimental conditions and ensure consistent feedback delivery across participants. Therefore, future work should evaluate *StrikeGuide* in real-world settings such as tracks or other outdoor environments to validate its effectiveness beyond controlled lab conditions. The overall weight and form factor of *StrikeGuide*'s components are comparable to those of commercial running trackers, such as RunScribe [41] or Stryd [49]. We therefore do not anticipate substantial limitations for outdoor deployment, as lightweight modern power banks can readily support the system throughout a longer running session. In the lab setting, we could already observe that the participants adapted their running style over the short distance. This case study primarily focused on individuals who regularly run 5 kilometers or more, which may not accurately reflect the experiences of beginner runners. Consequently, the applicability of our findings to novice runners may be limited. The low number of participants in our proof-of-concept case study raises concerns about the generalizability of our results to a broader audience of runners. The differences in running experience and fitness levels between our participants and other runners could impact the effectiveness of *StrikeGuide* in different contexts. Future work should nevertheless investigate long-term usability, comfort, and acceptance during real-world use.

Perception of Running Technologies: Another limitation of our project is the emphasis on addressing the perception of running technologies rather than running itself. While *StrikeGuide* aims to enhance running technique, the initial training focuses on familiarizing runners with the technology and its feedback mechanisms. This may not directly address the underlying issues related to running form, potentially requiring additional interventions to ensure users can fully benefit from the app's features.

Foot Strike Differentiation: StrikeGuide incorporates two different foot strike types for adjusting running technique. The prototype directly detects lateral foot and forefoot strikes. However, it assumes that users may not initially know how to run correctly. While the app can condition users toward better running techniques, it does not address the fundamental issue of incorrect running habits that may need to be addressed prior to using the app effectively.

Limited Feedback: Our system relies on ambient feedback to guide runners in real time. However, the effectiveness of this feedback may be limited by various external factors, such as the runner's environment, device compatibility, or user sensitivity to feedback. These limitations could impact the overall utility and user experience of *StrikeGuide*. Further, we recognize that using audio implies that sounds are not available as a modality for other kinds of in-run interactions, e.g., soundscapes [43].

In conclusion, while *StrikeGuide* presents a promising solution for improving running technique and preventing runner injuries, these limitations must be considered when interpreting the results and assessing its applicability to different user groups and running scenarios. Future research and development should address these limitations to enhance the effectiveness and usability of the app for a broader range of runners.

9 Conclusion

In this work, we explored how real-time feedback can be used to assist runners in achieving more satisfying running by improving their running techniques. For this purpose, we followed an exploratory, user-centered design approach to first develop a basic understanding of runners' needs and build on this to create an effective solution. We conducted interviews to gain an understanding of runners' behavior, known metrics, and helpful feedback to improve their running style. We explored the use of current feedback technologies as well as requirements to assist with real-time feedback. As a result, we provide design factors that serve as guidelines to create real-time feedback while considering the user. We applied the interview outcomes in a prototype. The evaluation showed that we successfully modulated the number of foot strikes with the feedback from *StrikeGuide* compared to running without any intervention. While our work focused on reducing lateral foot strikes and promoting forefoot strikes, *StrikeGuide* can be adapted to foster individually preferred running techniques. This work lays the foundations for developing user-centered real-time feedback to assist runners in improving their running technique and fostering awareness of one's running technique.

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A Survey Device Description details

The following device descriptions were used in the survey:

There are four decisive factors that play a role in the use of real-time feedback during running. These four factors are different in different technologies (types of devices).

The devices are as follows:

- Smartphone: A mobile device used during running to provide runners with feedback and information via various apps during their workout.
- Fitness watch: A wearable watch that is worn on the wrist and can provide feedback and information to runners.
- Headphones: Audio devices that are worn in/on the ear while running to provide music or additional information about the run.
- Augmented reality glasses: Glasses that display augmented information about the run in the runner's field of vision.
- LED strips: Light strips that attach to the body or clothing and provide visual feedback through colors or patterns to visualize information.