Adaptive Music Synchronization for Jogging: Enhancing Experience and Performance through Real-Time Cadence and Heart Rate Feedback

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1 Introduction

Developing a system that adjusts music playback speed to match a jogger's pace is a concept that has gained attention over the years, with various implementations and research studies exploring the potential benefits of synchronizing music with physical activity.

Here we explore the possibility of enhancing the joggers' experience by developing a pace-setter running app with two modes:

- **Joy Ride:** uses accelerometers to detect running pace and adapt music's playback speed real-time to match with current pace.
- **Pace Setter:** uses heart rate and accelerometers, finds optimal running pace and adapts song speed real-time to help you reach it.

1.1 History

Early implementations in this field date back to 2011 with applications like RockMyRun, which introduced a feature called MyBeat [1] to adjust music tempo based on the runner's heart rate or pace. This app provided personalized playlists that adapted in real-time, aiming to boost motivation and performance during runs. In 2014, Moens et al. [2] developed D-Jogger, an adaptive music player designed to align music tempo with the user's walking or running pace, encouraging synchronization between movement and music.

The interest in this area was further evidenced by Spotify Running in 2015, a feature that matched songs to the runner's tempo by detecting steps per minute Although it was eventually discontinued [3], its popularity underscored the significant user interest in applications that synchronize music with running pace. Continuing this trend, Weav Run emerged in 2016 [4], offering an app that adjusts music tempo to match the runner's pace without altering the pitch. Other applications, such as TempoRun [5], categorized music based on tempo levels, allowing runners to select songs that matched their desired pace and intensity.

1.2 Academic Research

Academic research has consistently supported the benefits of synchronizing music with physical activity. In 2013, Bood et al. [6] revealed that synchronizing running cadence with musical beats enhances performance and reduces perceived exertion. The study found that using consistent beats, like those from a metronome or rhythmic music, helps maintain a steady pace, making runs feel less strenuous. This effect was attributed to auditory-motor synchronization, where the rhythm of the music influences the runner's movement patterns.

Building on this foundation, Moens et al. [2] discovered that **aligning both the tempo and phase** of music with the user's movements significantly **improves synchronization and engagement**. Specifically, adjusting the music to match the runner's pace and starting musical beats in sync with footfalls enhanced the natural synchronization between the runner and the music.

In 2015, Alter et al. [7] examined the role of personalized music in exercise adherence. Their study demonstrated that tempo-pace synchronized personalized music playlists significantly improved adherence to physical activity. Participants who received personalized playlists synchronized to their exercise pace showed higher weekly activity levels compared to those who did not receive music interventions.

Later, Buhmann et al. [8] found that **positive phase angles** —where footfalls occur after the musical beat— **increase motivation and cadence**. Their study suggested that precise synchronization strategies, including both tempo and phase alignment, can enhance motivation and performance.

2 Sensor Placement for Measuring Cadence

While wrist devices are convenient for their simplicity, they may introduce noise due to arm movements unrelated to leg motion. This would need advanced signal processing techniques that may not work as well real-time. Hence, we should consider other options for the sensor placement.

For **optimal accuracy**, placing the accelerometer on the **foot or ankle** seems to be the best option, as these locations directly capture foot strikes, leading to precise cadence measurements.

For this purpose, **inertial footpods** (Figure 1) have been widely used by runners. These are compact devices consisting on a series of accelerometers that help track measurements such as speed, distance travelled, pace, etc. [9]

In the absence of an inertial footpod, any device with accelerometers can be attached to the jogger's foot to obtain the same information.

Figure 1: Foot pod attached to a running shoe.

3 Cadence Calculations

An accelerometer measures linear acceleration across three axes: x, y, and z. When attached to a runner's foot, ankle, or hip, each step causes a distinct spike in acceleration along the vertical axis (often the z-axis). These spikes correspond to foot strikes, which we can use to calculate cadence.

The process involves the following steps [10]:

1. **Extracting the vertical component**: since we're interested in detecting foot strikes, we'll focus on the vertical acceleration (z-axis), as this axis most directly reflects the impact of each step.

2. **Filtering**: to clean any possible noise, we could apply a low-pass filter to remove high-frequency components (unwanted noise), leaving only the main signal that corresponds to running motion. The normal cadence while running is around 3 Hz (180 steps per minute). This means we would expect a single foot to cycle at half the frequency: 1.5 Hz. Hence, we should set the cutoff slightly above this value (around 2 Hz).

3. **Thresholding**: as the runner's foot strikes the ground, there will be a distinct peak in the vertical acceleration data. To reliably detect these peaks, we must set a threshold value. Only peaks that exceed this threshold are counted as steps, which helps avoid false positives from smaller movements.

4. **Peak detection**: we then apply a peak detection algorithm to identify each peak that represents a foot strike. The number of these peaks corresponds to the number of steps taken.

Once the peaks are detected, we can easily compute the runner's cadence in steps per minute as:

$$\text{Cadence (SPM)} = \left(\frac{\text{Number of peaks}}{\text{Time interval (in seconds)}}\right) \times 2 \times 60$$

The multiplication by 2 accounts for the fact that we are only measuring acceleration in one foot.

This cadence in SPM is directly comparable to song rhythm in BPM, which will allow for a better synchronization between both.

4 Music BPM Calculations

The implementation of BPM detection in real-time is intricate, since it involves several steps including audio stream segmentation, onset detection, inter-onset-intervals calculations, and further processing. Covering all of these in detail is over the scope of the subject.

Luckily, there exist some libraries such as **RealTimeBPMAnalyzer** (TypeScript/Javascript), that allow beats-per-minute (BPM) real-time detection from any audio or video source.

5 Optimal Cadence

There is no such thing as an optimal cadence. While 180 steps per minute (SPM) is often cited as an ideal cadence [11], this number isn't universal and should be adjusted based on individual characteristics:

- **Performance**: for many runners, a cadence around 170–180 SPM works well at moderate to fast paces. However, beginner or slower runners may find a cadence between 160–170 SPM more comfortable.
- **Height**: taller runners with longer legs may naturally have a lower cadence, while shorter runners may have a higher natural cadence due to their shorter stride length.
- **Speed**: elite marathon runners typically maintain a cadence between 180–190 SPM, while sprinters may exceed 200 SPM.

It has been demonstrated that gradual increases in cadence can improve form and reduce injury risk, provided the adjustment feels comfortable and sustainable [12].

5.1 Heart Rate and Cadence

According to the American Heart Association, the target heart rate during vigorous exercise is typically between 70-85% of the maximum heart rate, i.e. around 140-170 beats per minute for young adults [13].

Moreover, the idea that running efficiency (and hence performance) can be improved by coupling stride rate to the heart rate during exercise is known as **cardiolocomotor synchronization**. According to some studies, trained distance runners approach a 1:1 ratio of cadence and heart rate during steady-state running, leading to increased performance [14].

Hence, an **ideal system** for helping runners improve their performance should ensure heart rate stays **within the target range** (70-85% of the maximum) and **synchronized to the stride**. This synchronization does not need to be 1:1, but could be any simple ratio.

Nowadays, heart rate can be easily monitored with **smartbands**, which are usually inexpensive. Heart rate detection in smartbands typically relies on **photoplethysmography (PPG)** [15], a technology that uses light-based sensors to measure blood flow.

6 Conclusions

Our study demonstrates the feasibility of using wearable devices, such as **an inertial foot-pod and a smartband**, to effectively monitor cadence and heart rate, respectively, for synchronizing music playback with a runner's pace. By leveraging these sensors, we can provide a responsive and tailored auditory experience for runners through two primary modes: **Joy Ride** and **Pace Setter**.

In **Joy Ride mode**, the system simply adjusts the playback speed of the music to match the user's cadence, creating a fluid synchronization that enhances the jogging experience. This mode prioritizes maintaining a steady cadence without additional goals, making it ideal for recreational jogging.

For **Pace Setter mode**, a more structured approach is employed. In this mode, the system ensures that the runner's heart rate stays within 70-85% of their maximum, aligning with recommended zones for vigorous exercise. Additionally, cadence is synchronized with the heart rate, with music playback speed set slightly faster than the current cadence. This subtle increase will encourage the runner to elevate their cadence until both heart rate and cadence requirements are met, promoting a more intensive and beneficial workout.

Both modes could incorporate a **phase-adjusted synchronization**, where the musical beat slightly follows each footfall. This positive phase alignment has been shown to enhance motivational effects and improve the natural rhythm between the runner's movement and the music.

In conclusion, our system will provide an effective and engaging way to enhance the jogging experience, whether for enjoyment or performance improvement. By adjusting the music's playback speed in response to cadence and heart rate data, we provide an adaptive, and beneficial tool for joggers at all levels. This approach not only supports physical performance but also contributes to an enriched auditory experience, setting the stage for future research into optimizing exercise through music.

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