Sonification: A proposal for explosive subsecond sport movements

The Track Cycling Standing-Start

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The movement

In track cycling, some races (kilo, pursuit, and team sprint) involve riders starting from a dead stop, the bike held in place by a human holder or mechanical block. Special technique is required to launch the bike out of the hold (first pedal stroke) and accelerate the bike to race speed (through at least two additional distinct phases). All phases of the start are technical movements, but here the focus will be on the initial pedal stroke (fig 1), which is a quintessential subsecond, explosive sport movement presenting sensorimotor challenges to learn and execute.

The challenge

Subsecond, explosive sport movements are difficult to learn and execute because:

1. The subjective experience of the body in these conditions is poor and unreliable, making voluntary control difficult.
2. Interoceptive musculoskeletal proprioceptive feedback is (a) inaccurate and sparse, (b) too slow to deliver real-time feedback, and (c) suppressed [10, 29, 30, 25].
3. Real-time correction and multi-trial learning require an error signal, i.e. feedback signaling mistakes.

Exteroceptive proprioception

The brain is able to make use of information from exteroceptive senses, specifically vision (sight) and audition (hearing), to augment sparse and impoverished interoceptive musculoskeletal feedback [28, 3, 12, 16]. For example, when you reach to grasp a nearby object, seeing your hand position is normally an important part of your motor execution [14]. Similarly, mirrors can be used to augment bodily awareness. Natural movement noises, such as foot fall sounds, are also used by the brain to track body position and coordinate movement [8].

Movement sonification

The hope of movement sonification is to augment interoceptive musculoskeletal feedback further using an artificial exteroceptive signal. For example, a coach shouting "head up" as an athlete squats would be a crude form of movement sonification. Richer information can be provided with a more sophisticated setup. For example, a tone can be played that covaries with some relevant measure of body position [e.g. 15] or deviation from ideal movement [e.g. 6].

Why sound and not visual display?

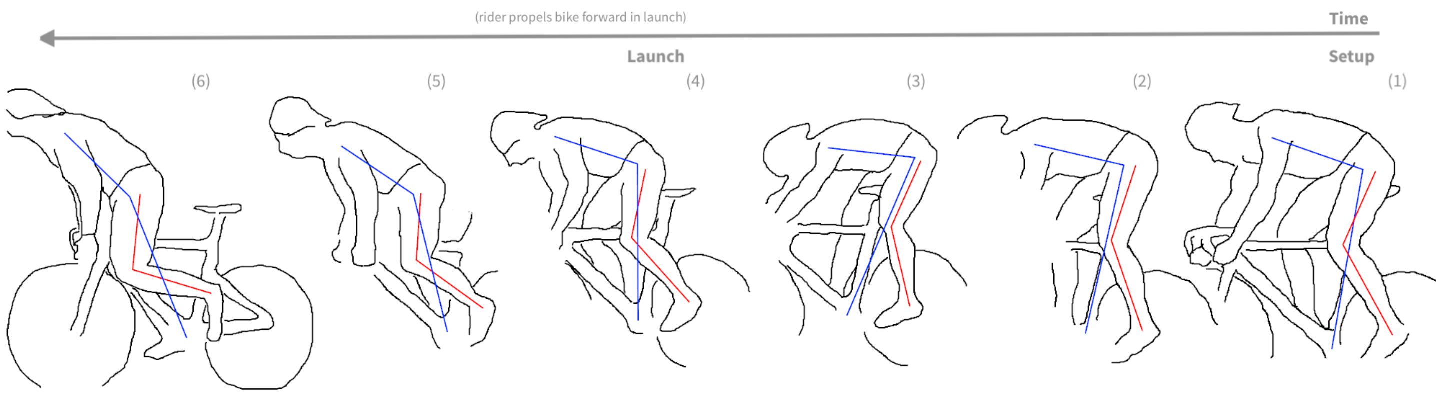
Why sonify movement, instead of visualizing it?

1. Vision is attentionally demanding. An athlete performing a skilled, explosive, subsecond movement (e.g., a standing start, baseball pitch, high jump, etc.) can't watch a screen while they perform the movement. In contrast, sounds can be used with minimal distraction. This is both obvious from everyday experience, and can be measured in a lab [e.g. 11].
2. Vision is too slow and temporally imprecise. It takes about 150ms to visually register a stimulus and vision can only discriminate changes across a timescale of about 100ms (1/10th of a second). In contrast, sounds are registered in about 30–50ms and (more importantly) audition can discriminate changes over millisecond timescales. Hence, audition can potentially capture very precise information about the timing of a movement [5, 4, 24, 7, 26, 23, 27].

Figure 1: The standing start

Thomas Hums performing the first pedal stroke of a standing start.
Photo credit: Alicia Hums.

Figure 2: Standing start sonification (first pedal stroke)



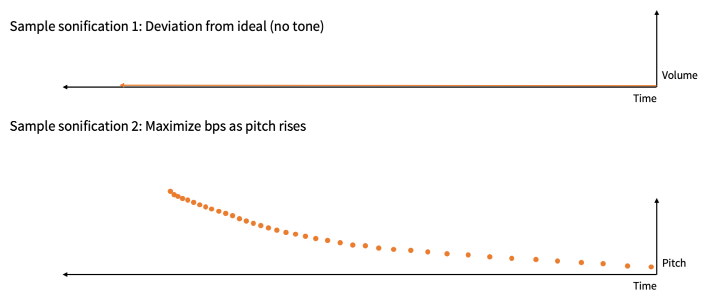


Figure 2: Caption Images 1–3 depict the rider in the block, bike fixed. The hips are raised above the saddle and pushed back. Images 4–6 depict the first pedal stroke. The right foot (far side) is pushed down as the hips and shoulders are thrust forward towards the handle bars. Red lines: Show trailing knee angle (α). Blue lines: Show the hip angle between the rider's back and bike's bottom bracket (β). Left: Two sample sonifications shown. Top (#1): Rider hears no sound when movement is done correctly. Bottom (#2): Pitch increases as knee angle (α) decreases, frequency (bps) of repeating rhythmic tone increases as hip angle (β) increases.

The technology

- A few unobtrusive wearable sensors are placed on the athlete's body or other relevant sport equipment, e.g. around the knee or on the bike.
- No external measurement devices (not on the athlete or on equipment they control) are needed. Athletes are able to move about freely with no restrictions.
- The sensors monitor a small number (1–3) of body position variables (e.g., knee angle) or some correlate (e.g., distance between two points).
- The signal from these sensors is transformed into sound the pitch, intensity (volume), or timbre of which covaries with the body position variables.
- Alternatively, the deviation between the measured variables and the ideal values of a properly performed movement can be sonified, so that the athlete attempts to maximize or minimize the sound.
- Another approach is to play a repeating tone, converting the body position variable into the frequency (beats per second, bps) of the rhythm.
- A simple tuning (10–15 min) is required at the start to normalize the sonification to the athlete's body and specific movement patterns.
- The sound is played for the athlete either through earphones connected to the sensors through a wire, or through an amplifier controlled by an analogy radio signal from the sensors.

Sonifying standing starts

For the first pedal stroke of a standing start (launch), knee angle α of the trailing leg (red) decreases as the hip angle β between back and bottom bracket (blue) simultaneously increases (fig 2). This naturally suggests two potential sonifications of the first pedal stroke:

Deviation from ideal: Since α (trailing knee angle) should decrease as β (hip angle) increases, there should be some function $f(\alpha)$ such that $\alpha = f(\alpha)\beta$ when the launch is performed correctly. Thus, the difference $\alpha - f(\alpha)\beta$ could be used to control the intensity (volume) of a tone. Any heard tone would tell the athlete that their hip/knee angle ration was off and that they need to pull their hips further forward.

Maximize bps: Alternatively, α and β could be sonified separately: α (knee angle) could control the pitch of a repeating tone, so that decreases in α raised pitch. β (hip angle) could control the frequency (bps) of the repeating tone, with frequency increasing as hip angle increases. Thus, as the athlete hears the pitch of the tone rise (knee flexion), their aim is to move their body in a way that increases the bps of the tone.

Real-time feedback (not data)

- The aim of movement sonification is to provide useful real-time feedback.

- It is a method of sensory substitution (replacing or augmenting impoverished interoceptive musculoskeletal feedback with richer auditory feedback) [9].
- Movement sonification is not a method for capturing data for post-movement analysis.
- Of course, sonification could be used in tandem with data-capturing technologies.

The potential

There are two things you could hope to achieve with sonification in explosive subsecond sport movements:

Integration: A real-time signal of movement or body position that can be integrated (in the brain) with motor commands to improve those commands.

Adjustment: You could aim to get that signal to the brain fast enough that real-time adjustments can be made, even in the middle of explosive subsecond movements (e.g., a high jump or baseball pitch).

Mere integration can handle some lag (perhaps upwards of half a second). Any integration (binding of auditory movement feedback with motor commands) at all would be valuable, allowing the brain to learn and do better on the next movement (multi-trial learning). The ambition is to be fast enough with the signal that mid-movement ("on the fly") adjustments are possible. Imagine, for example, a novice rider making corrections (pulling the hips further forward) mid-pedal stroke in a standing start based on the sound they hear. (Note that the higher temporal resolution of audition offers advantages for integration, even if adjustment isn't possible.)

Does it work?

Movement sonification has already shown promise in a number of sport applications. As Schaffert et al. [16, p. 4] summarize: "Investigations examining the use of sonification in elite or high-performance sports have demonstrated that the presentation of artificially generated sounds optimize movement control and execution (e.g., stability, velocity, pattern and force symmetry) in sports such as swimming (Chollet et al., 1988 [2], 1992 [1]), rowing (Schaffert et al., 2010 [21], 2011 [20]; Schaffert and Mattes, 2011 [17], 2015b [18], 2016 [19]), and cycling (Sigrist et al., 2016 [22]; Schaffert et al., 2017 [15])." For example, Effenberg et al. [3] show that rowing novices trained with sonification improve their technique faster and more than controls without that sonification, and also retain that technique after sonification. Insofar as the basic workings of sensorimotor processing and control are understood in the human brain, there is good reason to think sonification can improve performance of sport movements along a number of dimensions.

1. It's known that interoceptive musculoskeletal proprioceptive feedback is delayed, impoverished and suppressed [10, 25], so conveying body and movement position in an auditory signal gives the brain information it did not have [28].
2. There is an abundance of evidence that the brain naturally uses exteroceptive sensory information from vision and audition to control movement [14, 3, 12, 16].
3. Audition has millisecond temporal resolution and extremely short latencies (response time), meaning that it's able (in theory) to capture the extremely fine position changes of subsecond explosive sport movements and potentially deliver that information fast enough to be used in real-time [5, 4, 7, 23, 27].

Breaking new ground

Thus far, typical applications of movement sonification studied in sport involve sonifying rhythmic motion [e.g. 3]. For example, the force data from a power meter in a bicycle crank arm might be converted into a covarying tone, so the athlete can "hear" how much force they put through the pedal as they pedal [e.g., as done in 15]. The hope is that this information will help them smooth out their pedal stroke and apply power more evenly through the downstroke. In this application, the sound essentially takes the place of the well-known (visually displayed) polar force graph on a WattBike. What I hope to achieve is sonification that's not just usable for repeating rhythmic movements (e.g., running, pedaling, swimming), but for explosive subsecond movements (e.g., standing start, high jump, baseball pitch). This demands extremely fast and temporally precise sonification at a level I don't believe has been done before. The path forward involves both creating the technology which produces this temporally precise and fast sonification, and testing various aspects of its performance role:

Subjective feel: Do athletes feel as if the signal is usable? Do they report using the signal as they execute the movement (either in trial or across trials)? Do coaches notice a difference with athletes when using sonification?

Physiological results: Do objective measures of brain response (such as ERPs in EEG) suggest that the auditory signal is being received and used? Does sonification during explosive subsecond sport movements change motor cortex (M1) activity relative to recordings taken during the movements without sonification?

Behavioral measures: Do athletes using sonification perform explosive subsecond sport movements more consistently and accurately, as measured by independent data collection and measurement (e.g., video motion capture)? Can it be shown that athletes using sonification take fewer practice trials (compared to those not using sonification) to achieve the same level of movement accuracy?

Bespoke design

Each sonification must be approached individually. There is no one algorithm or setup which will usefully take time-varying sensor data on body position and convert it into a useful auditory signal.

- For each new movement (e.g., other phases of the standing start beyond the first pedal stroke, high jumps, pitches, etc) a few key body-position or movement variables need to be identified for measurement and sonification.
- These variables might be general to the movement (e.g., as I've assumed here in discussing the standing start) or specific to an athlete. For example, there are many dimensions of body movement to pitching a baseball or throwing a football. Different athletes will struggle with different parts of the movement, thus requiring different movement variables to be captured.
- Once these variables are identified, appropriate means of measurement (sensors) need to be identified.
- Once the type of measurements made by the sensors' are known, a sonification (conversation of the measured movement variable into a useful auditory signal) must be designed.
- Finally, the setup needs to be fitted to an individual athlete. Each sonification will have constants that need to be set and normalized for each athlete (e.g., so that, given the individual athlete's body position, there is no tone at rest).

Phenomenology: From the athlete's perspective

Athletes are conscious subjects. They experience their own body and (to varying degrees) control it deliberately. Just as everyone has to learn to use their regular senses, athletes using movement sonification will have to learn to use and interpret the auditory signal. At first, the sound will be meaningless. With some practice, athletes will learn how their own movement (and voluntary motor commands) affects the sound. At that point, the sound will take on meaning and become a conduit through which they experience their own body. Just as one comes to experience (what was at first) diffuse whole-body pain sensations as a torn bicep by noticing how the pain changes as the arm is bent, so too athletes can come to subjectively, consciously experience (what was at first) a meaningless sound as the position of their own body. In this way, movement sonification is like sensory substitution [e.g. 9], although some think all perception is fundamentally a matter of learning how "sensation" or stimulation covaries with movement [e.g. 13]. In any case, the point is that while athletes might at first find the sound awkward, after a few trials they will hopefully come to experience their own body through the artificial sound (just as they already experience their body through their own sight of it and through natural movement sounds like foot falls).

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