MOBILE SONIFICATION FOR ATHLETES: A CASE STUDY IN COMMERCIALIZATION OF SONIFICATION

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ABSTRACT

Several companies, including Under Armour, Nike and Adidas, are taking advantage of advances in sensor technology to sell wearable systems that measure, record, and analyze the motion of athletes. To date, these systems make little, if any use of sonification. Therefore, there is an opportunity for sonification methods in this domain, including the potential to reach a mass market. In the fall of 2013, Under Armour and NineSigma created the Armour39 Challenge, an open call for proposals to build new technology for the Armour39, Under Armour's wearable motion and heart-rate sensor. The authors of this paper responded to the challenge, proposing novel sonification systems to exploit the data from the Armour39. This paper presents these systems, including issues, solutions, and tools for sonification performed on a mobile device with a wearable sensor. The sonifications are rhythmic, exploiting the periodicity of human motion, and are demonstrated by sonifying athletic performance metrics in real-time for speed skating and running.

1. INTRODUCTION

The advent of microelectromechanical systems (MEMS) has revolutionized mobile computing by providing cheap, low-cost sensing to mobile devices. Motion sensors such as accelerometers and gyroscopes are now commonplace in consumer electronics. These sensors are showing up in wearable devices that measure the physical activity of athletes. When combined with the computing power of current mobile devices, these wearable sensors are providing new opportunities for consumer-oriented training systems. For example, consider the following consumer devices.

- **Under Armour Armour39:** The Armour39 has an embedded heart-rate monitor and accelerometer that is worn on the upper torso [1]. Figure 1 shows an Armour39 with a 7-inch Android tablet that communicates with it.
- **Nike FuelBand:** The FuelBand [2] contains an accelerometer and is worn on a person's wrist.
- **Adidas MiCoach:** The MiCoach system [3] uses an accelerometer worn on an athlete's shoe.

Figure 1: An Under Armour Armour39 (below) communicating with an Android Nexus 7 tablet (above).

The Armour39 Challenge [4] was an effort by Under Armour, Inc. [1], represented by NineSigma, Inc. [5], to develop new applications to exploit the Armour39 sensor.

> Under Armour wants to make the Armour39 more interactive for competitive athlete users. They would like to develop new features that will generate excitement, enhance level of use, and improve training or conditioning sessions. While they actively seek solutions to the three areas listed, they also are interested in any new way Armour39 can "make athletes better".[4].

The challenge had three phases.

1. Phase I (November 2013): Participants submit a proposal and optional video to describe a technology to enhance the Armour39.
2. Phase II (December 2013 to March 2014): Successful Phase I participants receive an Armour39 development kit that consists of an Armour39, software, and specifications on how to communicate with the device. Participants develop a demonstration application with the development kit and whatever other platforms they care to use, then submit a report and video to NineSigma at the end of Phase II.
3. Phase III (April 2014): Successful Phase II participants travel to Baltimore, MD to present their demonstration to Under Armour directly.

While there is some prize money at stake in Phase III, obviously the real goal is to produce a demonstration that will eventually become part of a consumer product.

We see the Armour39 Challenge as an opportunity to bring the sonification of athletic movement to a mass market. To that end, the authors participated in Phase I, were selected for Phases II and III, and implemented a mobile sonification system built around the Armour39. This paper describes our system including:

- how we analyze motion from the Armour39,
- how we map periodic athletic movements to sound, and
- specific goals in athletic training for runners and speed skaters that we address with sonification.

2. BACKGROUND

2.1. Sonification in Athletics

Sonification of sporting movements is an active research area. Speed skating [6] [7], running [8] [9], rowing [10] [11], karate movements [12], swimming [13] and golf [14] have all be successfully sonified as part of an interactive experience.

Most current interactive sonification is done through parameter mapping [15]. Looking at acceleration data, in the case of golf [14], karate [12] and rowing [10] the mapping of acceleration (force) to musical pitch allows the users to perceive the level of force being applied. Sensor data has been parameter mapped to sound characteristics to allow users to perceive changes in their posture [8] or orientation of their equipment [11]. Most closely related to the goals of this work are those examples that use sound to convey information about the timing of movements and especially repeating locomotive movements [7], [9].

2.2. Mobile Sensing in Athletics

There are several established technologies available to capture the motion of a person for analysis and sonification. These include:

1. video-based marker-tracking systems (e.g., those built by Vicon [16]),
2. inertial measurement unit (IMU) systems (e.g., the motion capture suits made by Xsens [17]), and
3. exoskeletons (e.g. the Meta Motion Gypsy 7 system [18]).

Of these, only inertial measurements are viable for mobile applications.

In a conventional IMU motion capture system, a single IMU contains both a three-axis accelerometer and a three-axis gyroscope. With these six degrees of freedom, it is possible (within the bounds of sensor errors) to integrate the spatial trajectory of the IMU over time. For a full motion capture solution, a person wears several IMUs to acquire trajectories of limbs and joints.

In contrast to a full IMU motion capture system, the current generation of motion sensors for consumer devices is most often just a three-axis accelerometer. As such, it is not generally possible to integrate a trajectory from these sensors, but it is possible to infer the translational forces experienced by the sensor. To illustrate, the following summarizes the properties of three well-known body-worn motion sensors available in consumer devices.

The Adidas MiCoach product line consists of several devices [3]. We consider specifically the *speed cell*, a device that is either attached to, or embedded in a shoe. The device is a variant of Dynastream's [19] speed and distance measuring (SDM) technology [20] and uses data from an accelerometer to do stride analysis and estimate speed and distance travelled. A wireless link shares data with a mobile device.

The Nike FuelBand [2] is worn on the wrist with wireless connections to smart phones. To measure motion, it uses a three-axis accelerometer.

According to specifications posted for the Armour39 Challenge, the Armour39 has both a three-axis accelerometer and a heart-rate monitor and has wireless links to mobile devices [4].

Note that the heart-rate monitor is not unique to the Armour39 - other vendors provide this function too depending on the packaging of the devices. In any case, MEMS accelerometers are common to all these devices and should be considered as standard equipment for the current and future generations of consumer motion measurement. In fact, anybody carrying a smart phone almost certainly has an accelerometer available to them, even if it is not packaged as an athletic device. To our knowledge, no vendor is taking advantage of sonification of the data available from these devices. The goal of these devices is primarily to record performance and real-time feedback to athletes is minimal.

3. SONIFICATION FOR THE ARMOUR39

Our response to the Armour39 Challenge has two specific objectives:

1. show that a mobile device can synchronize to periodic human motion as measured by the the accelerometer in the Armour39, and
2. show that sonifications built on this synchronization can provide useful feedback to an athlete.

Of course implicit in these goals is to show that sonification of data from the Armour39 (and by extension other body-mounted accelerometers) increases the utility of the device to the consumer.

The following subsections summarize our synchronization and rhythmic sonification methods, the tools we used, and the specific sonification schemes we designed to enhance speed skating and running.

3.1. Synchronous Rhythmic Sonification

Figure 2 illustrates our approach to sonification of periodic human motions from sensor data in real time. In Figure 2(a), as a person engages in periodic motion (e.g., walking, running, or skating), sensors on the body produce periodic signals. We also have a computer model that tells us what these signals *should* look like. The model typically originates from measurements of a skilled athlete demonstrating the motion, but might also be derived from a biomechanical ideal. Algorithms described by Godbout and Boyd [7, 21] synchronize the model with measurements from the person in real time.

Figure 2(b) illustrates how the synchronization leads to rhythmic sonification. The output of the synchronization algorithm is a phase (normalized to the range $[0..1]$) that varies over time and also a correlation coefficient indicating how well the signals match. When the motion is periodic, the synchronized phase is a ramp from zero to one, then repeating once for every cycle of motion. To sonify phase, we set phase triggers, ϕ_T. As the phase ramp crosses ϕ_T, it triggers a sonic event. One or more phase triggers

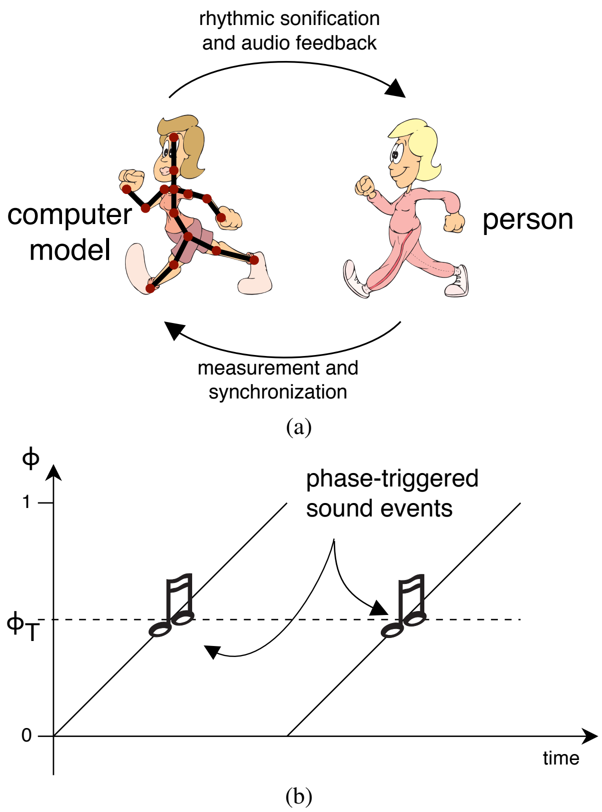


Figure 2: The concept of rhythmic sonification. (a) A computer model of a periodic motion synchronizes to the motion of a person based on measurements of the person. A sonification system provides rhythmic feedback to the person, synchronized (by the computer model) to the person's motion. (b) The output of the synchronization is a phase signal that ramps from zero to one, repeating for every cycle of the motion. Phase triggers produce sonic events that form a rhythm synchronized to the person's movement.

results in a rhythmic sound pattern that is synchronized with the motion of the person. The synchronization also allows person-to-model comparisons at specific moments in the phase cycle, and these comparisons can be sonified, rendered synchronously with the motion.

3.2. Tools

We chose the Nexus 7 tablet (Figure 1) to host our demonstration application [22]. The Nexus 7 has the following specifications that make it suitable for our demonstration:

- a 1.5GHz ARM processor for real-time processing of signals and sound,
- Bluetooth 4.0 (required to communicate with the Armour39),
- size (small and light enough to be carried by a skater or runner with a fanny pack), and
- the Android development environment (open, and the authors have experience with this environment [23]).

Since a key element of our demonstration is sound, we required a way to synthesize sound on the Nexus 7. Fortunately,

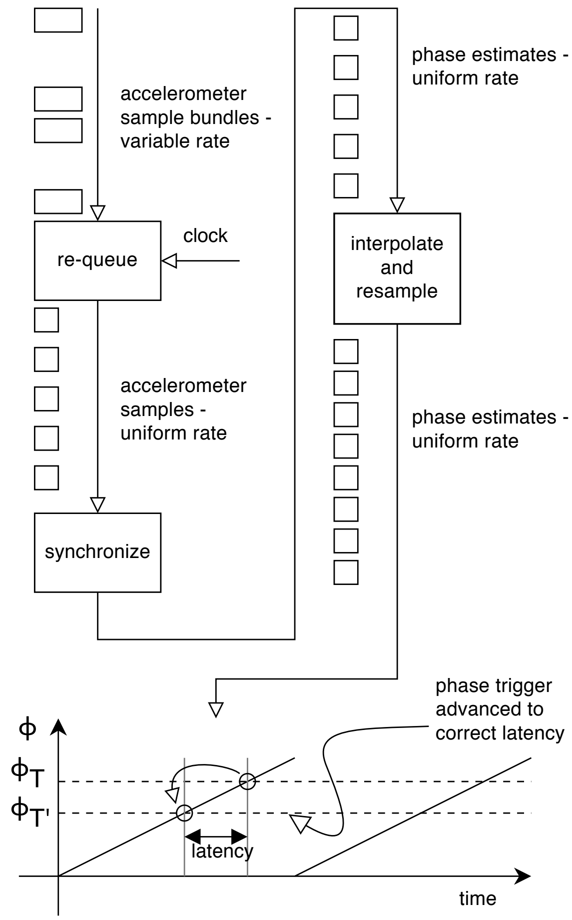


Figure 3: Illustration of process to address sampling and latency issues for sonification. Bundled samples are re-queued and clocked out at a uniform sample rate for the synchronization. Interpolation and resampling at a higher rate allows more precise placement of phase triggers. Advancing phase triggers for sonic events addresses latency.

Pure Data [24] has been ported to Android in the form of PdDroidParty [25]. PdDroidParty offered the immediate advantage of allowing us to develop in the higher-level Pure Data environment rather than the lower-level world of Android Java apps. The combination of Android development tools [23] and PdDroidParty facilitated easy development of custom extensions to perform synchronizations efficiently. PdDroidParty does not currently provide access to the accelerometers onboard the Nexus 7. However, because PdDroidParty is open source, we were able to add accelerometer access, thus allowing us to develop without the Armour39 (we had only one Armour39 available). Finally, PdDroidParty uses an Android port of *libpd* [26], the code library that is the foundation of Pure Data, thus ensuring that there is a development path to a stand-alone app.

The volume and quality of the sound produced by the internal speakers of the Nexus 7 is too poor to be of use for sonification. Therefore, we used external headphones for the speed skating examples. We also used headphones for runners, except on a treadmill when we could use external speakers.

3.3. Sampling and Latency

The Armour39 exploits Bluetooth 4.0 to communicate with mobile devices while minimizing power consumption to maximize battery life. However, the way Bluetooth 4.0 minimizes power consumption has implications for sonification. Ideally, we want a continuous stream of samples at a uniform sample rate of approximately 30Hz, and minimal latency. In reality, Bluetooth 4.0 transmits data intermittently to reduce power consumption, which poses these challenges for sonification:

- samples come in bundles rather than streams, and
- large latencies occur as the device accumulates data to fill the bundles.

Figure 3 shows how we address these challenges. To deal with bundling, we use a first-in-first-out queue to accumulate samples from the bundles, then clock the samples out at a uniform rate. The rest of the processing sequence then sees single samples arriving at a uniform rate. We configured the Armour39 to sample at 30Hz, so we use a 30Hz clock to time removal of samples from the queue. The synchronization step then produces phase estimates at the sample rate, 30Hz. Finally, if we need the precision in audio trigger timing, we interpolate and resample the phase signal at a higher frequency. For most of our work, 30Hz, is sufficient, but if we need events spaced closer than 33ms, this is an option.

Between the bundling and re-queuing, the latency between the true phase of the athlete and the phase signal output by our system can be large. Fortunately, the synchronization process provides its own remedy. We simply advance the phase triggers for the sonifications - early triggers compensate for the latency so that sound events occur at the right time. In Figure 3 for example, if we need a trigger at ϕ_T, advancing the trigger phase to $\phi_{T'}$ compensates for latency. In effect, we are using the locked phase to *predict* the correct time for sound events.

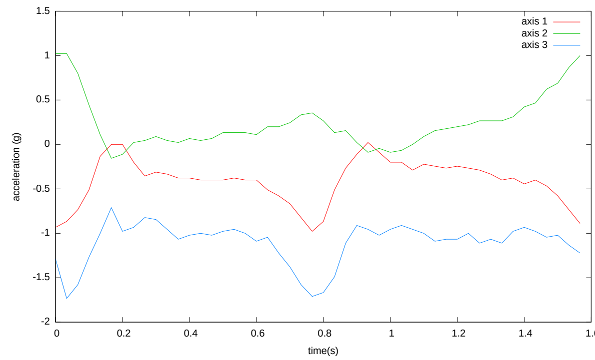
3.4. Speed Skating

Speed skating encompasses two separate repetitive movements: one for navigating the straight sections of the speed skating oval and one for navigating the corners (Figure 4). The first challenge to tracking speed skating movement is to automatically distinguish between corners and straights using the incoming data from the Armour39.

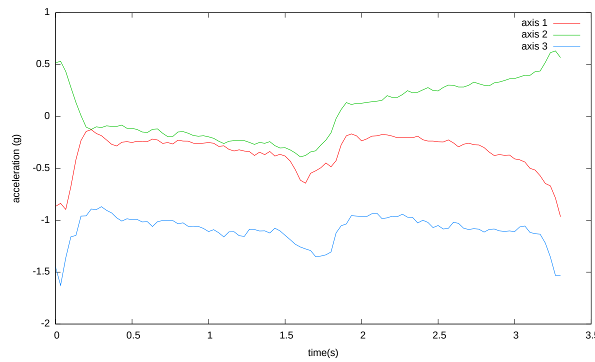
To resolve this we simultaneously synchronize to a pair of models: one for the straight and one for the corner (Figure 5). The synchronization algorithm computes a correlation coefficient that indicates the quality of match to the model. By comparing the correlation coefficient for each model, our system can determine which model is best and automatically distinguishes between the two stride types while simultaneously synchronizing.

We sonify the basic movement as a rhythmic arpeggio synchronized with the stride. We transpose the arpeggio to different chords corresponding to the stride type. Thus the skater hears the arpeggio shift pitch as they make the transitions into and out of corners.

A challenge in speed skating is to determine velocity and report it back to the skater. Some speed skating ovals have sensors embedded in the ice that communicate with sensors worn on the skater's ankles. Such a set-up allows velocity to be estimated over known distances between the in-ice sensors. More traditionally, coaches manually time skaters in one lap intervals, in both cases



(a)



(b)

Figure 5: Model measurements for speed skating strides: (a) corner cross-over stride, and (b) straight stride. The models are averages of examples acquired from a real skater. Sample rate is 30Hz.

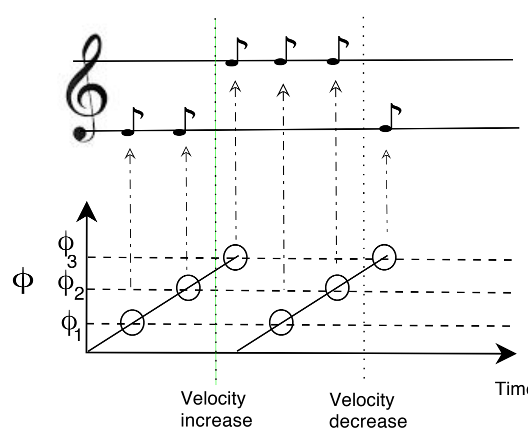


Figure 6: Modifying the sonic phase triggers based on estimated velocity. The notes in the upper part of the figure are sine waves modulated a series of pulses, producing a buzzing sound. The changes of pitch implied by diagram correspond to the frequency of the modulating pulses.

the coach reports the information to the skater, or review it after skating is complete. One lap takes roughly 30 to 35 seconds and consists of two straight sections and two corner sections. If the skater maintains constant speed throughout a lap then the lap time

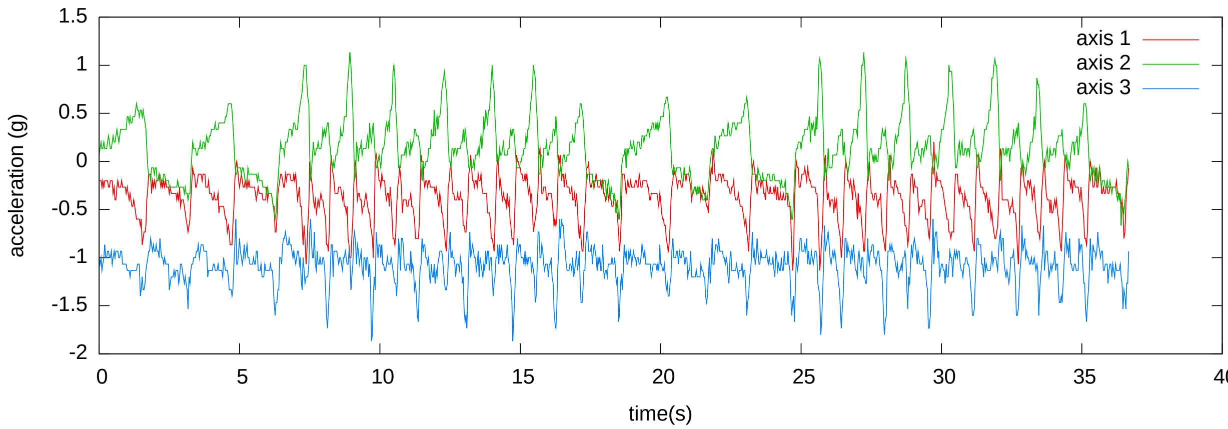


Figure 4: Example of typical measurements seen over a full 400m lap of speed skating. Zero to 7s and 16s to 24s cover straight sections of track while the remainder is in corner sections. Sample rate is 30Hz.

allows them to know velocity. In practice, constant speed is not maintained and a skater is left to guess where in a lap they gain or lose speed.

As part of our submission to the Armour39 Challenge, we created a system to estimate velocity and report it to an athlete as part of our rhythmic sonic feedback. We first synchronize speed skating strides against model strides as described above, and then estimate speed from the acceleration. Note that centripetal acceleration varies with centripetal force, so we expect to see our integrated energy per stride correlate to velocity in the corner. The acceleration maps to the sound in the feedback, shown schematically in Figure 6. We experimented with various sounds to convey the velocity information, and learned that an important requirement is for the sound be heard above the wind noise in the headphones. For that reason, we use a less musical (and therefore less pleasant) buzzing sound that is easily heard over the background noise, i.e., a sine wave modulated by a short-duty-cycle pulse train. Increases in acceleration map to increases in the frequency of the pulse train. The effect is a more *intense* buzzing as the skater accelerates. Thus a skater given a target speed can hear not only when they are going faster than the target speed (higher pitches) or slower than the target speed (lower pitches) but also which strides are contributing to changes in speed. In the straight portion of the track the system maintains a baseline rhythm.

3.5. Running

Once we had implemented our system for speed skating, it was a simple matter to apply it to running. This has the distinct advantage of connecting to a much larger consumer market. Figure 7 shows typical measurements acquired from an Armour39 during running, and Figure 8 shows a corresponding model. The model covers a complete stride cycle, one step for each foot. Two things are immediately obvious from the model.

1. All the information is in axis one, the vertical axis, which shows a sinusoid that matches the step-rate of the runner. The Measurements in the other two axes do not appear to correlate with the periodicity of the motion.
2. It is impossible to distinguish between left and right footsteps. Axis one (vertical) shows a sinusoid with a mean value of -1g with alternate cycles being identical.

To test the synchronization, we set phase triggers to play short tones at the footfalls, alternating in pitch between left and right feet. As expected, the synchronization algorithm easily synchronized the model to the walker, but it occasionally switches between left and right foot. That is, we would hear a high pitch tied to the left footfall for a while, then the high pitch would switch to the right foot. The switch between left and right was arbitrary. From this we concluded that sonifications that distinguish left from right are not practical with this instrumentation.

Rhythmic feedback for a runner is not likely to have market appeal on its own – it is difficult to see the utility – although we suspect there may be some applications in helping runners to recover a normal gait after injury.

Recently, there has been much discussion about the effect of heel striking versus toe striking while running and its connection to running injuries [27]. We have no opinion to offer on the matter, but we can at least suggest a method by which sonification might be used to encourage toe-striking (or encourage heel striking, as the case may be). It is known that increasing step rate and shortening the step length correlates to toe striking [27]. As a bi-product of synchronization, we know the step rate with reasonable accuracy. We then introduce a phase trigger that varies with the step rate as illustrated in Figure 9. When the runner steps at the desired, fast rate, the phase trigger, ϕ_1, corresponds with the runner's footfalls. We choose the footfall for its perceptual significance [28]. However, if the stride rate is too slow (corresponding to long strides), the phase trigger moves before the footfall, ϕ_2, audibly suggesting to the runner that they put their foot down late. We have implemented this and verified that this is possible with the Armour39 and our synchronization system. However, we do not have data to indicate that this can help a person to alter the way they run.

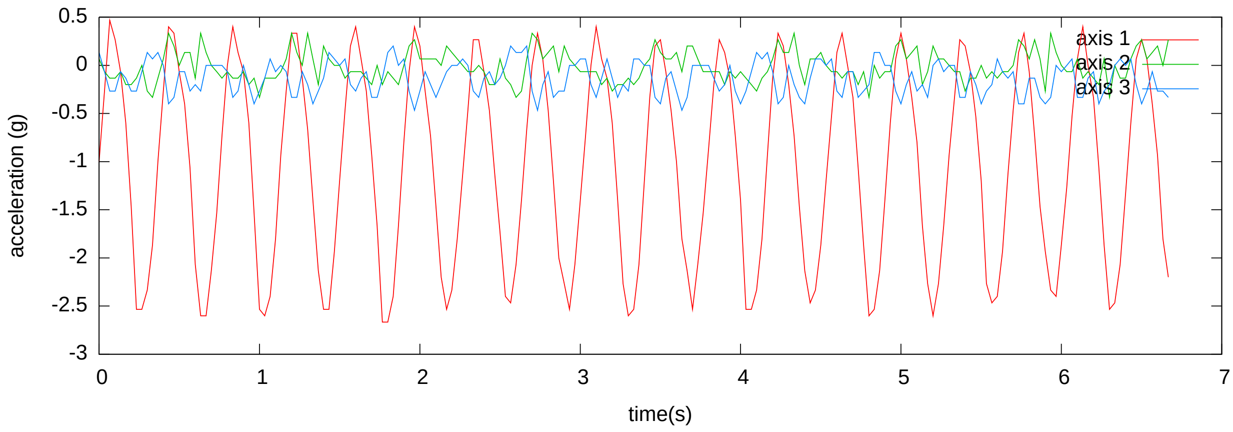


Figure 7: Example of typical measurements seen while running. Note that it is difficult to distinguish between left and and right foot movement. Sample rate is 30Hz.

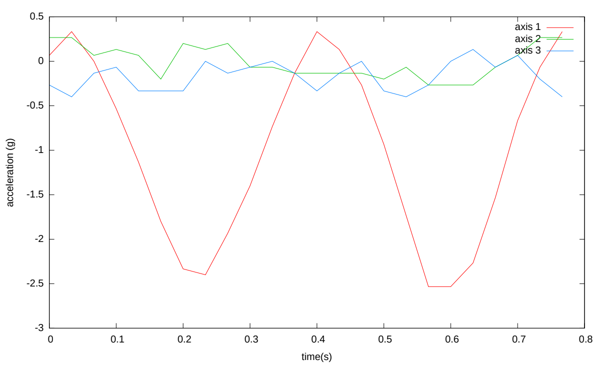


Figure 8: Running model measurements. Note that this model represents two steps, one left and one right. Sample rate is 30Hz.

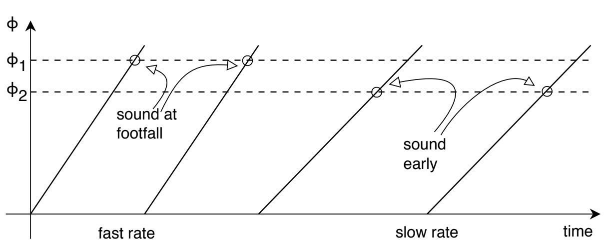


Figure 9: Stride rate sonification to encourage toe striking in runners. At the desired stride rate (with a short stride length), rhythmic sounds are synchronized with the footfalls. When the stride rate is too low (corresponding to a long stride length), the rhythm advances to encourage the runner to set their foot down earlier.

4. DISCUSSION

4.1. System

When we prepared a Phase I submission to the Armour39 Challenge, it was not immediately clear that sonification would be practical with the Armour39. We knew what could be done with a light-weight netbook computer and an IMU attached by a USB cable, but this has a much faster CPU, established development environment, and better control over sensor communication than one typically finds with consumer and mobile systems. Fortunately, the latest generation of mobile devices does meet the CPU requirements, and between Android and PdDroidParty, we had adequate development tools.

Bluetooth 4.0 power optimization posed challenges. We worked around these challenges, but ultimately a steady stream of data with low latency is what we need for sonification. It is our hope that we can establish sonification as an important part of wearable athletic sensors so that future devices will work better for that purpose. There are certainly design alternatives available, but for a vendor to chose these alternatives, they must see sonification as an asset to their product.

With respect to sonification, we built on previous work to produce synchronized rhythms that convey timing information to the athlete – essentially confirming for the athlete that the timing of the motions is correct. Beyond that, we proposed two variations. First, the mapping of performance estimates (e.g., the estimated speed of the skater) that are synchronized with the motion we believe is novel, albeit incremental. Others have mapped performance measures to sound rhythmically (e.g., [13] and [10]) but the rhythm is a natural consequence of periodic input rather than a phase synchronization to model movement. Second, our proposed method to sonify desired footfalls versus actual footfalls is new – rather than sonify what the athlete's timing actually is, we sonify what the timing should be to encourage correction. These proposed innovations only suggest where sonification might be used with wearable, mobile systems. This needs more work than the timeframe of the Armour39 Challenge allows. We have shown what might be possible with the device should sonification be adopted as part of the product.

4.2. Athletes

For our speed skating systems, the model data came from one of the authors who is a former elite-level speed skater. We had an opportunity to test the systems with a currently-competing elite-level skater. Synchronization was robust and reliable. The skater observed, without prompting that the tones shifted automatically betweens straight and corner strides. Although we do not expect that an elite-level skater needs the rhythmic feedback, he did speculate that it might be useful for training as a skater tires - when a skater becomes fatigued, technique falters and the skater looses speed. Performing motions correctly, even when fatigued, is critical to winning.

Testing the velocity feedback was particularly satisfying. When the author tested this feature, his immediate reaction was to try to increase the buzzing intensity, and pushed himself to skate faster. The effect was similar with our elite skater - he pushed himself harder to hear an increase in sonic intensity. Obviously, a skater cannot accelerate indefinitely, so some thought will have to go into how this feedback can fit into an athlete's training regime.

We expect the best benefit from our systems will be for training young athletes. The rhythmic feedback can help to reinforce good technique while the velocity feedback can help a skater to improve technique in corners. The velocity feedback may also have use as a motivational device during workouts.

While the authors spent time with the running system, we did not test with any elite athletes. That said, the simplicity of the acceleration signals during running makes the synchronization almost trivial, and extremely reliable. The timing of sonified footfalls worked well. Testing will be necessary to verify that the advanced footfall sound actually does encourage the runner to shorten stride and increase cadence. Beyond that, the sports medicine community can determine if a shorter stride really is a good idea.

4.3. Armour39 Challenge Results

The authors submitted a Phase II report and video to Under Armour in March 2014. The substance of that report is reflected (in more detail) in this paper, and the video may be viewed at *www.youtube.com/watch?v=YZ_E5FgB_pY*. Subsequently, we were one of five teams invited to present at the Under Armour Future Show in Baltimore, MD, April 2014. Under Armour liked the work enough to award it second place in the Armour39 Challenge.

Contrary to the norm in academic conferences and journals, participants in the Armour39 Challenge did not share their work with their peers. For that reason, we know very little about what other technology was proposed in the Armour39 Challenge, although we are reasonably sure that we are the only team to have proposed real-time sonification.

5. CONCLUSION

Through our Armour39 Challenge submission we have shown that the sonification of athletic movements from wearable, consumer sensors and mobile devices is possible. The utility to athletes is yet to be determined, and will take more time than available in the Armour39 Challenge. Nevertheless, if the utility can be demonstrated, current and future wearable devices have the potential to bring sonification to athletes in a mass market.

Although we had some success at Under Armour's Future Show 2014, it is still too early to tell, if or when real-time sonification for athletics will reach a mass market. Nevertheless, there is a spark of interest to encourage the sonification community.

6. ACKNOWLEDGMENT

The authors thank NineSigma, Inc. and Under Armour, Inc. for their support during the Armour39 challenge.

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