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Corrective Sonic Feedback in Speed Skating

by

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Abstract

We present a method for providing real-time audio feedback to people performing repetitive, periodic movements. Our method synchronizes the temporal signals from the repetitive periodic movements of two people. Our synchronization method utilizes relative data and as such we demonstrate the method in a speed skating test case using a simplistic and cost effective sensor system. We use this system to synchronize a speed skating subject who had a specific anomaly in his skating stride against a model skater. We sonify this synchronization allowing the subject to hear and react to the differences between himself and the model in real-time.

Acknowledgements

The seeds of this project took root in April 2006, with an email I sent to Dr. Jeffrey Boyd asking if he would be interested in taking on a student interested in applying computer analysis to the sport of speed skating. I quickly received an email reply asking me to fill out the master of science program application forms. Despite being past the application deadlines for the master program at the University of Calgary, Dr. Boyd ensured me he would take care of it. Over the course of my degree, which was intertwined with my own, often demanding, sporting career I came to appreciate the combination of flexibility and avidity Dr. Boyd provided. It truly is unlikely this project would have prevailed under the supervision of anyone else. For that I thank Dr. Boyd, a great friend, mentor and supervisor.

I would like to acknowledge the support of our case study participant. His input and testing pushed the project forward in an immeasurable way. Despite his strenuous and stressful competition schedule he always found the time to put our system through the paces. Being witness to his drive and work ethic is something that will forever inspire me.

My lab-mates and fellow students in the Vision lab at the University Of Calgary, Chris, Ori, Akil and David in particular, deserve credit for their input, discussion, and helpful banter.

Finally, I acknowledge the support and encouragement of my friends and family. A special thanks to my Sister, Mother and Father for their constant encouragement and interest in my work.

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Chapter 1

Introduction

Repetitive periodic movements are common motions that people perform. Running, walking and skating are all examples of repetitive periodic movements. In therapeutic, sporting and everyday settings people attempt to refine, improve and correct these types of movements. As we see in Figure 1.1 the kinematics associated with the body parts of someone performing a repetitive movement is periodic. Consequently, measurements of the motion lead to periodic waveforms. It is possible to compare periodic waveforms to measure how closely two waveforms match. Thus, comparing periodic waveforms representing the motions of two people can indicate how closely the movements of those individuals match.

In this thesis we introduce a novel signal processing technique to compare and synchronize relative data from multiple people performing a repetitive movement and use that information to form the basis of real-time interactive sonic feedback. The sonic feedback comes in a novel discretized format synchronized to periodic movements. In addition, we show how the comparison information can be used to identify key windows when corrective or instructive sonic feedback can be provided.

Our methods are unique in that we create a ***rhythmic*** sonic feedback by synchronizing two signals in real-time. We can communicate corrective information regarding a specific movement with little specific knowledge about that movement. The system we demonstrate requires little calibration and makes use of relative data, allowing for simple and cost effective sensors to be employed.

We demonstrate our methods in the context of a case study involving a speed skating athlete who had developed a specific anomaly in his stride. We built a custom system to track the movements of this skater and broadcast real-time feedback relating his movements to those of

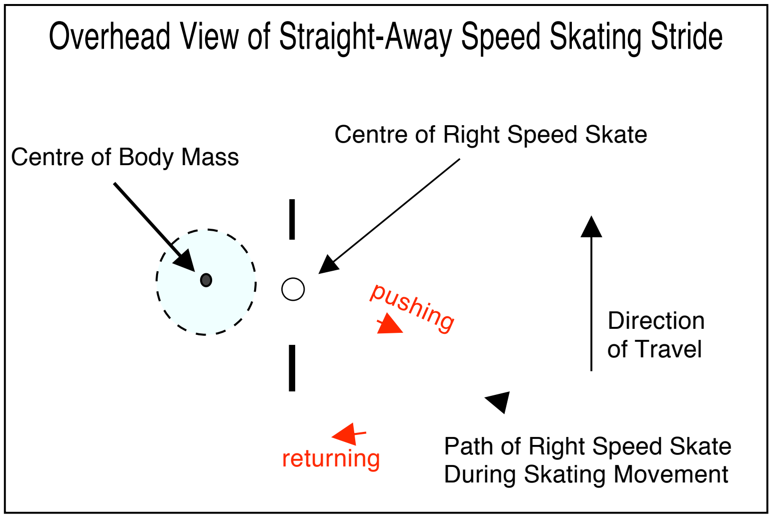

Figure 1.1: Overhead view of the path followed by the right skate during a straight-away speed skating stride relative to centre of body mass. The dotted red line represents the path followed by the skate as it pushes away from the body then returns to its original position ready to push again. This path forms a periodic function in position and time.

a model skater. The feedback is designed to both correct an undesired movement and elicit the positive behaviour of a model. Our methods and motivation were often inspired by what was practical for solving the particular problem of our speed skating subject. The results of this case study were published [1] and awarded the distinction of best paper at the 2010 International Conference on Auditory Display[2].

The following three important aspects of our research should be noted.

1. We do not require absolute measurements of pose (joint angles and body positions). This reduces the cost and complexity of sensor systems.

2. We show that relative data from two repetitive motions is sufficient to synchronize them. While we demonstrate this with speed skating, it can be applied to any repetitive motions.

3. We give a framework for how to provide sonic (or other) feedback sychronized to a periodic motion.

1.1 Opportunity

"Necessity is the mother of invention" -proverb

During the course of this research we became aware of the special case of a speed skating athlete that had developed a particular anomaly in his speed skating stride. Traditional coaching methods were unsuccessful at fixing his movement. He performed the same incorrect movement on a consistent basis.

While we were investigating synchronization and sonification, the unique opportunity posed by this skater provided motivation for our work. It changed our focus from the hypothetical to the actual. Rather than ask, "what might synchronization and sonification do for some person in the future?", we asked "what can synchronization and sonification do in the next few months?" Answering the latter question constrained options, but also lead to a novel solution that was available and practical. It also lead to a novel method of synchronizing motion and forming rhythmic, sonic feedback.

We felt that this situation was a good opportunity to demonstrate and refine our sonic feedback techniques. We developed a system that could capture and analyze the necessary repetitive data to test our algorithms. We exploited our synchronization information to provide sonic feedback eliciting certain movements from the the subject and correcting other undesired movements.

The athlete used our system to help correct his movements and we consistently refer back to this case study throughout the thesis to demonstrate the implementation and potential of our sonic feedback system.

1.2 Goals

1.2.1 Long Term Goals

The long term goals of our research are to analyze human movement and convert those movements into sound or sonic feedback in real-time. The feedback should allow a subject to hear and react to sounds, then adjust and improve his or her movements as they are occurring. Specifically, we are interested in repetitive movements, which we feel algorithms for synchronizations are well suited to exploit. Examples of repetitive movements include walking, running and skating. During such activities a person's body performs the same movements over and over. Improving athletic performance is an obvious application of such research, as are therapeutic applications involving subjects who may be improving or regaining proper movements.

1.2.2 Thesis Goals

For the purpose of this thesis we have developed a method to synchronize the relative pose measurements of a person performing a repetitive movement with a model signal and broadcast synchronized sonic feedback to improve or elicit certain behaviour relating to the movement. We have a general interest in the sport of speed skating relating to our involvement and knowledge of the sport and our proximity to a high performance speed skating training centre. Many of our decisions are based on what is appropriate for this speed skating application. We applied our synchronization and sonic feedback methods to the special case of an athlete who had developed a particular anomaly in his sporting movement. Our goal was to provide a system to capture and analyze his movements then produce sonic feedback designed to help him to correct those same movements. As we use a case study with a single subject, we had no controls for validity. Nevertheless, the opportunity to test sonic feedback for correcting and improving an athletic movement provides a valuable lesson, and suggests future direction for studies where controls are possible.

The apparatus for this had to meet the following requirements.

1. Non-intrusive - Speed skating is a complex movement performed at high speeds. It is not safe to impede the movements of a speed skating athlete.

2. Affordable - The budget for this project did not allow thousands of dollars for commercial camera or motion capture options.

3. Consistent and reliable - A user must be able to trust any feedback they receive.

4. Intuitive - It must be simple for a user to understand and use the apparatus. We do not want to waste training sessions learning the system or having difficulty interpreting the sonic feedback.

5. Non-distracting - Unpleasant feedback could distract a user from their task and is likely not to be tolerated over the long term.

1.3 Overview

1.3.1 Relative Data

A measurement system that can consistently reproduce a measurement under identical conditions is said to be precise, while a sensor that produces a measurement that closely matches the true value is said to be accurate. A measurement that may not be accurate but is precise within a single session we call a relative measurement. Relative measurements preserve the shape of a signal but not the absolute value or scale. Our methods require only signal shape to be preserved and as such relative measurements are sufficient.

1.3.2 Synchronizing Relative Periodic Data

Two sets of measurements can be compared with a cross correlation. If we do this with relative measurements, we need to scale for the lack of accuracy and changes in measurement conditions. We can do this by normalizing the measurements and thus applying a normalized cross correlation, similar to the Pearson correlation coefficient[3], r, in statistics. With periodic signals we must also account for phase, a brute-force search allows us to find the best phase match.

1.3.3 Sonifying Synchronization Information

We provide sounds timed to the period of a repetitive motion. We use synchronization with model motion to know where a subject is in the motion, i.e. their phase. We use the phase to time the delivery of sound feedback.

1.4 Outline

In the remaining chapters we will first introduce prior research about the interaction of sound and people, different approaches to motion analysis and sonification methods. Next we introduce the sport of speed skating, and talk about the unique and valuable opportunity to work with our subject. We present a system that implements our synchronization and sonification strategies for this speed skating application. Next we provide details of how we tested the system within our speed skating case study. Finally we present some observations, conclusions and discussion including future directions for the sonic feedback we present.

Chapter 2

Background

The multidisciplinary nature of this research means we are building upon work from a number of areas. Although there are few examples of research directly relating to our project, we have drawn on prior work from otherwise independent research areas to help mold our own research.

2.1 Sound, Movement and Rhythm

This thesis is not an investigation in neuroscience or the workings of the brain and body but it is important to note that those topics are related. We are investigating the use of sound in acquiring, correcting and refining motor skill movements. Some of the work we are building upon comes from the field of neuroscience. Our senses are related and intertwined, we use multiple senses to accomplish many of our tasks. Distorting any of the senses relative to another can produce dramatic results [4]. As an example, consider sitting in a stationary train looking out the window at another train that is moving on an adjacent track. Our body will produce the inertial sensation that we are moving because of the visual cues we are receiving and have related with our own body's movement. *"Perception is a function not so much of the intensity of a stimulus as of the agreement between the stimulus and an assumption the brain makes"* [5].

It is logical to note that our visual senses and our movement senses are closely related, and so the train example may not be too surprising. Linking sound and movement is a little less intuitive, but that does not mean our hearing senses are any less powerful. We need only think of the link Pavlov produced between salivating and the sound of a bell to see that sound has a strong link to our other senses [6]. In fact, the motor regions of our brains are closely linked with musical rhythms. In a study by Chen et. al. [7], subjects instructed that they would first be listening to music and then later tapping along with the rhythm of the music, displayed activity in the motor regions of the brain before the tapping actually occurred. This brain activity is expected as the tapping was anticipated, however a second set of subjects showed similar brain activity in their brain's motor regions while listening to the same music without knowing they would later be asked to tap along to the rhythm . This human tendency to keep time and make motor responses to rhythm is referred to as entrainment. Humans are precise at keeping rhythm and anticipating beats. We are able to remember hundreds of melodies, detect wrong notes and have typically internalized the rules about appropriate or typical chord progressions by the age of five [8]. Galileo's discovery that objects free fall with the same acceleration has been linked to his ability to keep time to music [9]. Singing a song as he charted the acceleration of balls on an incline, Galileo was able to accurately measure accelerations in a period when accurate time measuring devices were unavailable. Comparing the distance travelled of the ball and the note he was at in the song allowed Galileo to accurately form his theory of free falling objects.

In a study involving violin players, Drake et al.[10], show that learning to sing a song facilitates learning to play that song on a violin. The reverse scenario however does not seem to hold, that playing a song on a violin facilitates learning to sing the song. While violin play is a complex motor skill, Sacks [11] points out that sound and movement are excellent for coordinating basic locomotor movement. A familiar example is the case of military personel marching in step, marching songs and the sound of their boots facilitate their synchronization. Sacks [11], provides a number of examples of people using sound as therapy to regain basic motor skills. Among those examples, he introduces an elderly woman who reclaimed leg movements while listening to irish dance tunes, a man who used drumming to mute the jerky movements associated with his Tourette's syndrome and an injured man using violin concert music to learn how to walk again.

Even infants display the ability to associate movement with the rhythm of music. Infants bounced at a certain beat pattern show a preference for songs with that same beat pattern [12]. In a study by Chen et al.[13], subjects instructed to tap along with a musical beat, found themselves tapping asynchronously with complex musical beats. As such we are cautioned that as music complexity increases our ability to synchronize to those complex sounds becomes strained.

2.2 Computers, Sound and Sports

Computers are increasingly used to analyze a number of data sources. Human movement is one of the sources of data that is interesting to a number of applications. Capturing the data related to human movement is a challenge in itself. Cameras and sensors operating in lab and real-world settings are not trivial to set up and use effectively especially when planning to work with real athletes in a sporting setting. Chi [14] identifies a number of issues related to getting technology accepted in a sporting community in his article about a force plate sensor system to be used in taekwondo. He cautions that a primary focus when developing technology for use in sports has to be how it affects the athletes, judges and spectators. Ignoring or placing little emphasis on those effects will severely hamper one's acceptance with those involved in the sport. As such our goal is always to produce technology and results that have impact, both within the scientific and sporting communities.

Increased portability, power and decreased size of computers makes them less intrusive and more appropriate for use in real-world sporting settings such as human motion capture and analysis.

2.2.1 Human Motion Acquisition and Analysis

Many human motion acquisition systems are bulky, intrusive and designed explicitly for lab use, and as such are not particularly useful for our application. We will however present a brief overview of a number of acquisition methods as there is no one tracking method that is considered the best for all situations [15].

Vision-based solutions [16],[17] are a nice starting point as they involve tracking motion using video cameras. The advantages of vision-based methods include portability, cost effectiveness and unobtrusive data collection. Those apply nicely to our particular problem. A strictly video based approach, [18], with no markers that uses regular video cameras is very enticing as it allows us to operate without affecting the performance of an athlete. However, the requirement to operate in the vast size of a skating arena, as well as the speed of the athletes' movements and distance covered push the limits of video-based approaches.

Optical approaches [19], [20], [21], typically using reflective markers and multiple cameras have increased accuracy over typical video-based tracking approaches. Triangulation allows for extremely accurate results with high refresh rates. In a lab setting and other small areas an optical approach is appropriate, as line of sight issues can be overcome by adding more cameras or limiting subject movement. In an environment such as a speed skating oval, the number of cameras required to capture the movements of an athlete easily exceeds 100 cameras, consequently monetary and labour costs are extremely high. Each camera must be calibrated, meaning set-up, calibration and take down would require hours of work before any recording could be completed. Limiting costs and labour by recording only a portion of the speed skating oval is also not applicable for repetitive movement analysis where multiple consecutive cycles of the movement must be viewed. In short, the high cost, set-up times and restrictive field of view make this type of solution impractical for our particular project. Inverting the idea of how typical video-based apparatus operates, attaching cameras to the subject as opposed to strategically placing them within the environment [22] is an interesting idea. For our particular project, head mounted cameras, or cameras mounted strategically on the body, eliminate the problem relating to capturing video throughout the large skating arena. With this set-up other problems relating to athlete movement, line of sight obstruction, accuracy and image stabilization remain

Figure 2.1: The Gypsy 7 Mechanical motion capture system. The intrusive nature of this suit and cost make it non-applicable to our project. Photo from: http://www.metamotion.com

an issue.

Mechanical systems [23] are sensor systems worn by the subject. They use electric resistance to measure data such as joint angles. The subject wears an exoskeleton with sensors aligned at key body joints to facilitate the motion capture. The bulky nature and cost of an entire exoskeletal suit makes it impractical for our application. The speed skating motion is complex and the speeds achieved are high, this combined with the low friction of the ice surface and sharp speed skating blades mean crashes during speed skating are dangerous. Wearing an obtrusive and bulky full body suit as shown in Figure 2.1 is simply not safe for speed skating athletes. Reducing the scope of a suit like this from total body capture to capture of a single limb or joint is possible and make it more practical for our project.

Inertial capture [24], makes use of gyroscopes and accelerometers to measure body movement. Inertial sensors are placed at key locations on the body, allowing total body movement to be captured. The major problem associated with inertial sensing is drift. Even the best sensors have drift and after only a few moments an inertial device has typically drifted by a few meters

[15]. Canceling this drift is a major concern and solutions have been developed for certain movements, such as in running [25], as evident in the commercially available Nike Plus running tracking system [26]. Combining inertial sensing with other tracking systems is another way of alleviating the drift, such as combining inertial sensing with acoustical tracking [27].

The commercial video game market has experimented with motion capture devices to be used as input to video games. Real-world player movements are captured, analyzed and used to control video games. These games often attempt to simulate the experience of playing sports. The Nintendo wii-mote [28] is an example of device that uses inertial sensors in a hand-held controller to capture movements. An inertial device designed for a general audience and for use with multiple games means eliminating drift is particularly difficult. After a few minutes of playing a game with the Nintendo wii-mote the inaccuracies associated with inertial drift quickly become evident. Nintendo released an accessory for the wii-mote to help address this, the Wii MotionPlus [29]. This accessory adds gyroscopes to the accelerometer to help increase the accuracy of the device. The Sony Playstation Eye Toy [30] is another example of a motion capture device for use with video games. It is designed to capture video of the game player and use that to control the video game. The limits and inaccuracies associated with video motion capture make complex game play with this device difficult. Sony released an update to this device called the Playstation Move [31], adding light-emitting bulbs attached to a controller to be used in conjunction with the camera to increase the accuracy of the video-based motion tracking. Microsoft also recently released the Microsoft Kinect [32] for its Xbox platform. The Kinect contains a camera combined with a depth sensor, to do its tracking. Regardless of the game-play, these devices have helped decrease the price of this type of technology and help push technological development in this area.

In an interesting study [33], mechanical sensors were used to capture snow boarding data and analyze it in real-time. Corrections such as bending the knees or adjusting the centre of mass were communicated to the athletes using haptic feedback. The system operated both in a lab setting, and on the ski slopes. The study successfully captured and analyzed certain snowboarding movements. Haptic feedback was found to be effective at conveying the required adjustments the athlete should make to improve their snow boarding form. We concern ourselves with repetitive movements and we feel that rhythmic sounds and our abilities to synchronize to those sounds makes sound an enticing feedback form for our research. Still we are intrigued by the success of the haptic feedback employed in this study and will track further investigations into using haptic feedback with repetitive movements.

Chi [34] instructs us to avoid over-kill with motion capture. Understanding what you need and which are the most appropriate capture techniques and tools is paramount to success.

2.2.2 Sonification

Sonification refers to the process of converting data into sound. Typically sonification is designed to improve data comprehension. In its simplest case, a musician reading music notes on paper and playing those notes on an instrument is a form of sonification. In the example of the musician, we understand that sonifying the music notes allows us to process the information in a much different and in this case, a richer way, than simply reading them on the page. It should be noted that sound does not always take a musical form and there is no requirment for sonification to take a musical form.

There are three typical methods of sonifying information [35]:

- Earcons
- Auditory Icons
- Parameter Mapping

Earcons refer to short musical motifs. They are simple and designed to be pleasant to listen to but not necessarily intuitive; their meaning must be learned. Earcons are commonly employed in user interfaces [36]. The start-up sounds signifying your computer has booted, the *you've* *got mail* alert on your phone, or the *fasten your seat-beat* reminder in your car are all examples of earcons.

Auditory icons are intuitive sounds that take advantage of what we already know or associate with. Using a coughing noise to represent smog data [37] is an example of an auditory icon. Auditory icons are often coupled with earcons in user interfaces. As an example, when deleting files on your computer, operating systems often use a *trash can* sound relating to previous experiences with recycling and trash collection thus conveying the message that files have been removed from your system.

Finally, **parameter mapping** refers to the idea of matching information from the data directly to sound characteristics. Characteristics such as, pitch, intensity or timbre are commonly used in parameter mapping. Figure 2.2 outlines a parameter mapping example. A major issue with parameter mapping is that the sounds produced can be unpleasant to the ear and thus difficult for a user to listen to for any duration [35]. Data is not typically organized into patterns that can be trivially matched to sound characteristics to produce a pleasant sound. Creating an aesthetically pleasing sound from scratch is in itself not a trivial task, and mapping existing data into sounds, such that it creates a pleasant easy to listen to sound is even more complex. Visualizing, exploring and mining large data sets is often a difficult task, parameter mapping is an effective way of presenting large data sets [38]. Seismic data [39] lends itself nicely to sonification, as the wave-like structure of the data already shares characteristics with sound data.

A simple example showing an effective use of sonification by parameter mapping is used to beat the odds in a casino game [40],[41]. Thorp and Shannon created an algorithm to predict which section of a roulette wheel a ball was likely to land in. The algorithm factored in the ball's speed, starting location and the particular wheel it was rolling on. Sound being a discreet form of communication, with discretion being a major concern when one is *beating the odds* in a casino, they trained themselves to identify eight musical notes. They divided the roulette

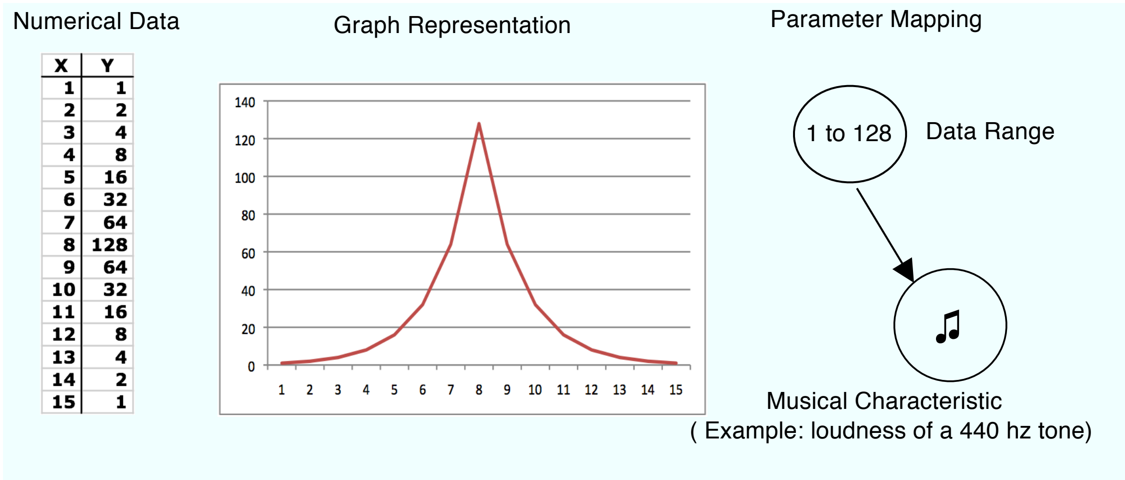

Figure 2.2: Sonification by Parameter Mapping. The numerical data is displayed in tabular and graphical form. A mapping of Y values to the loudness of a 440 hz tone (‘A’ Note) provides an example of sonification of the data by parameter mapping. In such an example, as the data value X progresses from 1 to 15 an ‘A’ Note could ramp from 1 decibel to 128 decibels and back down, conveying information about the data in a different way. The smooth shape of the data lends itself nicely to parameter mapping.

wheel up into eight sections, each corresponding to a musical note, this being the parameter mapping. Programmed into a wearable computer, their algorithm produced sounds that communicated the predicted finishing position of the ball on the roulette wheel. The success of this sonification has forced casinos to change their approach to roulette.

Interactive sonification is defined by Thomas Hermann [42] *“as the use of sound within a tightly closed human-computer interface where the auditory signal provides information about data under analysis, or about the interaction itself, which is useful for refining the activity.”* Our interests lie in this area of interactive sonification and specifically applying it within the sporting environment. In sports, there is already interactivity between sounds produced in the field of play and athletes.

Sound plays a natural role in sports, often providing complementary information to an athlete. An example is a runner hearing the foot steps of a competitor approaching from behind. Typically these sounds occur naturally, like the sound of a skate blade gliding on the ice or the impact of a golf club on a golf ball, but they do provide information that can influence an athlete [43]. In speed skating, we have informally observed that the sound of an athlete's skate blade on the ice is used by some athletes to determine information pertaining to ice conditions and skate blade performance. As the athlete presses their skate blade into the ice the sound produced is used to determine certain characteristics like ice hardness or the sharpness of their blade. Our sonification system requires that headphones be worn and as such, natural sounds like those produced from a skate blade on the ice, may be more difficult to hear or interpret.

Technological advances in sensors, cameras and computers allow for sonification of all sorts of sporting movements. Running pace [44][45], rowing boat acceleration [46], jumping height [47], golf swings [48], karate movements [49] and walking gait [50],[51] have all been successfully analyzed and used to create or control a sound that is broadcast to the athlete.

In the running paces examples above [44], [45] we observe a repetitive movement similar to skating. In these two examples we have the pace or stride rate of the runner, along with other factors such as heart rate, being used to select a song featuring a complimentary number of drum beats per minute. These studies are interesting because of the repetitive nature of running and the insight into how a stride rate corresponds to the drum beat in a song. We do not classify these examples as true sonification as the sound is not generated from the data. More accurately these two cases can be classified as interactive song selection.

Because in general, data does not share obvious characteristics with sound data, parameter mapping often leads to sounds that are difficult to listen to over a period of time. Creating aesthetically pleasing sounds is not trivial. Aside from the rowing boat and gait examples, each of the other examples are short duration movements. A golf swing [48], a karate kick [49] or a jump [47] are all one-off movements where important things, such as max acceleration or power, can be matched nicely to sound intensity, or pitch. Parameter matching makes sense for producing a useful feedback in those cases because of the natural association between power and intensity of a sound, the short duration of the movement, and respectably the sound, means the aesthetics of the sound are less important. A displeasing sound heard over a length of time will not be tolerated by users.

In another example, Shaffert et al.[46] sonify the acceleration of a row boat. Boat acceleration follows a repetitive pattern corresponding to the repetitive rowing strokes used to propel the boat. This is a case study and so it is difficult to draw conclusions, however, the athletes did comment about wanting the ability to turn the sound off and on and 50% of the athletes mentioned that the sound was distracting.

Literature is full of examples of sonification with parameter mapping [52]. It is trivial to map data to sound and most mappings are arbitrary and without practical benefit. By focusing on a real, existing problem, we overcome this and arrive and an effective sonification.

Sadikali [50],[51] investigates a problem that is very similar to our own. He looks at the repetitive movement of walking or gait and proposes that gait sonification can be used to ameliorate a problematic gait. He uses Boyd's [53] method to synchronize an array of oscillators to periodically varying pixel intensities using phase-locked loops. This provides a phase image showing the relative timing of the motion of body parts as they pass pixels in the image. He explores a number of different strategies to parameter map this data to sounds. He found that mapping to drum beats or MIDI notes produced the most aesthetically pleasing sounds, while more complex mapping strategies producing continuous sounds were not. Our research builds upon this gait sonification work, building specifically in the area of effective communication with sound and using their experience with continuous sounds to help shape our choices.

On the whole sonification is an active area of research with many open questions. How to sonify data and which data are well suited for sonification is open for debate. Areas where visual displays are not practical or effective for communicating information are considered prime candidates for exploration with sonification. In many sports, athletes are already taxing their visual processing abilities and so research into sonification of sporting movements is an attractive area.

2.2.3 Sonification Tools

There are a number of options emerging for sonifying data. Some options come in the form of a computer programming language or environment. Examples include:

- Pure Data [54],
- Max/MSP [55],
- Supercollider [56],
- Chuck [57],
- SoniPy [58].

Naturally, there is an upfront learning curve associated with using a computer programming language. However, the ability to integrate a programming language into other projects is beneficial, especially for real-time data. The freedom associated with program development allows for a wide range of complex sounds to be created.

Some computer applications are developed to ease the technical requirements for creating a sonification [59], [60]. These applications are often designed to facilitate typical sonification tasks. For instance, a typical task could be to create a parameter mapping from a common sound characteristic like pitch to a list of numerical data. In this case using Sonification Sandbox [60], which is designed for that purpose, is a good choice.

For our purposes we use the Pure Data [54] programming environment. It gives us the ability to integrate with our real-time motion capture technology as well as the freedom to use custom algorithms in our sonification. The Pure Data programming environment is not strictly a language but rather a graphical programming environment. Programmers control program flow by dragging, dropping and connecting objects to create a visual interpretation of their code called a patch. Figure 2.3 shows a screen shot of one of our Pure Data patches.

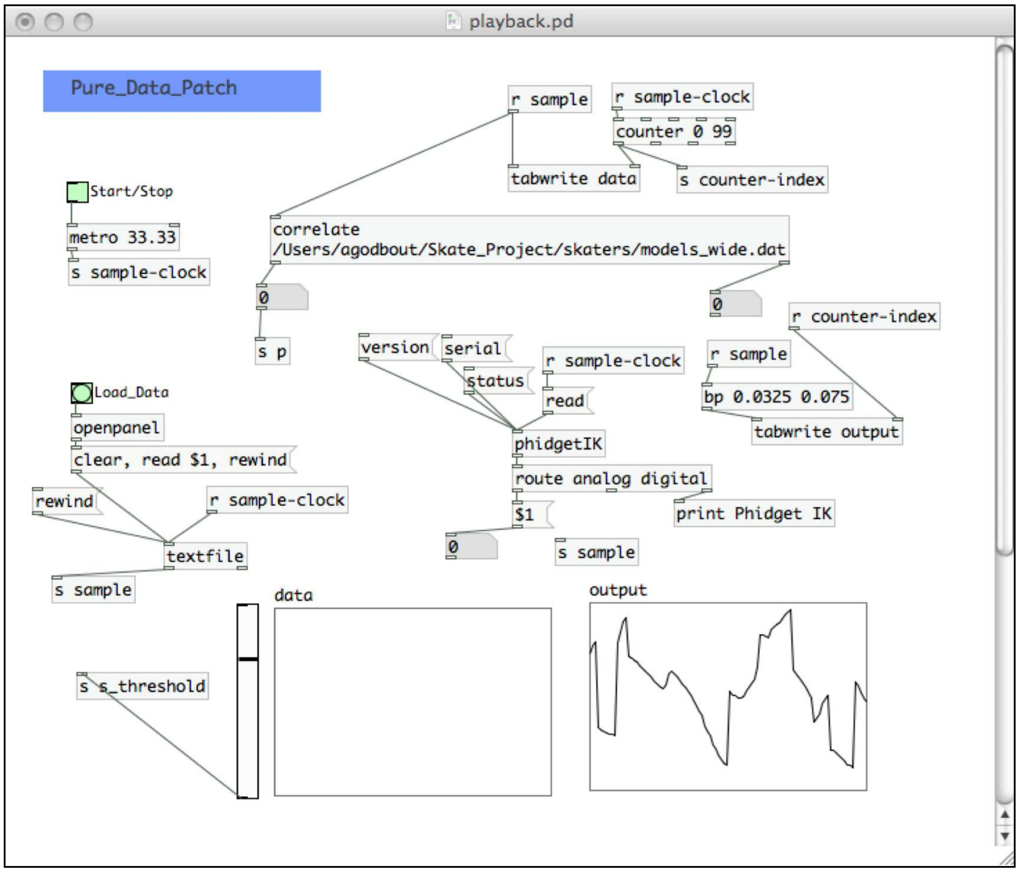

Figure 2.3: Example of a Pure Data patch. We chose Pure Data because it is a graphical programming environment that facilitates sound generation. Boxes represent algorithms and data processing while links between boxes control program flow.

Chapter 3

Speed Skating Case Study

Some knowledge of the sport of speed skating is required to fully understand this project. We worked with an athlete who had a specific problem that needed to be solved. His particular skating problem and how it relates to the speed skating motion are important in understanding our methods and results.

3.1 Speed Skating

Speed skating takes place on a 400 meter oval ice surface, divided into two 100 meter straight-aways and two 100 meter corners with approximate radius 25 meters. Figure 3.1 shows a speed skating oval. Speed skating athletes are able to achieve speeds in excess of 50 km/hr as they

Figure 3.1: The Calgary Olympic Oval at the University Of Calgary. The Calgary Olympic oval is an indoor facility housing a 400 meter speed skating track made up of two 100 meter corners and two 100 meter straight-aways. Skaters can reach speeds in excess of 50 km/hr.

skate counterclockwise around the oval. Typically a coach is stationary while evaluating and critiquing their student. The speed of the athletes and size of the skating arena make it difficult for coaches to evaluate athlete movements and provide appropriate feedback.

The small amount of friction between a skate blade and the ice allow a skater to achieve fast speeds, but also make reducing air resistance a priority. For this reason the skaters bend into an unnatural crouched skating position [61]. Body position, joint alignment and direction of push are all important factors relating to generating speed. The unnatural skating position requires that the athletes spend a great deal of time learning, perfecting and becoming comfortable with these movements. Tennekes [62] compares the speed skating stride to a bird flapping its wings. Flapping is natural, for a bird, but for a human, skating is unnatural and must be trained.

There are two distinct movement sequences in speed skating. Straight-away strides performed by a speed skater to navigate the 100 metre straight-away and cross-over strides, which a speed skater performs to navigate the 100 meter long, 25 meter radius corners (Figure 3.2). At a moderate pace, it takes approximately 35 seconds to complete one lap of the speed skating oval. Skaters spend roughly equal amounts of time in the corners as in the straight-aways. The subject of our case study had a problem that occurred only in the corners. As such we only focus on the cross-over strides and so we go into detail of what is entailed in that movement only.

Figure 3.3 shows the angle of the right ankle during a cross-over. The cross-over stride can be categorized into three components that make up the right foot portion of the stride (the left foot portion mirrors the right):

1. **Right Foot Pushing:** the skate is in contact with the ice as the skater pushes (Figure 3.3 - A and Figure 3.2 - frames 1 and 2),

2. **Right Foot in Air:** the skater lifts the right skate off the ice and moves it across the left skate (Figure 3.3 - B and Figure 3.2 - frames 3 and 4), and

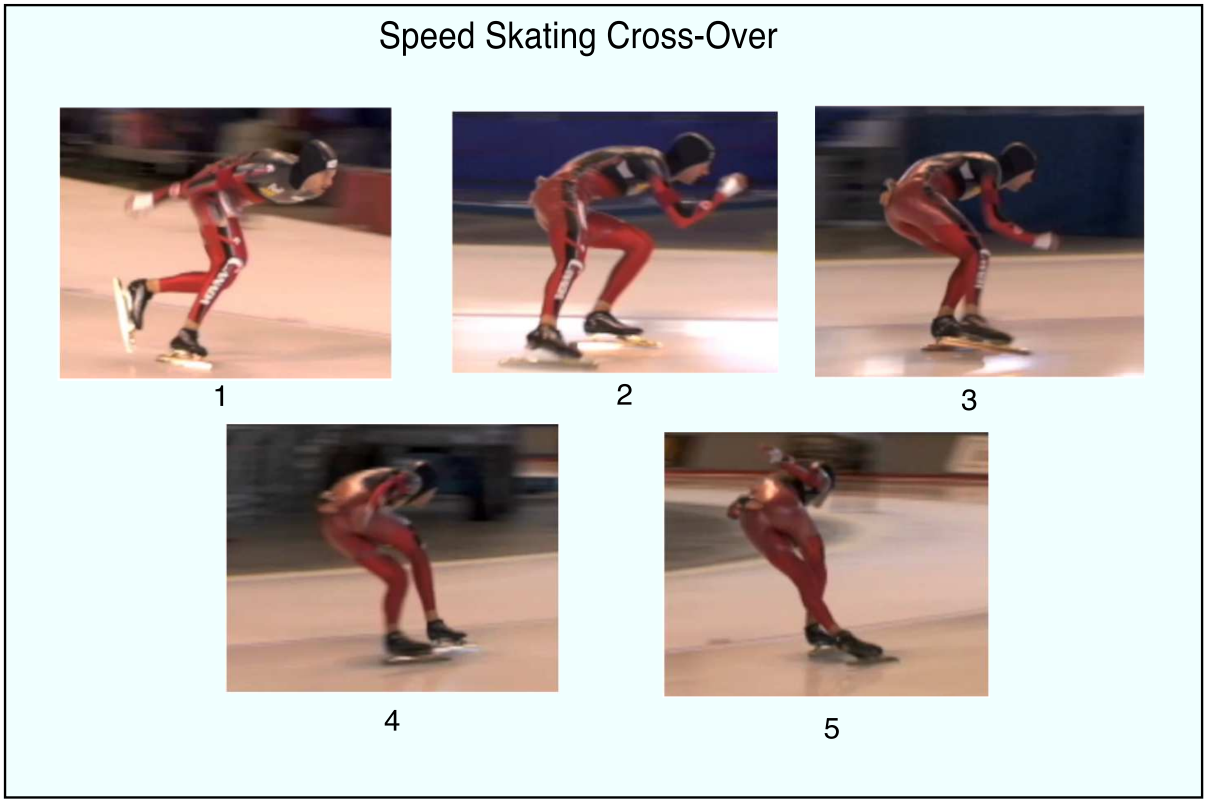

Figure 3.2: Photos from a video sequence of a cross-over. Descriptions from the right foot perspective: 1) The right foot is pushing. 2) The subject exhibits plantar flexion at the end of the push 3) The right foot is in the air, crossing over the left foot. 4) The right foot returns to the ice. 5) Right foot preparing to push again. This graph was generated from data collect by our sensor system.

3. **Right Foot Prepares to Push:** the skate blade contacts the ice (the set-down) as the skater prepares to push again (Figure 3.3 - C and Figure 3.2 - frame 5).

Skaters perform between 6 and 10 cross-overs to complete a corner. Ankle angle is important in speed skating as it is a good indicator of the amount of pressure being applied into the ice during the pushing segment of the stride. Maintaining a small ankle angle during certain portions of the speed skating stride is paramount for maintaining skating speed as one fatigues [63]. For the purposes of our case study it is particularly interesting to examine the ankle angle of the right foot.

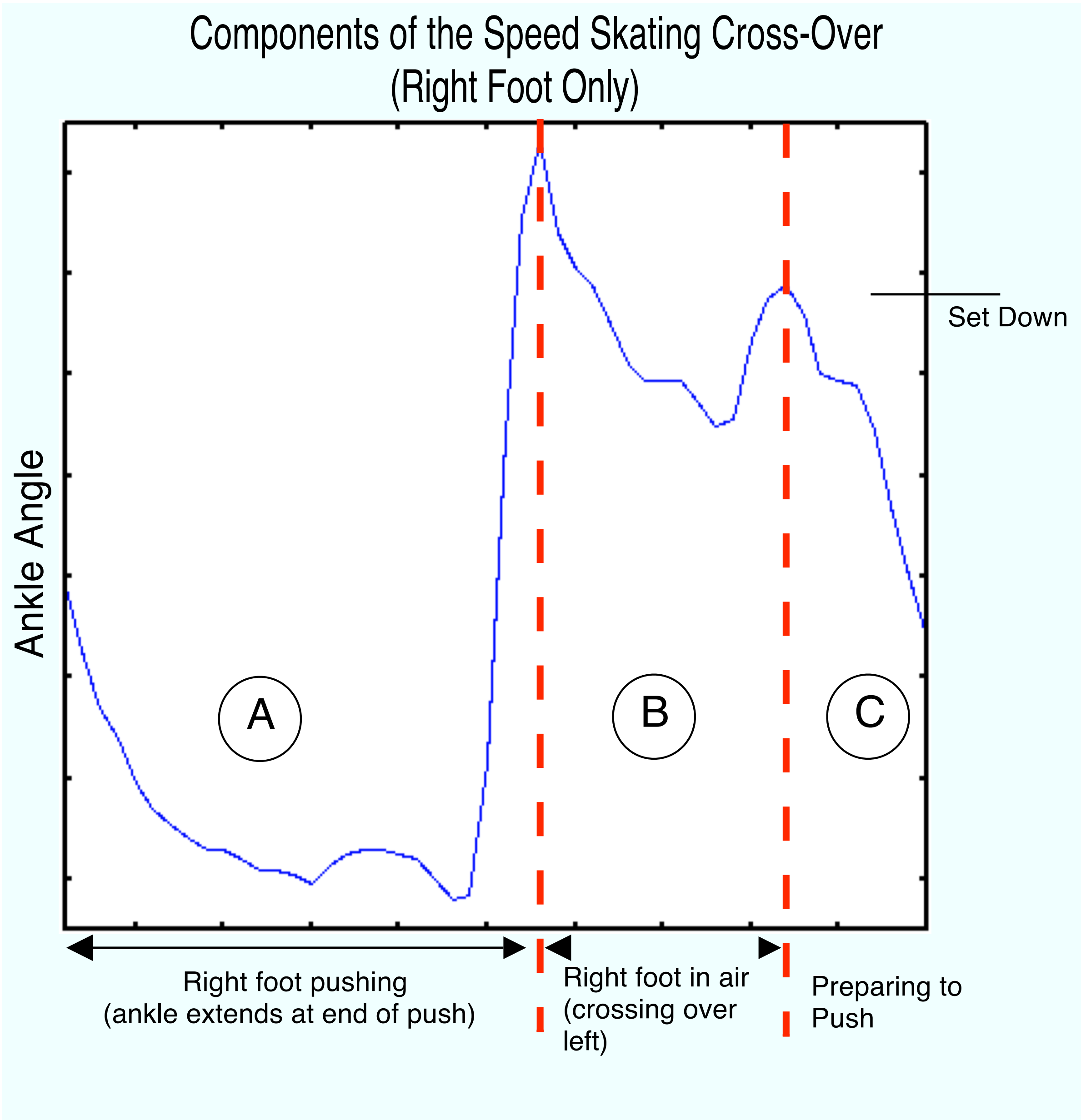

Figure 3.3: The Speed Skating Cross-over - Ankle Angle versus Time. The Cross-over is divided up into 3 components for the right foot. A) The right foot is pushing. The ankle is compressed with the knee over the toe for the first portion of this phase (small ankle angle). During the end of this phase ankle angle increases as the calf finishes the push. B) The right foot is in the air crossing over the left. The ankle retreats from its fully extended position. During the second portion of this phase the ankle comes back to neutral or level so that the skate can set down flat on the ice. C) The right skate is back on the ice, the knee moves back over the toe and ankle angle reduces in anticipation of the next push phase. The set-down, when the right skate comes back into contact with the ice is labeled.

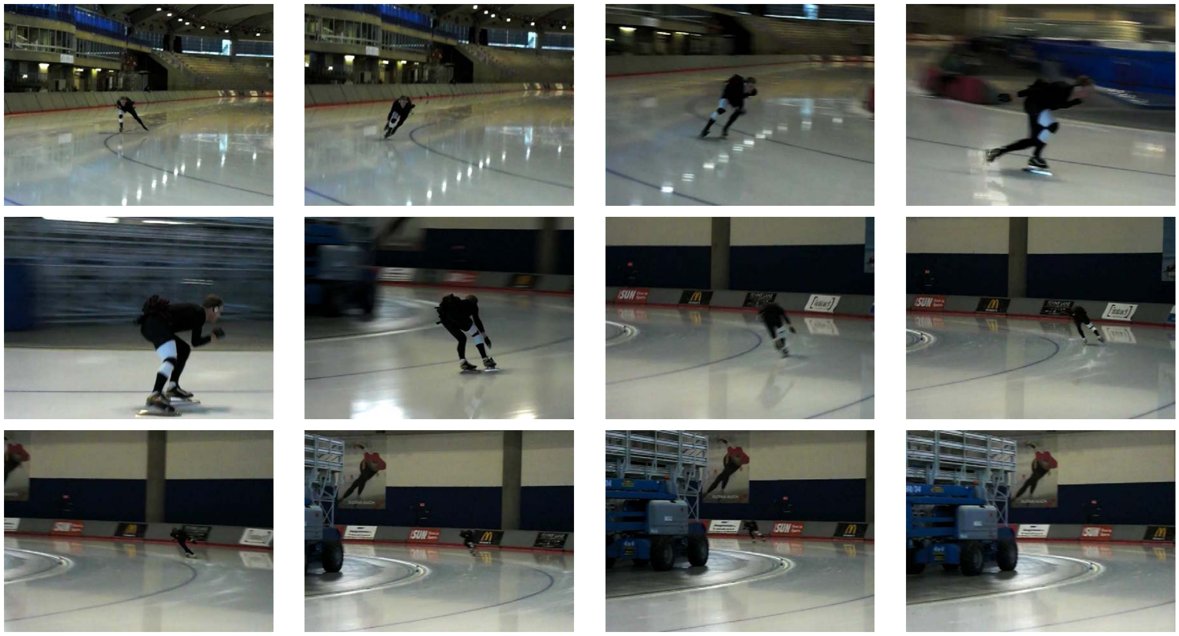

Figure 3.4: The window for coaching feedback. This sequence shows a subject skater over an interval of $8s$ during which time he travels approximately $80m$. At $10m/s$ ($36km/h$) it is difficult for a coach to see more than one or two single strides and give meaningful verbal feedback.

3.1.1 Speed Skating Coaching

A speed skating coach is stationary and therefore is only able to provide limited real-time feedback to a moving athlete. In addition, the speed skating motion is complex and a stationary coach is seldom at an optimal viewing angle. Figure 3.4 illustrates the problems associated with traditional coaching. Add in the complexities of translating the words of the coach into movements, and it becomes apparent how immediate and continuous sonic feedback could benefit athletes. Sound is a viable communication medium for an athlete that is taxing their visual, tactile and balancing senses. We feel that continuous sound feedback compliments the other forms of feedback an athlete uses and could facilitate learning or improving a motor skill.

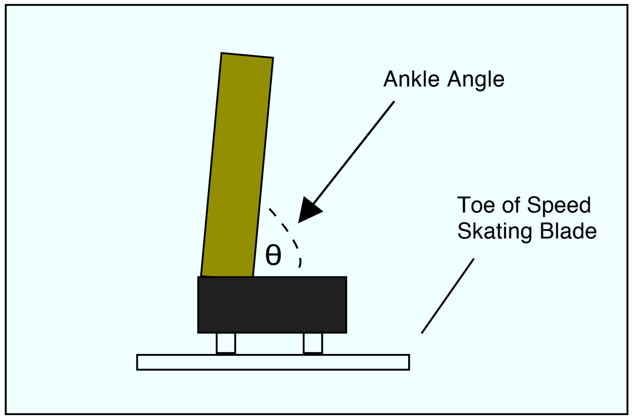

Figure 3.5: Speed Skating Terminology. The angle formed by the leg and foot is labelled as θ. We refer to the front of the speed skating blade as the toe of the blade, or simply in some instances as *toe*. We often describe θ by using the orientation of the toe of the blade. As an example an athlete displaying a large angle θ can be described as *'The athlete pointed his toe down'*.

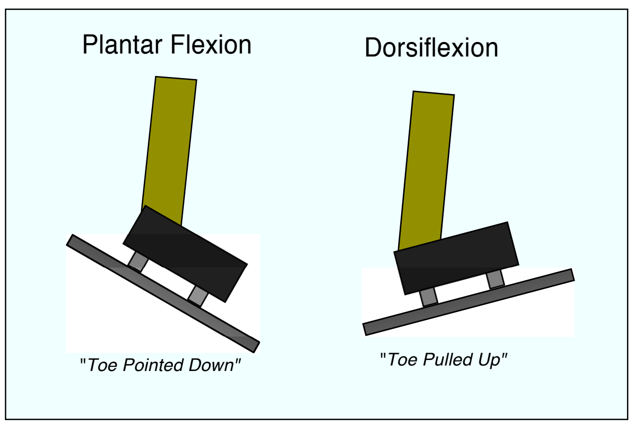

Figure 3.6: Plantar Flexion Versus Dorsiflexion. Plantar flexing refers to pointing the toes down, while dorsiflexing is pulling the toes up.

3.2 Terminology

It is important to be familiar with the terminology we use to describe skate blade and ankle orientation in this thesis. Figures 3.5 and 3.6 outline some common terms we use, included are dorsiflexion (pulling the toe up) and plantar flexion (pointing the toe down). The term *toe* or *toe of the blade* is used to refer to the front tip of the speed skating blade. We often describe ankle orientation using only the toe of the blade in the description.

We mention set-down and point of set-down frequently in this thesis. Point of set-down refers to the instant in time when the athlete returns his skate blade to the ice.

3.3 Skating Subject

We introduce a skater who developed an abnormal skating motion relating to the amount of plantar flexion he exhibited during key portions of the speed skating cross-over. Previously a nationally ranked skater, he lost his ability to perform a proper cross-over, which had an adverse affect on his results. This skater made the same error during the same part of his stride during every cross-over. Although rare, an athlete no longer being able to perform a previously known movement is referred to as ‘Lost Move Syndrome’ [64]. Building our research around this athlete’s problem provided a unique opportunity to develop sonification of motion as a solution addressing a problem rather than a solution in search of a problem.

The specific problem with our subject’s cross-over movement occurs during Component B of the cross-over, this is when his right skate is in the air. Prior to setting his right foot back onto the ice, our subject extends his ankle (plantar flexing) thus pointing the toe of his skate blade towards the ice. At the point of set-down his skate digs into the ice with detrimental consequences, namely instability, loss of speed, and risk of crashing. Figure 3.7 illustrates the problem with images from consecutive video frames of our subject. The hinged clap skate used in speed skating allows the heel of the blade to detach from the boot. It is designed to allow a skater to generate more speed when pushing. In this scenario it may prevent some crashes for our subject as it absorbs some of the impact generated when he digs his skate blade into the ice. This is not the designed purpose of the clap skate. The open position of the clap skate is not a stable position. Ideally a skater will set his blade back onto the ice in a neutral or flat position, the blade touching evenly back onto the ice.

Figure 3.7: Consecutive frames in video of the subject during component B of a cross-over. Notice the ankle is plantar flexed thus pointing the blade towards the ice before set-down. The clap skate opens at the point of set-down creating instability and loss of speed. The blade is highlighted with green.

Our subject displayed this skating problem for a period of 14 months and tried numerous traditional training techniques to correct it. On ice coaching, video analysis, equipment modifications, and sport psychology were all employed with limited or no success at correcting his problem. The subject described that he is unaware of the orientation of his ankle during his skating and is always surprised when his skate blade digs into the ice. He feels he is dorsiflexing his ankle. A speed skating cross-over happens quickly, and it is not possible for a coach to view, analyze and provide feedback to the subject during his movement.

Analysis of this type can be done using a computer and we felt this subject was a strong case study to demonstrate the effectiveness of computer analysis with sound feedback for teaching motor skills.

Chapter 4

Synchronization and Sonification

In this chapter we present our methods for synchonization and sonic feedback. Phase is a key aspect of our synchronization and sonification methods. The phase of a periodic waveform is simply the fraction of a wave cycle that has elapsed. Even though we are dealing with continuous repetitive movements and we capture certain joint or limb movement forming a periodic waveform, we assign a starting and ending point to the movement. We reference all phases to the start of the right foot push. The reference is arbitrary, so we choose to conform to our own description (Figure 3.3). Someone performing a repetitive movement will move through phases from zero to one repeatedly. We refer to this as phase ramping.

4.1 Apparatus

We built a device to capture the repetitive periodic movements of our speed skating subject's right ankle. As seen in our later examples we synchronize to the periodic data captured by this device. The problems associated with our subject's skating seem to be isolated to his erroneous ankle movements. While the subject displays general instability and erratic movements, all these problems seem related to his ankle issues. We want to capture the movements of the ankle to compare our subject with a model skater.

We develop a system using a variable resistance elastic (Figure 4.1). This allows us to continuously measure ankle angle. The athlete attaches the elastic between his or her toe and shin. A netbook computer worn by the skater in a waist pack captures the data. The sensor circuit is shown in Figure 4.2. The ability of the elastic to stretch and its light weight make it unobtrusive for the skater. Mounting the waist pack around the hips allows us to keep the

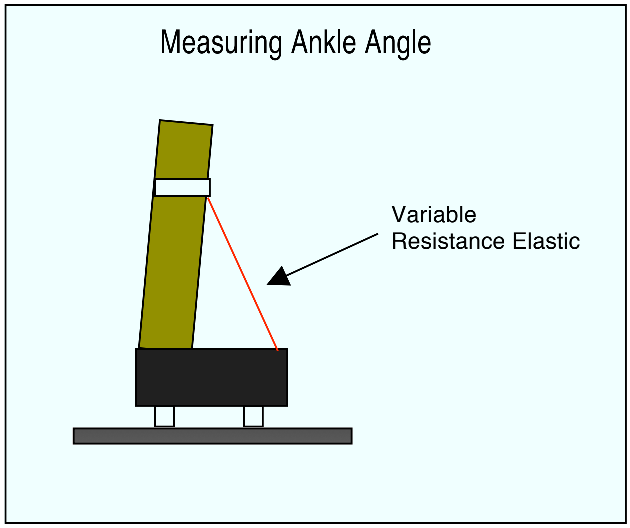

Figure 4.1: Measuring Ankle Angle. A variable resistance elastic is attached between the toe and a tensor bandage on the shin of the athlete. Ankle angle is measured by running a current through the elastic and examining the resistance.

heavier items near the center of mass of the skater. A skater wearing the system is shown in Figure 4.3. We analyze the data coming out of the system and produce sound feedback designed to improve the skating of our subject. The sound is broadcast via headphones worn by the subject.

We run a current through the elastic, and measure the voltage across it. Stretching the elastic changes its resistance and therefore the voltage we measure. This gives us a measure of ankle angle. Extending the ankle to point the toe down, stretches the elastic causing the voltage we measure to go up.

We do not calibrate the elastic as any calibration would not be repeatable. Temperature changes, material degradation over time and body placement all effect any absolute measurements we acquire. We look only at relative measurements coming from the elastic and the pattern being formed in that relative data. From the data we can determine that the ankle is in plantar flexion or dorsiflexion but not the exact angle of the joint. For speed skating, sampling the sensor at 30 Hertz captures enough information to determine what the ankle is doing at all

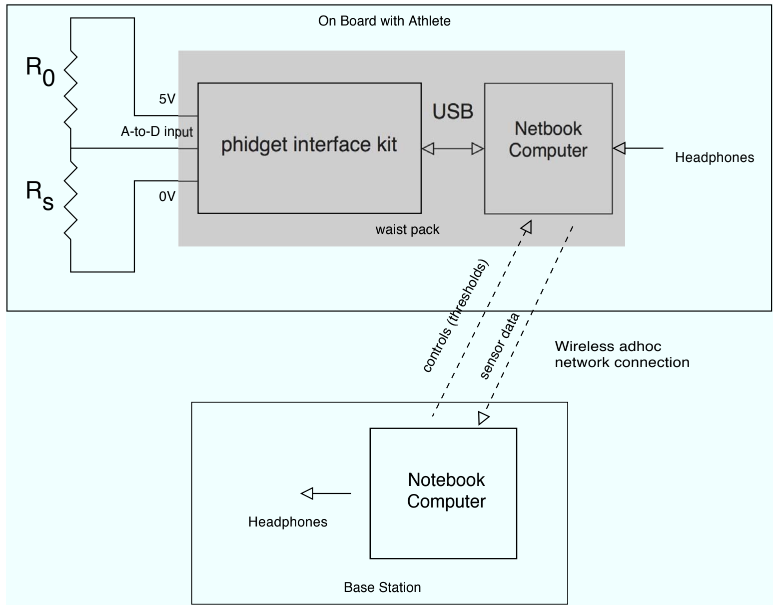

Figure 4.2: The sensor circuit: The sensor is a variable-resistance elastic (R_s) approximately 20mm in length . R_0 and R_s form a voltage divider. 5V supplied by the Phidget Interface Kit (http://www.phidgets.com) is applied across the voltage divider. An analog-to-digital converter in the Phidget Interface Kit measures the voltage across R_s, thereby measuring the stretch of the elastic. A netbook computer acquires the digital data from the interface kit, making it available for sonification. A wireless adhoc network allows for remote monitoring and control of the system on a separate computer at a base station.

times. A sample graph of the output from our system is shown in Figure 3.3.

This system is cost effective, the variable resistance elastic is priced under $5.00. A relatively inexpensive netbook computer and Phidget interface kit (http://www.phidgets.com) keep the total cost of the entire system at less that $500.00. Other motion capture options range into the thousands of dollars. In addition our system is practical for use with athletes. We require little calibration, no time-consuming body measurements and we operate in whatever environment the athlete is in.

We design our system such that we can monitor the output of the sensor at a base station communicating via ad hoc network. We have controls that allow us to adjust the system remotely changing things such as volume for the user. In addition we can remotely synchronize the signals and generate the same sound feedback the subject is hearing.

Figure 4.3: The sensor installed on the model skater: The variable-resistance elastic (a) is connected between a skate lace near the toe (b) and an elastic joint-support band (c) (used only to fasten the sensor). In this configuration, R_s (and therefore the voltage measured by the interface kit) increases with plantar flexion. Leads (d) connect the sensor to the phidget interface kit (http://www.phidgets.com) and netbook computer worn by the skater in a waist pack (e). Sound is broadcast using headphones (not shown).

Our system, through a process of synchronization of ankle measurements, is able to determine at all times, phase of the subject's skating stride. We accomplish this by synchronizing the data from one skater, the subject, with pre-recorded data from another skater, the model. Offline, we have analyzed the stride of the model and so as the subject's stride is synchronized with that model stride we can infer where we are in the subject's stride as well. Simply put, if we know what one person is doing, then we also know what someone else who is moving in unison is doing.

This synchronization allows us to not only track the progress of our subject through the skating stride but also allows us to identify erroneous movements and predict when problems are going to occur. Figure 4.4 shows both the data captured from the model skater and the data captured from our subject skater. The similarities in the global pattern of the graph are strong

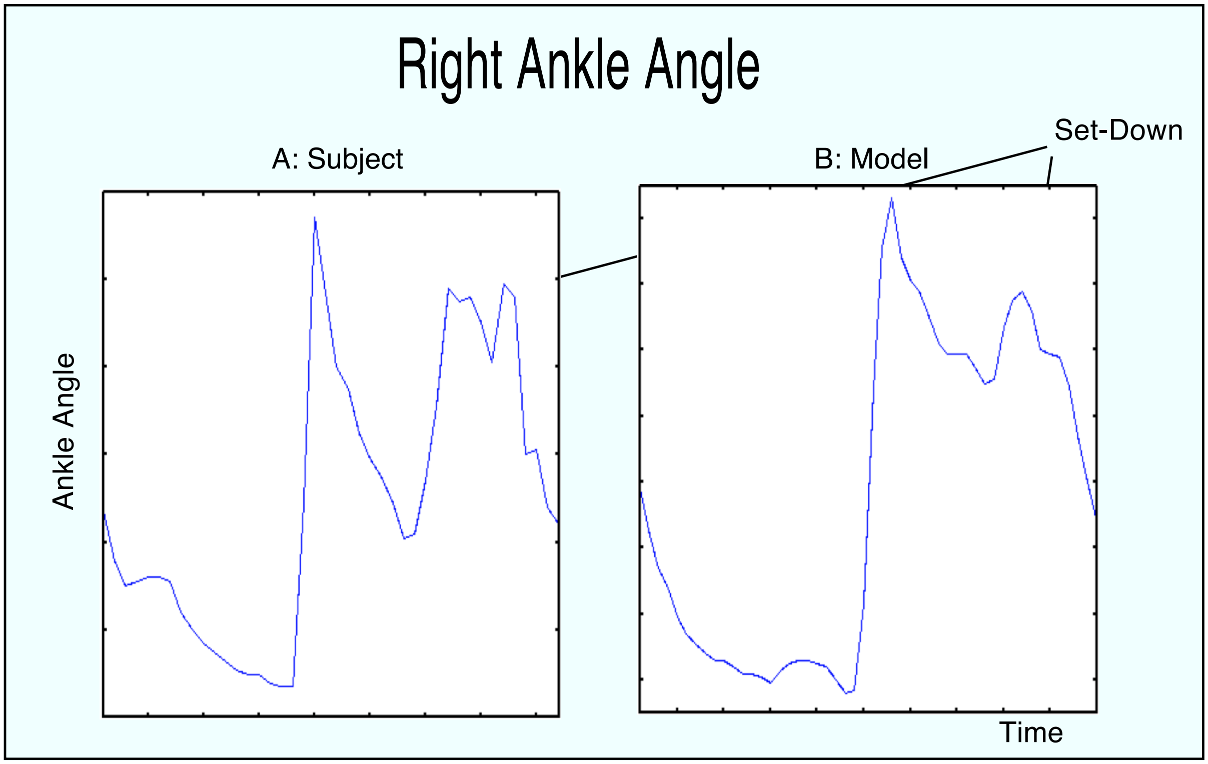

Figure 4.4: Side by side the data relating to ankle angle captured from A: Our Subject Skater and B: Our Model Skater. The shape of the graphs are close enough to synchronize the signals, yet the differences are noticable enough to predict problems. Note specifically the differences around the set-down point.

enough to synchronize and yet localized differences in the graph allow us to spot and predict problems.

4.2 Synchronization

The most important aspect of our method is the ability to *synchronize the movements of one person with those of another*. To do this we use a brute-force method to estimate the phase of a repetitive movement from a single sensor stream.

Let g be the signal of n samples containing a single cycle of data from a model movement (Figure 4.5). If f is an n-sample segment from on-line sensor data from subject data (we use the most recent n samples when synchronizing on-line in real-time), we can use a correlation

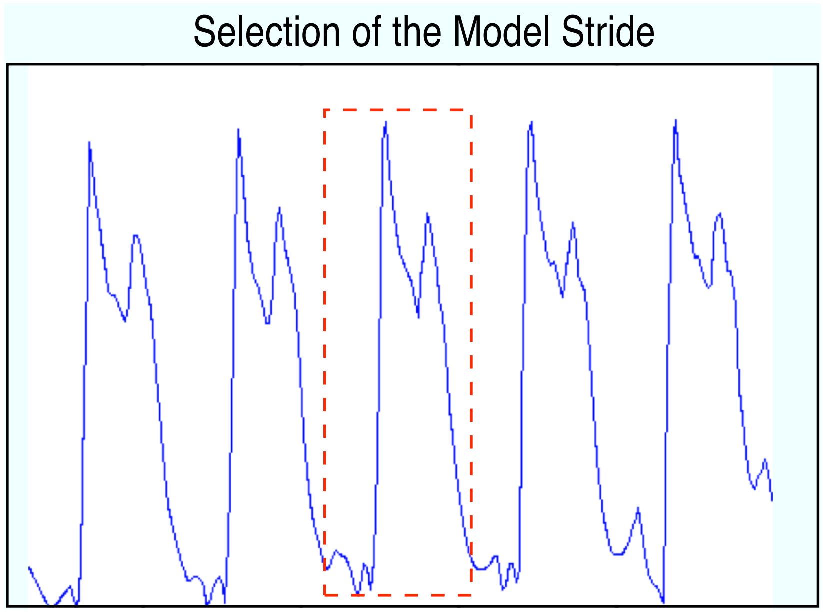

Figure 4.5: Selecting a model speed skating stride. A single cycle of data from the sensor is selected as the model signal, g. The size n selection is shown in the dashed box above. Since g is cyclic we iterate though the n phases of g when synchronizing to a subject stride, f. The data shown is from a few cross-over strides of our model skater.

to compare f to the model signal, g, i.e.,

$$h = f \otimes g, \tag{4.1}$$

$$= \sum_{i=0}^{n-1} f(i)g(i). \tag{4.2}$$

The magnitude of h is a measure of how well f matches g. However, f is periodic, and there is no guarantee that the phase of f will match that of g, so we must consider the set of models given by

$$g((i+s) \bmod n), \tag{4.3}$$

where $0 \leq s < n$ determines the phase shift of the model. Now consider the correlation

$$h(s) = \sum_{i=0}^{n-1} f(i)g((i+s) \bmod n). \tag{4.4}$$

Therefore, phase, ϕ of f is

$$\phi = \frac{1}{n} \operatorname*{argmax}_s h(s). \tag{4.5}$$

and

$$\max_s h(s) \tag{4.6}$$

indicates how well f matches the model. Note that $0 \leq \phi < 1$.

Now suppose that we know the shape of each cycle of the signal, but we do not know the frequency. In this case, we need a set of models, g_n, where the subscript n indicates the number of samples in g_n. Thus n determines the period (and therefore the frequency) of the stride. The matching function becomes

$$h(s,n) = \sum_{i=0}^{n-1} f(i) g_n((i+s) \bmod n). \tag{4.7}$$

We can determine the correct period of the model, $\hat{n}$ with

$$\hat{n} = \operatorname*{argmax}_n \max_s h(s,n), \tag{4.8}$$

and the phase with

$$\phi = \frac{1}{\hat{n}} \operatorname*{argmax}_s h(s,\hat{n}). \tag{4.9}$$

To eliminate dependency on the accuracy of absolute measurements and body or sensor calibration it is essential to *normalize* f and g with a linear transformation such that:

$$\sum_{i=0}^{n-1} g(i) = \sum_{i=0}^{n-1} f(i) = 0 \tag{4.10}$$

$$\sum_{i=0}^{n-1} g(i)^2 = \sum_{i=0}^{n-1} f(i)^2 = 1 \tag{4.11}$$

Note that a perfect match between subject and model will yield

$$h(s,n) = 1 \tag{4.12}$$

when f and g are normalized this way. It is this normalization that allows us to use a simple sensor in our speed skating study. The absolute measurements of the variable resistance elastic

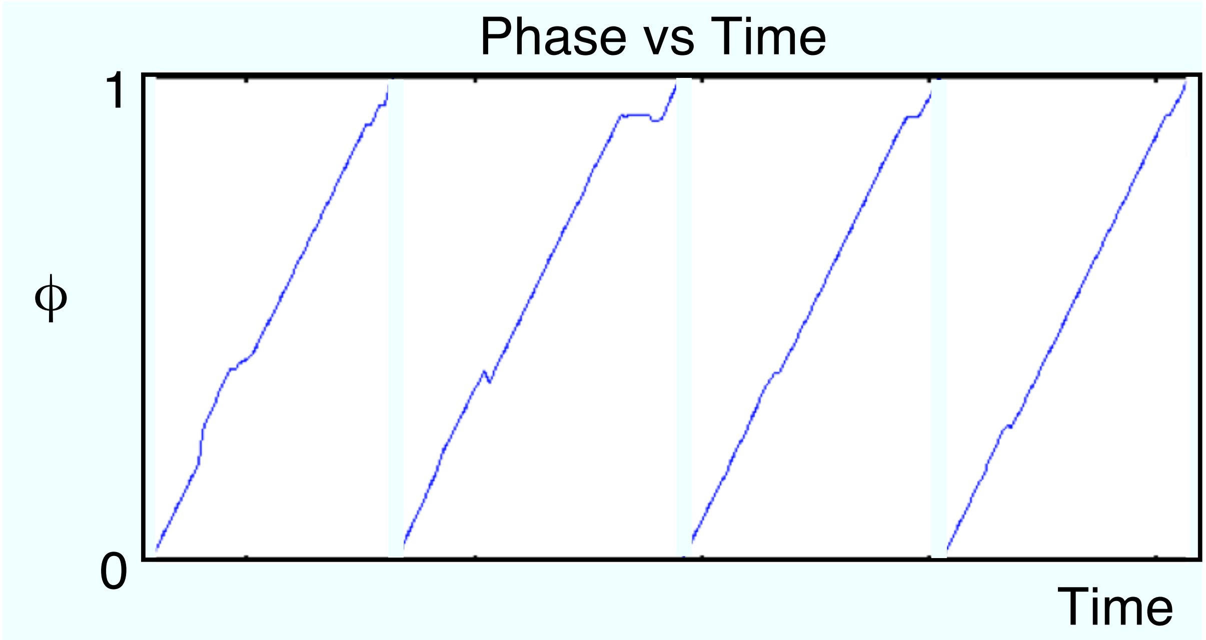

Figure 4.6: Phase synchronization between model and subject. Phase, ϕ, ramps from 0 to 1 during each of the four strides shown

are dependent on temperature, body mounting position and sensor length. Normalizing the data removes the impact of such dependencies.

Figure 4.6 shows phase progression during a sequence of samples from our subject skater. Notice that the phase ramps from 0 to 1, also notice that the slope of the plotted line is not constant. As the period, $\hat{n}$ changes, so too does the slope of the line formed in a plot of the phase. This is an expected outcome when dealing with a skater displaying erratic and unstable skating. Hurried portions of the stride, match to a model with short period. Slow or apprehensive movements match against a model with longer period. While f is controlled by our subject, we choose the appropriate g_n and ϕ giving an optimal match. When the phase plot is displaying a stable ramp from 0 to 1, synchronization has been achieved.

4.3 Sonification

Repetitive movements, lend themselves nicely to rhythmic, repeating sounds. We use the information from our synchronization to control the cadence of musical notes we broadcast to a subject. We design the system to communicate timing information relating to the model's execution of the movement. We divide the movement into equal sections, the number of sections is based on the typical duration of the movement. For the speed skating stride, which lasts one to two seconds we found that four divisions was appropriate.

We mark milestones at the border line of each of these four divisions and embed a musical note at each milestone.

We have milestones at:

$$\phi = \begin{cases} 0.25 \\ 0.5 \\ 0.75 \\ 1 \end{cases}$$

As a subject progresses through a movement we synchronize him against a model producing a phase ramping. Upon crossing a milestone we broadcast a sound in the form of a musical note. We would like to retain the sequential aspect of the movement and so we produce a sound that also has an ordering. Specifically we produce an arpeggio or broken chord of music notes. An arpeggio is a group of music notes played sequentially that typically form a chord. We choose notes forming a four note C-Major arpeggio, their frequencies are: 261.6 hz, 329.6 hz, 391.6 hz and 523.2 hz. We assign each note to a corresponding phase milestone:

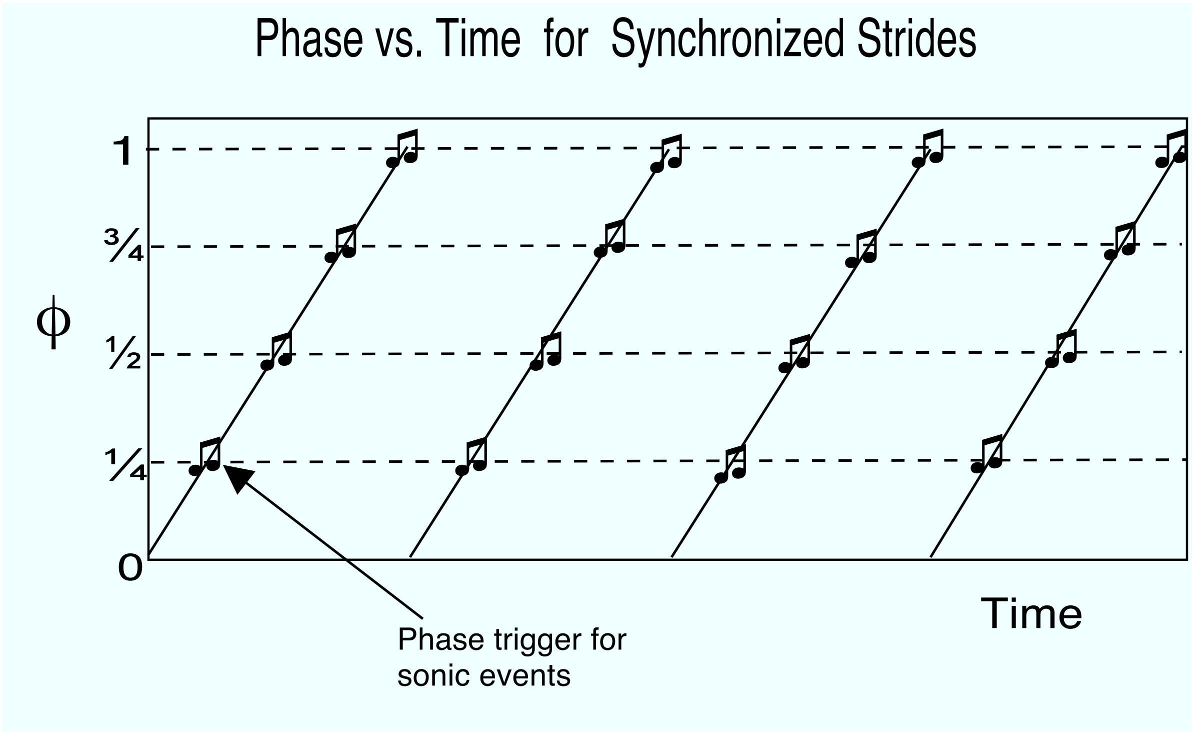

Figure 4.7: A simulated successful synchronization between a model and subject. ϕ ramps from 0 to 1 during each stride. Sound events are triggered as the subject progresses through the stride.

$$\phi = \begin{cases} 0.25; \text{♫} = 261.6hz \\ 0.5; \text{♫} = 329.6hz \\ 0.75; \text{♫} = 391.9hz \\ 1; \text{♫} = 523.2hz \end{cases}$$

Sonifying a movement in this way, as shown in Figure 4.7, provides a subject with rhythmic reference, allowing him to hear his progression against a model. Matching the timing of a model produces the desired evenly spaced rhythm. Rushed or delayed movements are communicated in the disruption of musical rhythm. A delayed or slowed movement translates to a longer period before the next musical note is broadcast, similarly a rushed movement will reduce the period between notes.

It may be beneficial to picture a ballroom dancer who matches the beat pattern of music to their steps. They may count one-two-three-four one-two-three-four to follow the rhythm of the music and use that counting to synchronize their steps to the music. Our rhythmic arpeggio works in the same way, except that we can align the musical note with any phase value, not just a phase relating to a step.

We would like a subject to mimic the movements of a model and so we instruct the subject to use our system to produce an evenly paced rhythm. Uneven distribution of the musical notes are directly linked to those areas of the stride that the subject differs in relative frequency from the model. For the purposes of our speed skating test case we found that dividing the stride into four sections allowed the subject to isolate the area of the stride a musical note corresponded with while being able to perceive differences in the amount of time elapsing between notes.

4.3.1 Specific feedback

While the rhythmic arpeggio is appropriate for any subject, we have a subject with a special problem. Addressing the issues associated with our subject digging his toe into the ice, we additionally develop a corrective sonic feedback solution. Our subject predictably and consistently makes the same mistake at the same point in his stride. Prior to setting his right foot back on the ice, our subject extends his ankle and points his toe at the ice. He invariably stumbles and loses speed.

We focus on that problematic portion of the stride, and examine the angle of the ankle at that time. We use phase to determine when the subject is in the problematic window and set a threshold on the amount of plantar flexion that is allowed. Should the subject exceed the allowable ankle angle, we broadcast a sawtooth tone with harsh harmonics. The intensity of the sawtooth is directly related to the degree by which the subject exceeds the threshold. Figure 4.8 illustrates how we use phase information to identify a window of time when we examine ankle angle.

We set the threshold manually when the subject is skating. Our program allows us to

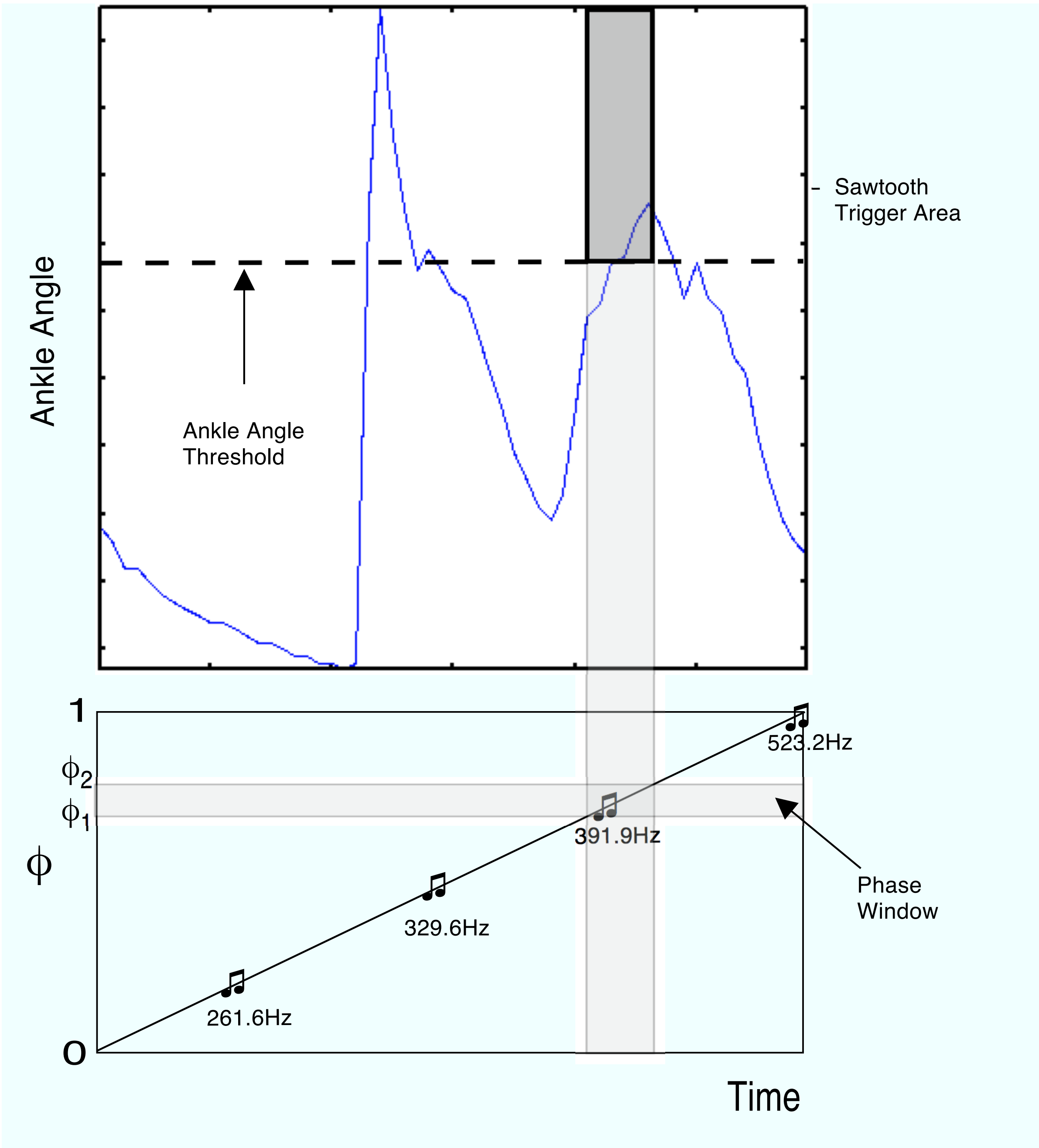

Figure 4.8: Phase is used to identify the window of time (highlighted rectangle) when we check if the subject is performing an incorrect movement. Phases between ϕ_1 and ϕ_2 form this window of time. Ankle angles exceeding the threshold, occurring during phases between ϕ_1 and ϕ_2 are considered to be incorrect. Incorrect movements trigger a corrective sound in the form of a sawtooth tone. Any sawtooth tone interrupts the background sine tones which are marked on the phase graph.

monitor the output of the sensor in real-time. We can also set and adjust thresholds at any time from the base station. This gives us the ability to set the amount of plantar flexion that will trigger the sawtooth. With a sensor that does not produce absolute measurements, the ability to manually adjust any thresholds is important. Also, this gives us flexibility to adjust our training methods based on what is most effective.

Our ability to synchronize to a model gives us the ability to examine any portion of the phase. We set a key window in the period immediately prior to the set-down and during that window we examine certain aspects of the skater's movements. We can examine any phase window using our methods.

We are using sonification by parameter mapping. With regards to the rhythmic arpeggio it is the movements of a subject through the phases of the skating stride that is controlling the pitch of the note that is broadcast. We have discretized the number of matches between phase and musical notes, limiting it to four different notes for our speed skating example. We apply an envelope to the tone to get discrete notes as opposed to a continuous tone. This is done to keep the sounds simple and pleasing. With the harsh sawtooth tone, the intensity of the tone is matched with the plantar flexion of the subject.

The end result is that we have a system that produces a rhythmic arpeggio when the subject matches a model skater, but changes to a harsh sawtooth tone when the skater deviates at critical points in the stride. It is also important to note that speed skating athletes alternate between corners and straight-aways. The movements in the corner are different from those in the straight-away. Our synchronization was built only to match corner strides (cross-overs) and as such does not synchronize during the straight-aways. Fortunately, the effect of matching a cross-over to a straight-away stride, while not useful was not distracting. So we instructed the subject to ignore any feedback generated during the straight-aways. A corner lasts approximately 9 seconds alternating with approximately 9 seconds for a straight-away.

Chapter 5

Testing

We worked with our subject during a period of two months, training approximately two times per week during that time. Our subject skated approximately six times per week as part of his normal training regime. We did not work with him during all of his training sessions, although he carried forward some of the work we did with him into his other practices. Occasionally during this two month period our subject had scheduled races and our involvement would taper off during this time, so as not to interfere with his racing routine.

During a training session we determined that skating for three or four laps in a set was the most practical. We had the subject do three or four lap sets over the duration of a one hour ice session. After four laps of skating our subject took approximately four minutes rest. Four laps of skating lasts approximately 150 seconds. Speed skating is a physically demanding sport, and we had to work within the abilities of our subject. Although we feel skating for a long continuous session of ten minutes or more with our system would be beneficial for familiarization with the sound feedback, it was not practical for this situation.

We were aware of our subject's previous attempts to correct his skating, and evaluated our training methods according to what we had previously seen the subject achieve. If we determined that our subject was not improving beyond what he had previously done, we modified our training strategy. During the course of the two months we attempted three major training methods. We assign names to our training methods as:

- Corrective Feedback Training: The original design of the system, the subject skates and the system corrects erroneous movements with harsh sounds.
- Awareness Training: The subject exploits the system to determine which movements are

acceptable and which are considered erroneous by using a modified skating stride.

- Instructive Training: At certain portions of the skating stride the system instructs the subject to perform a special movement designed to interrupt his typical progression of movements.

The rhythmic arpeggio is common to each of the methods we use, it communicates a progression through the speed skating stride. While we adjust the corrective nature of the system, trying different methods, the rhythmic arpeggio always remained in the feedback.

5.1 Corrective Feedback Training

Corrective feedback training is the term we use to describe the scenario of letting the subject skate and having the system identify erroneous movements. Figure 4.8 provides details on how an erroneous movement is identified. The subject skates and if his movements are correct (as determined by our system), he hears a rhythmic arpeggio. However, if at the critical window of time before he returns his foot to the ice, his ankle plantar flexes beyond the acceptable threshold, he hears a sawtooth tone with harsh harmonics. The degree to which he exceeds the threshold controls the intensity of the sawtooth tone.

The athlete is instructed to avoid the harsh sounds that are created when the system identifies an incorrect movement. Further instruction that the system considers too much plantar flexion before the right foot sets down on the ice during a cross-over to be an incorrect movement is all we provide.

During this training method we have control over the amount of plantar flexion threshold. We begin with a modest threshold, allowing a small amount of problematic plantar flexion but emitting the sawtooth tone for excessive ankle angles. Gradually, as the subject learns to avoid producing any sawtooth tones, we increase the strictness of the threshold. This process is continued until the threshold is strict enough that only an ankle angle producing a smooth set-down is allowed.

5.2 Awareness Training

Awareness training is the term we use to describe a training method where the abilities of the system are exploited to create awareness about which movements are acceptable and which movements are problematic for our subject. As in corrective feedback training the subject receives the rhythmic arpeggio as he progresses through the speed skating stride and when his ankle angle is determined to be incorrect, he receives a harsh sawtooth tone, .

The difference with this training is that we instruct the athlete to attempt to produce the harsh sawtooth tone. Rather than trying to avoid the noise, we instruct him to use a modified skating stride that allows him to control the sound. Specifically, we instruct the subject to modify Component B of the skating stride, the period of time when his foot is in the air, such that he is deliberately alternating between plantar flexing and dorsiflexing during this time. Our goal for the movements of the subject is shown in Figure 5.1. During this now extended Component B, our subject is controlling the sawtooth tone, as shown in Figure 5.2, the jigging motion of his toe, turns off and on the corrective sound.

The subject gains awareness about the relationship between the angle of this blade and a correct set down position. This allows him to reproduce the correct set down angle when he skates in a normal fashion. Jigging the toe up and down is not a normal movement and as such the subject must adjust his skating to facilitate that movement. He skates at a slower speed and in a more upright position allowing him time and room to produce the desired movements.

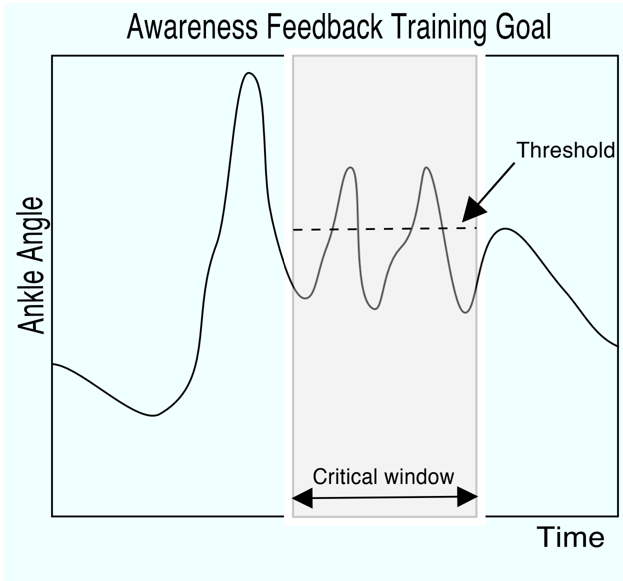

Figure 5.1: In this simulated graph, the subject purposefully extends and flexs his ankle during the critical window in Component B of the skating stride, turning on and off the sawtooth tone. He learns where the threshold of allowable ankle angle exists and uses this knowledge to set-down in a proper manner.

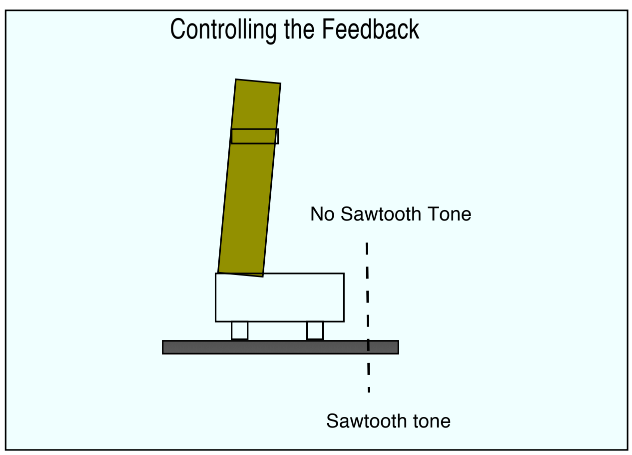

Figure 5.2: The subject controls the corrective sawtooth tone, by moving his toe up or down. A familiarization is developed with the movements the system will and will not permit

5.3 Instructive Training

We use the term *Instructive training* to refer to a method in which we instruct the subject to perform certain movements during key phases. This is a proactive approach designed to avoid

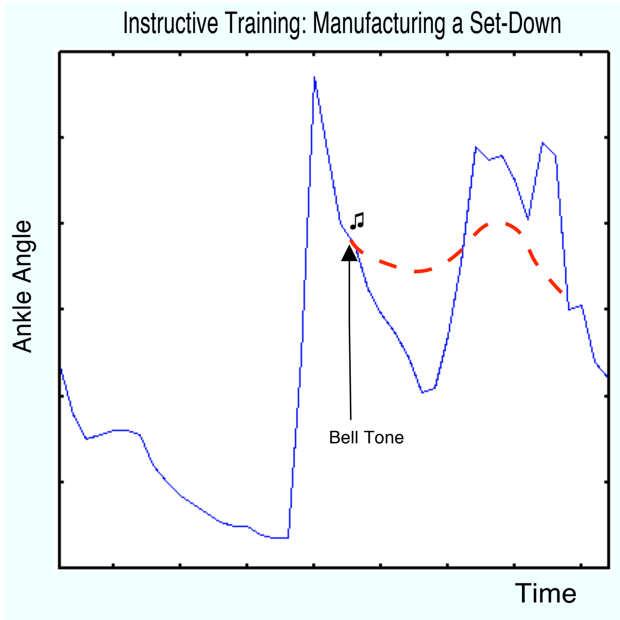

Figure 5.3: A graph of the subject's original movements overlaid with a dotted red line. Upon hearing a Bell Tone, the subject is instructed to initiate setting his foot back on the ice. The dotted red line is the proposed outcome of this new movement. Initiating an earlier set-down will avoid the problematic motions associated with the subject's skating.

the problematic movement. Our other training methods are reactive approaches, attempting to correct a problematic movement. Our subject has ingrained his improper movement for 14 months, we felt that introducing a new movement is easier than correcting a learned movement. A new movement would help our subject avoid entering the chain of movements that leads to digging his toe into the ice. Specifically we look at the time when the right skate leaves the ice and enters Component B of the skating stride. We use phase information to identify this window and prompt the athlete with a bell tone during this time. Offline we have instructed the athlete that upon hearing the bell tone he is to immediately start the process of setting his right foot back onto the ice. We are trying to initiate a proper set-down.

The dotted red line in Figure 5.3 shows the desired outcome of modifying the subject's movements. Initiating the process of bringing the skate back to the ice earlier than before will help avoid the problematic motions altogether. In trying the avoid digging his toe into the ice, the movements the subject has been using could be increasing the odds that he will do just that. The Bell tone occurs before the subject has time to control and manipulate his ankle angle. We may introduce other problems associated with instructing the athlete to do a movement he is not comfortable with but we feel those problems will be easier to fix than his ingrained problem. During this training the subject continues to hear the rhythmic arpeggio, giving him information about his synchronization with the model. However we remove the corrective sawtooth tone, and replace it with a Bell tone that occurs when the subject reaches a certain phase in the stride. It works in the same manner as the arpeggio , i.e., we set a milestone at a certain phase and generate the event as the subject passes that phase. In this case however we use a bell tone to make it distinctive from the arpeggio.

Chapter 6

Results

6.1 Results: General

As this is only a case study with one subject we cannot draw conclusions as to the effectiveness of our sonic feedback system. This case study is an interesting exploration into sonic feedback and provides insight into the potential of the system. With that in mind we examine the progress of our subject and comment on each of the previously mentioned training methods.

We evaluate our work with the subject based on the aesthetics of the skating stride. We have interest in racing results and skating speeds of our subject, however the factors affecting racing results are numerous and many of them, such as physiological training are out of our control. Working only for a period of two months with our subject, we quickly evaluate and modify our training methods to suit the athlete.

Comparing the stride of the subject, prior to training, with that of the model stride, shows obvious differences. Specifically, the jagged and erratic graph of ankle angle associated with our subject are displeasing. Erratic movements, indicate instability and are associated with a speed skating stride lacking in flow and efficiency. The model stride by comparison is pleasing, the movements of the ankle are predictable and the graph displays a less erratic look. The untrained subject skating stride is shown in Figure 6.1, the untrained subject stride and model stride are displayed side-by-side in Figure 4.4.

A major and immediate improvement to the skating of our subject was with regards to the timing of his stride. At first, combinations of hesitant and rushed movements were prevalent throughout his stride. His movements did not occur with consistent pace, furthermore the period of his stride was much shorter than our model. It took our subject approximately 1.3

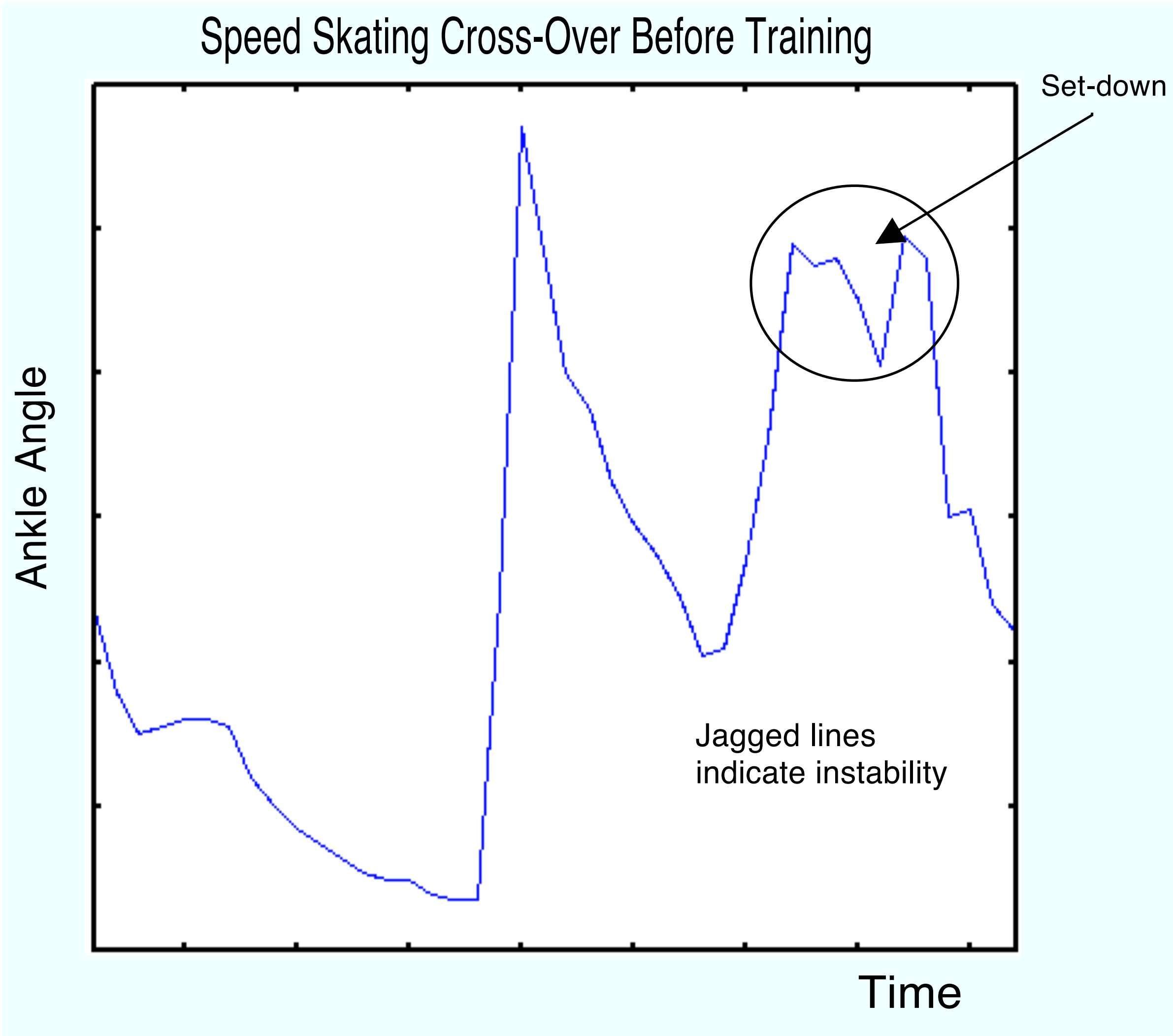

Figure 6.1: The skating stride of the first subject before training. Notice the jagged movements at the set-down resulting from skater instability when the toe of the skate blade digs into the ice. In general the abrupt changes in direction on the graph and lack of smooth curves indicate a lack of flow in the skating stride.

seconds to complete a stride, compared to approximately 1.5 seconds for our model. The skaters were traveling approximately the same speed, however the model was covering more distance per stride. In the span of a few laps our subject made adjustments to ameliorate his stride, matching the tempo and rhythm of the model.

6.1.1 Discussion

We were impressed to see improvements relating to the consistency of the subject's stride during our first sessions with him. Initially we had moderate expectations as we knew the subject had displayed his problem for 14 months and that he had unsuccessfully tried numerous methods to fix it. Executing an incorrect movement for that duration caused the motor pattern to become ingrained. Included in the methods the subject had previously employed to solve his issues included: changes to his skating technique, equipment modifications, psychological approaches, physiological approaches, video analysis and various on ice coaches. Although some of those methods showed promise, none of them rid the athlete of his problem.

We attribute the immediate amelioration in the subject's stride to the rhythmic arpeggio we were broadcasting to him. The subject questioned the differences in time interval between tones in the arpeggio and upon instruction to keep an even rhythm, he was able to match the model stride with increasing success. While this improved the flow of his skating stride, his toe problem persisted. Regarding the rhythmic arpeggio the subject commented, *"this device was highly successful in helping me achieve a more efficient and fluid stride pattern while skating"*.

6.2 Results: Corrective Feedback

During corrective feedback training our subject is reacting to a sawtooth tone that predicts when he is going to dig his blade into the ice. Upon hearing the corrective sound, our subject knows his ankle is plantar flexed, pointing his toes downward. He knows that pulling his toes up turns the sound off, and should improve his skating. We experienced mixed results with this method. Figure 6.2, shows a graph of one of his strides during this training. We notice an improvement over his original skating stride, by a reduction in the jagged and erratic ankle angles, especially around the point of set-down. It is not perfect and loss of speed and balance were observed during set-down. Our subject improved his skating during this training, but

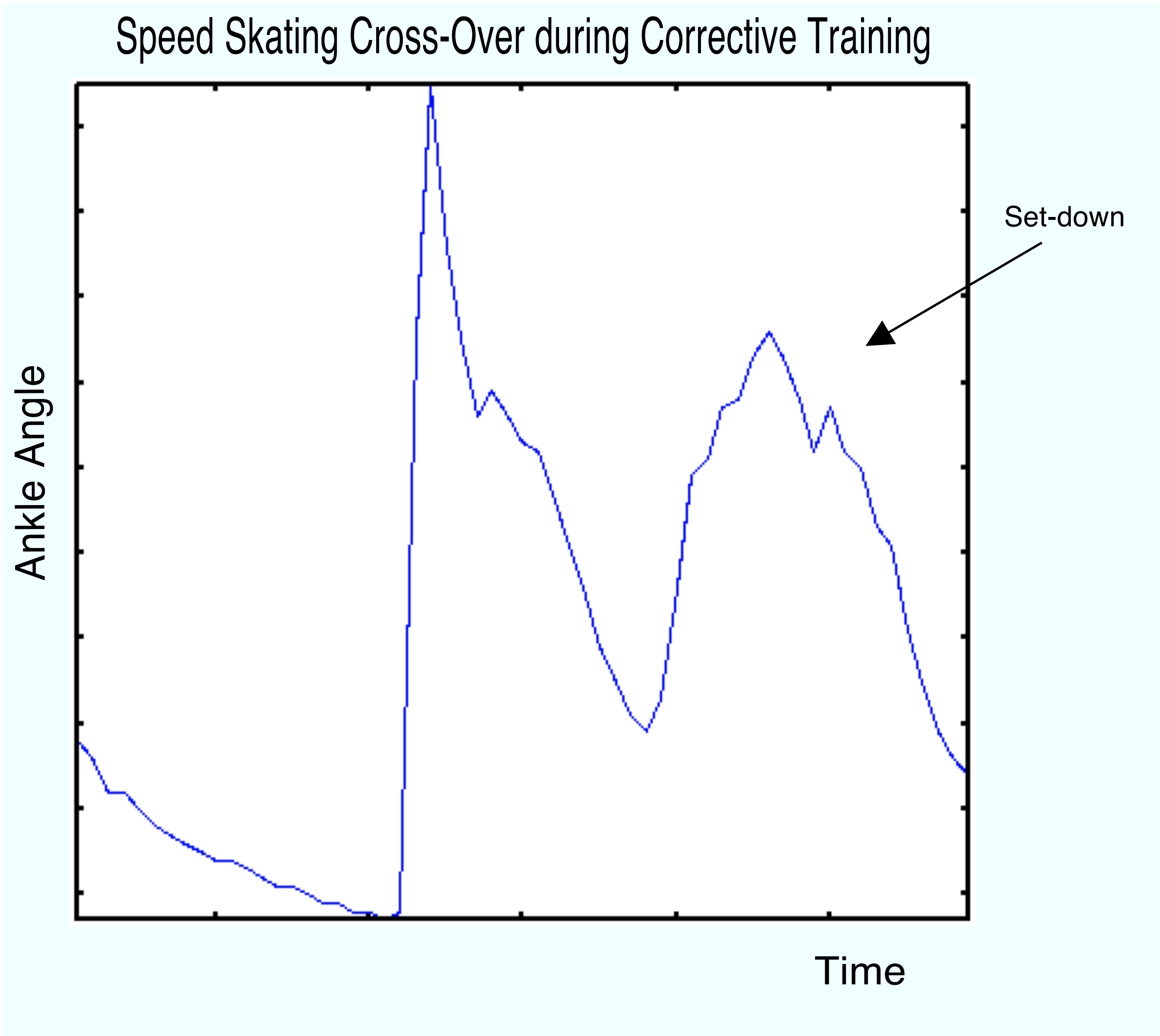

Figure 6.2: The skating stride of the subject during corrective training. The jagged lines during set-down indicate instability.

from a visual perspective we did not see improvements beyond what we had seen the subject previously able to achieve.

6.2.1 Discussion

We feel corrective feedback is able to mitigate but not solve the problem. In prior, traditional training our subject dorsiflexed as much as he could to *pull* his toes up and avoid a problematic set-down. With our corrective feedback he displayed the same tendancy. He was unable to *pull* his toes up any more than before simply because the sawtooth tone indicated he needed more dorsiflexion. The intensity of the sawtooth tone mitigates the problem by indicating a degree of dorsiflexion that is still required. At a certain point, the subject is not able to flex his ankle any more and so cannot fully control the sawtooth tone. It should be noted that flexibility or range of motion did not appear to be the issue here, it was the way in which the subject was moving and his instability that appeared to be the reason he was unable to flex his ankle an appropriate amount.

6.3 Results: Awareness Training

During awareness training our subject uses the system to determine what is and is not an appropriate ankle angle. Doing this our subject *was able to achieve a flawless set-down*, this was something the subject had not achieved during the previous 14 months.

We modified the normal skating style of our subject, slowing down his pace and having him skate in a more upright style. These modifications allowed our subject more time with his right skate in the air during a cross-over. This extra time allowed him to repeatedly plantar flex and dorsiflex his ankle (Figures 5.1 and 5.2). These movements turned off and on the corrective feedback from the system. Our subject attempted to set his blade back onto the ice, when the system indicated his skate was in a proper orientation.

As we see from Figure 6.3, our subject was able to return his skate blade to the ice correctly. On the first occasion of our subject performing a series of successful set-downs he raised his arms in triumph.

Having achieved some proper skating, we instructed the subject to cease the unnecessary plantar flexion and dorsiflexion prior to the set-down. The system performed as it did during corrective feedback, and our subject did as well. He was unable to carry forward his correct set-downs without first plantar flexing and dorsiflexing. Our attempts at having him phase

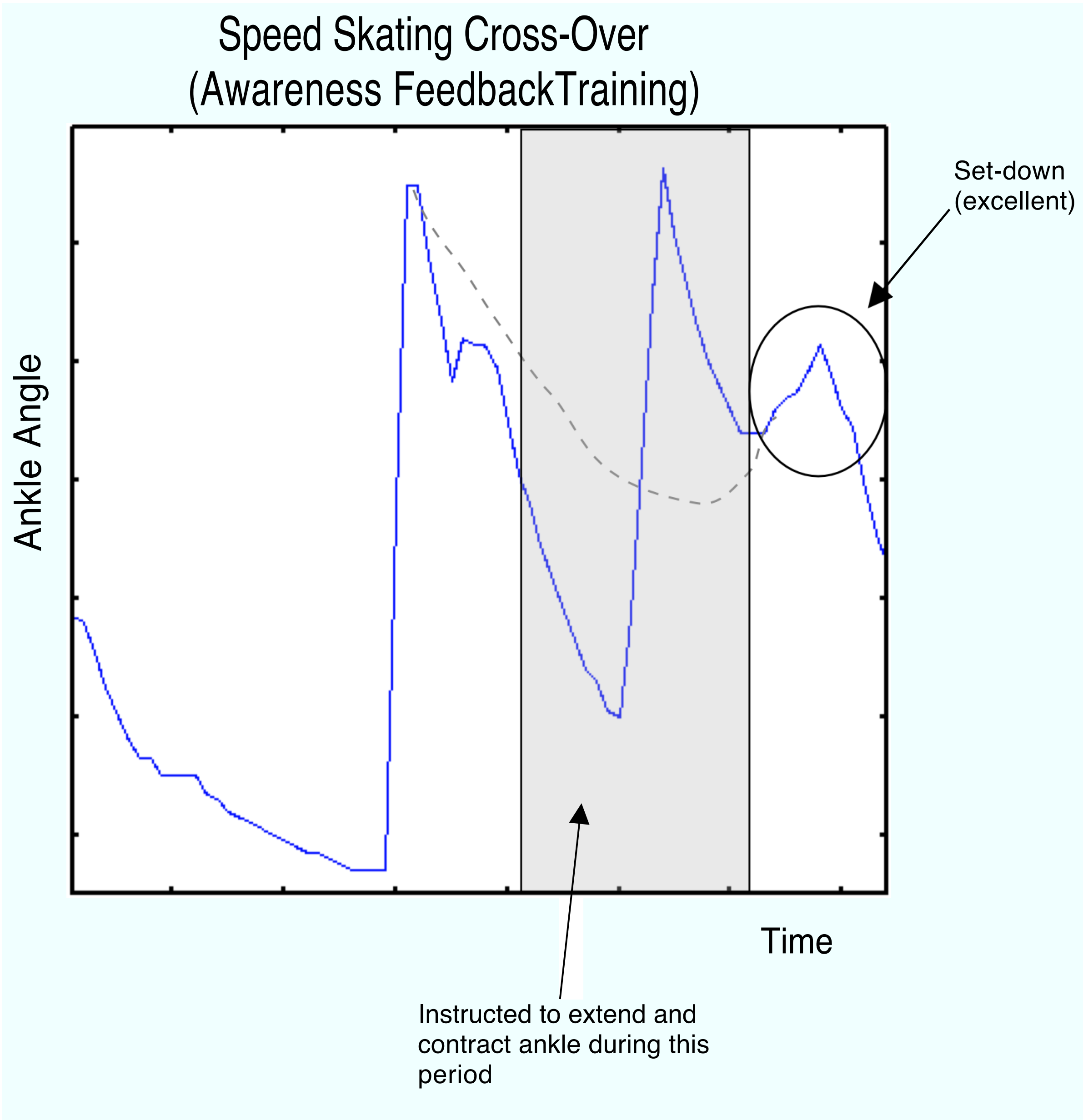

Figure 6.3: The skating stride of the subject during Awareness Feedback Training. Notice the smooth curves around the set-down indicating a flawless set-down. The dotted grey line represents a correct cross-over and what we hoped to achieve by removing the jigging of the toe.

out the new movement while maintaining his new found correct set-down were unsuccessful. To facilitate the time required to plantar flex and dorsiflex, our subject skated slowly and in an upright position. This is different from a typical speed skating style. Attempts at having the subject skate closer to his typical skating style, caused the instability around the point of set-down to return.

6.3.1 Discussion

We were enthused to see the flawless set-down of the subject. When asked about his triumphant moment our subject mentioned *"I didn't feel unstable, my leg was solidly on the ice. I knew I was skating properly again.*" When asked about where his focus was when he was completing this task he responded, *"I concentrated on which sounds I should try to avoid and which sounds I should try and replicate"*.

Unfortunately, to facilitate the added movements requested of the subject in this training, the skater had to slow his speed significantly and modify his skating position. Attempts to keep the proper movements, like the flawless set-down, while reducing and removing the unnecessary ankle movements were unsuccessful. Learning a new movement is difficult and integrating it with previously learned movements is just as difficult. Our subject needed more time to become familiar and comfortable with the new ankle movements so he could control them better. In our short training time, our subject had an all or nothing control of the movement and as such our attempts to phase them out were unsuccessful.

While training our subject in this manner two things became clear:

- this method was successful at correcting the problems occurring when the subject set his blade back on the ice
- reducing the amount of deliberate plantar flexion and dorsiflexion, while maintaining the flawless set-down requires a long training period

We felt that given enough time to become comfortable with the new ankle movements, our subject would be able to adjust and remove those extra movements altogether without compromising his progress at the point of set-down. Ideally we would have trained the athlete over a long period with this method and potentially solved his issues. This did not fit into the time-line and training schedule of the subject and so we moved on.

6.4 Results: Instructive Training

During instructive training, our subject is given a cue in the form of a bell tone during a crucial moment in his stride and he executes a new movement at that time. We want the subject to avoid initiating the chain of events that produce a flawed set-down. We instruct the subject that upon hearing a bell tone he is to immediately begin setting his right foot back on the ice.

The struggles associated with modifying a previously learned movement are shown in Figure 6.4. Our subject attempts to override his ingrained movement upon hearing the bell tone, and while his initial movements look promising, he ends up reverting back to his old movement enduring similar results.

Our subject achieved strong set-downs using this training method, however was unable to replicate the flawless set-down previously produced.

6.4.1 Discussion

We are aware prior to this training that we are again risking the problem associated with the long time required to learn a new movement and become comfortable enough with that moment to execute it at the high paces associated with speed skating. In this instance though we felt that unlike awareness training our subject is not modifying the underlying speed skating movement. He is using his normal pacing and position, only replacing one movement with another.

It became clear that training time was again the limiting factor. The two month time line associated with this project did not fit those constraints. Our subject never did become fully comfortable with the new movements, although we did witness some improvements over his original movements.

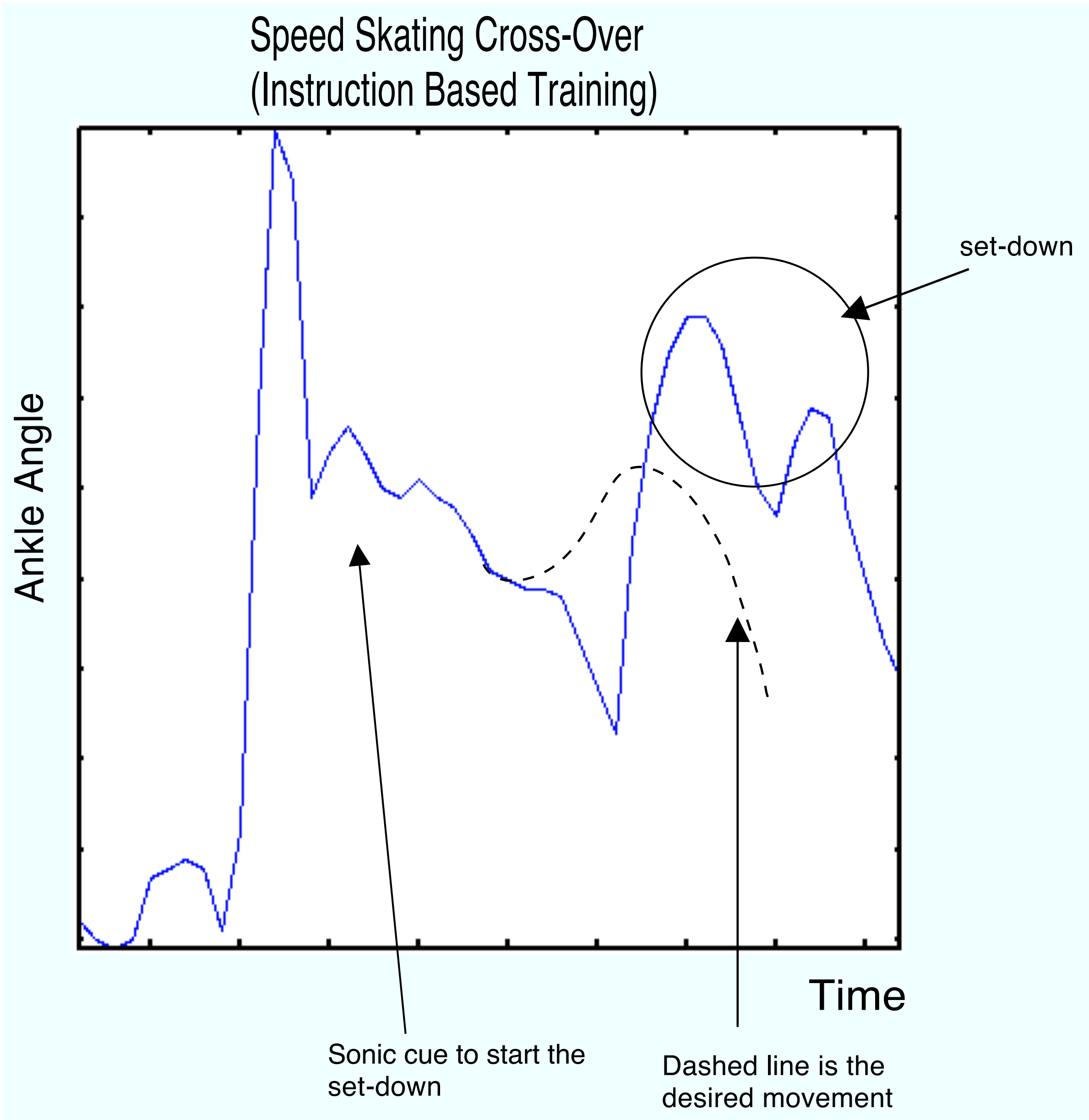

Figure 6.4: The skating stride of the subject during Instructive Training. The athlete is cued to start the set-down process while the right skate is in the air. Notice that the athlete attempts to do this but reverts back to a more comfortable pattern, shown in the highlighted box. The dashed line indicates our desired pattern of movement. At set-down a change in the direction of the plot indicates the skater was not perfectly stable.

Chapter 7

Conclusion

A question we consistently receive when discussing this project, is whether or not we were successful at returning the subject to his prior national calibre form. In answering that it is important to note that from our viewpoint assessing the skater's calibre is beside the point of the project. The most interesting outcome of this project is our successful synchronization and sonification of a repetitive movement. We have demonstrated a real-time sonic feedback method that has been well received and garnered awards within the auditory display community. Our algorithms, methods and implementation suggest that relative data can be effective for tracking and analyzing repetitive movements. We have avoided the problems associated with continuous sounds while using sonification to convey pertinent instructional information.

We attempted a number of different training methods with our speed skating subject, and while they were designed to fix his skating, they also exercised and demonstrated the capabilities of the system. The fact that our subject was able to control and react to the feedback he was hearing is the outcome we were hoping for. This system provides the base that other experts can use to design appropriate training methods. We used the case study to evaluate the potential of sonic feedback and to demonstrate the system with a real world problem.

With that said, with respect to his progress, the subject commented, "*The device was the only thing that was able to improve my skating.*". Our subject was under time constraints associated with his racing schedule. Specifically he was preparing for one important race, scheduled for two months after we started working with him. After that race he decided to retire from speed skating career. We worked with the athlete for only two months and that as much as anything influenced the progress we were able to make with him.

We feel that given enough time, we could have helped the subject develop the skills necessary to skate efficiently. Still we are encouraged at the progress we did make and feel we are on the right track with respect to using sound for teaching, correcting and refining repetitive motor skills. The system responded in a consistent and accurate manner, and that allowed us to alter our training approaches and find effective ways of using the system.

The rhythmic arpeggio was very effective at helping the subject synchronize his movements. This type of feedback is applicable to almost any repetitive movement. In fact, we have used the system without modification on other speed skating athletes and in walking feedback demonstrations.

With respect to sonification, the simplicity of the sounds we generate could be our biggest strength. Our subject never commented about the sound as being unpleasant and was able to use the device for a long duration. The combination of synchronization and sonification seems like a strong combination for creating effective and cost efficient motion capture and feedback systems.

7.1 Future Directions

One area our system could certainly be improved is in the brute force synchronization algorithms. As we attempt to add more analysis or reduce the computing power carried onboard with the athlete, our non-optimized algorithms would certainly require improvement.

We synchronized to a single stream of data, and that was effective for this particular case, however it is not obvious how to synchronize a multiple stream data set. For example when tracking both knee and ankle joint movement simultaneously, categorizing how similar the movement of one person versus another is not trivial. Whether phase locking would occur with a cross correlation alone or not, is not clear.

Carrying a waist pack with sensors placed on an athlete is not practical for all situations and not ideal in most of them. Moving to less intrusive sensors, such as cameras while maintaining the same level of accuracy as the worn sensors is something we will be exploring. Our system in its current state is portable and that is a major advantage over typical camera set-ups. With portability in mind we plan to explore camera mounted robots. Such robots would have the ability to track athletes in the sporting environment. In speed skating, for example, a camera mounted robot would have to be able to maneuver on the ice of the speed skating track. Developing robots that can track with athletes on the ice, presents a number of issues including safety, autonomous navigation, mechanical hurdles and power supply.

We have experimented within the sport of speed skating, however the same synchronization methods should apply to other repetitive movements, like walking or running. Experiments in those domains, could be a natural starting point for camera mounted autonomous robots, as the hurdle of overcoming navigating on the low friction of the ice surface is not present when operating on a running track.

Outside of the sporting domain, physical therapy is a domain we would like to explore. Commonly, physical therapy patients practice proper movements trying fix a problematic movement. An automatic feedback system could ensure their movements do not stray away from the desired motion even when their therapist is not present to evaluate them.

We would like to explore spatial sound generation, which involves projecting sounds into 3 dimensional space. We feel that spatial sound could maintain the simplicity of the sound a subject is listening to, while taking advantage of the implied information embedded in where a sound is coming from. In such a set-up, for example we could draw attention to a subject's left side simply by projecting a sound to the left of the subject. Chris Thornton [65] has also considered the idea of employing research from artificial intelligence to our sound feedback. Artificial intelligence methods could be used to teach our system how effective its feedback is. It could track and learn from the responses of a subject to a certain feedback then tailor the intensity of subsequent feedback to elicit a desired response.

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