CORRECTIVE SONIC FEEDBACK FOR SPEED SKATING: A CASE STUDY

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ABSTRACT

We present a system that provides real-time audio feedback to athletes performing repetitive, periodic movements. The system synchronizes the temporal signal from a sensor placed on the athletes body with a model signal. The audio feedback tells the athlete how well they are synchronized with the model, and whether or not they are deviating from the model at critical points in the periodic motion. Because the feedback is continuous and in real-time, the athlete is able to correct their motion in response to the sounds they hear. The system uses simple, inexpensive instrumentation (the entire system costs less than $500) and avoids the uses of expensive and inconvenient motion capture systems. We demonstrate the effectiveness of the system with a case study featuring a speed skater that had developed a significant anomaly in his technique.

1. INTRODUCTION

In sports, certain movements happen so quickly that it is almost impossible for a coach to give instructions while an athlete is in the process of executing the movement. A golfer performing a golf swing, a gymnast performing a flip or a speed skater executing a cross-over are examples of movements that through traditional coaching methods are analyzed only after they have been executed and adjustments made only on the next repetition. Figure 1 illustrates this problem. Advances in wireless technology, computing power and computing portability now allow for analysis of these fast movements to happen in real time in the sporting environment. Sound is the natural communication medium to communicate to an athlete that is already taxing their vision, balance and tactile senses to perform their movement. We have developed a computerized sonic feedback system that improves how these rapid and repetitive movements can be coached. We have focused on the sport of speed skating and a unique opportunity to work with one particular athlete who had lost the ability to perform a proper speed skating cross-over.

We developed a system to aid this athlete using corrective sonic feedback. Using a sensor, we matched the skating stride of our subject to that of a model skater. Using this matching information we were then able to sonify the data relating to differences or imperfections in the subjects movement and communicate it to the subject as it was happening. We were able to provide cues, timing and body position information all in real-time. The sonification we produced allowed the athlete to make corrections and adjustments on the fly, something he and his coach were not able to do through traditional means.

Our system is a cheap and effective alternative to expensive and bulky motion capture systems. The cost of the measurement sensor we employ is on par with a cup of coffee. The whole system costs less than $500. The system is unobtrusive and easily worn by an athlete, and best of all it requires little calibration. We are able to achieve this without expensive measurement apparatus because we match using a relative pattern in the data rather than absolute measurement values.

As a case study with a single subject, we had no controls for validity. Nevertheless, the singular opportunity to test sonic feedback for correcting an athletic movement provides a valuable lesson, and suggests future direction for studies where controls are possible.

2. BACKGROUND

2.1. Sound in Sport

Sound plays an important role in sport, generally providing complimentary information to athletes. Naturally occurring sounds like a skate blade gliding on ice or a golf club impacting a ball are common in sport and can influence an athlete [1]. Advances in computing ability allow for all sorts of sport related information to be analyzed electronically and converted into sound. Running pace [2], rowing boat velocity[3] and karate movements [4] have all been electronically analyzed and used to control or create a sound that is communicated back to the athlete. The ability of a subject to mimic the jumping height of another subject using sonified jumping data [5] shows the potential for sound as a teaching tool.

2.2. Phase Matching

To compare the strides of a skater with model data, we must synchronize two signals, i.e., we must compute the phase shift between the two signals. Measurement of the phase shift between two periodic waveforms is a well-known signal processing technique with cross-correlation being the most frequently used method [6]. A useful variation that accounts for linear transformations of the signals is the normalized cross-correlation. When a signal is known to be a sinusoid, a phase-locked loop is a good alternative for synchronization of a reference oscillator to an input signal [7]. The method we use, described later, is a normalized cross-correlation with modification to allow for signals scaled in time and frequency.

2.3. Speed Skating

In speed skating, athletes race counterclockwise around a 400 meter oval consisting of two 100m straight sections and two 100m

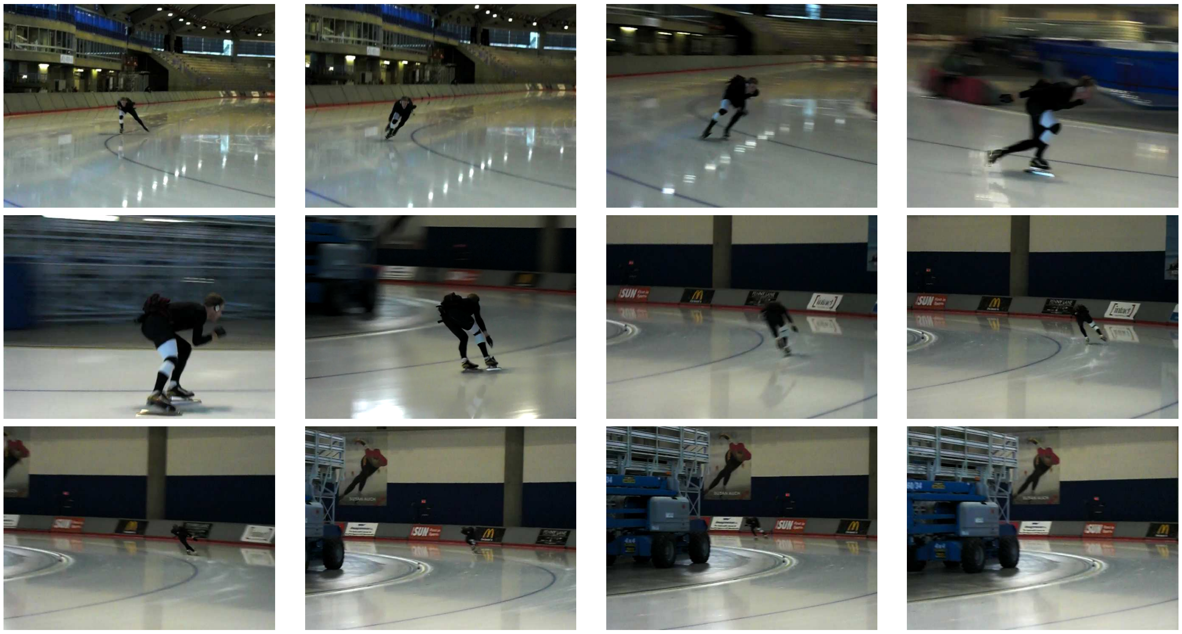

Figure 1: The window for coaching feedback. This sequence shows our subject skater over an interval of $8s$ during which time he travels approximately $80m$. At $10m/s$ ($36km/h$) it is difficult for a coach to see more than one or two single strides and give meaningful verbal feedback.

corners. To execute the corners a skater performs a cross-over, lifting the right skate over top of the left one. A skater will perform between 6 and 9 cross-overs in a span of 6-8 seconds as they navigate the 180 degrees that span the 100 meter corner. Figure 2 shows a plot of right ankle extension versus time in a cross-over from our model skater. The plot is divided into the three components that make up a cross-over:

1. **Right Foot Pushing:** the skate is in contact with the ice as the skater pushes (Figure 2 - A),
2. **Right Foot in Air:** the skater lifts his skate off the ice and moves it across the left skate (Figure 2 - B), and
3. **Right Foot Prepares to Push:** the skate blade contacts the ice (the set-down) as the skater prepares to push again (Figure 2 - C).

Efficient cross-overs are critical to achieve top performance in speed skating.

2.4. Our Subject

Our subject was unable to perform an efficient cross-over. He was able to perform component A and parts of component B without difficulty, however when he wanted to put his right skate back onto the ice at the set-down point he would dig the toe of his skate blade into the ice. This caused loss of speed and risk of crashing. The correct motion is to set the right skate blade down evenly onto the ice.

The athlete had previously been able to perform a cross-over and was a successful, nationally ranked racer. Cross-overs were a routine movement for him but at the start of a recent season he lost the ability to perform a cross-over properly. This condition is often referred to as *"Lost Move Syndrome"* and although uncommon, does occur in elite level sports[8]. Our subject sought help through traditional coaching methods like video analysis, sports therapists, and physiologists and over the course of 14 months was unable to improve the problem.

The subject was a perfect candidate for the sonic feedback system we have developed. He described his problem as not knowing that his toe was about to dig into the ice and feeling like he had a disconnect between what he was feeling and what was actually happening. His coaches were unable to provide feedback about the orientation of the toe of his blade during the process of the cross-over. We hypothesized that corrective sonic feedback would help correct his cross-overs.

We built a system to measure ankle extension and matched the amount of ankle extension during his skating stride to that of a model. In this way we were able to predict whether his toe would dig into the ice or not on any given cross-over and provide sonic feedback to the athlete in advance of the set-down.

3. SYSTEM DESCRIPTION

3.1. Apparatus

We used a single variable-resistance elastic, depicted in Figure 3, attached between the toe and shin of our skater (Figure 4) to measure the amount of ankle extension at any time. As the athlete skated, a netbook computer carried in a backpack measured the elastic's resistance, R_s at 33 Hz. The plot in Figure 2 was obtained from this apparatus. At less than $500, the cost of our entire system is only a fraction of what other options like video based motion capture or motion capture suits cost. The simplicity of

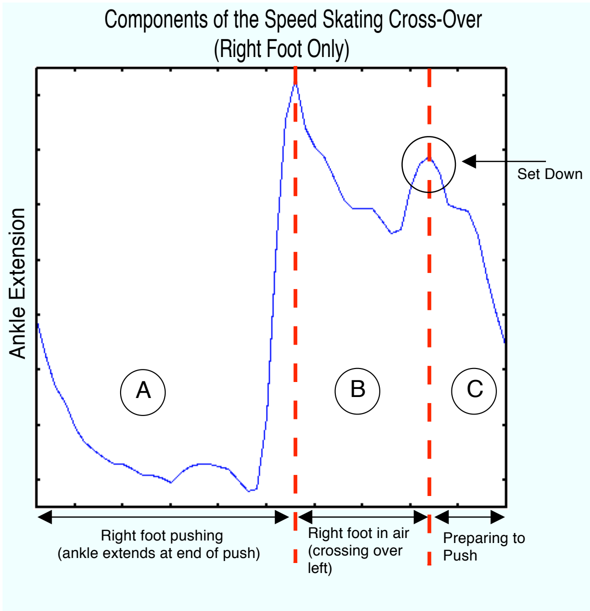

Figure 2: The Speed Skating Cross-over - Ankle Extension versus Time. The Cross-over is divided up into 3 components for the right foot. A) The right foot is pushing. The ankle is compressed with the knee over the toe for the first portion of this component (little ankle extension). During the end of this phase the ankle extends 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 component 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 extension reduces in anticipation of the next push component. The set-down when the right skate comes back into contact with the ice is labeled. This plot is from our model skater.

the system and little requirements for calibration or time consuming manual body measurements make this system practical for use with real athletes in the sporting environment.

3.2. Synchronization

The most important aspect of our system, is its ability to accurately synchronize the subject's skating stride to that of our model's stride. The following is a description of our brute-force method to estimate the phase of a speed skating stride from a single sensor stream.

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

$$h = f \otimes g, \quad (1)$$

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

The magnitude of h is a measure of how well f matches g.

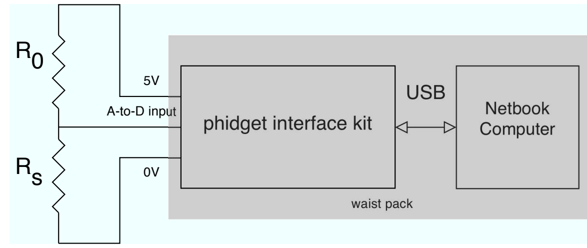

Figure 3: The sensor circuit: The sensor is a variable-resistance elastic (R_s) approximately 20mm in length . R_0 and R_s form a voltage divider. 5V supplied by the Phidget Interface Kit (http://www.phidgets.com) is applied across the voltage divider. An analog-to-digital converter in the Phidget Interface 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.

Figure 4: 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 ankle extension. 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 through headphones (not shown).

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

$$g((i + s) \bmod n), \quad (3)$$

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

$$h(s) = \sum_{i=0}^{n-1} f(i)g((i+s) \bmod n). \tag{4}$$

Therefore, phase, ϕ of f is

$$\phi = \frac{1}{n} \operatorname*{argmax}_s h(s). \tag{5}$$

and

$$\max_s h(s) \tag{6}$$

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

$$h(s,n) = \sum_{i=0}^{n-1} f(i)g_n((i+s) \bmod n). \tag{7}$$

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

$$\hat{n} = \operatorname*{argmax}_n \max_s h(s,n), \tag{8}$$

and the phase with

$$\phi = \frac{1}{\hat{n}} \operatorname*{argmax}_s h(s,\hat{n}). \tag{9}$$

The absolute measurements from the sensor vary with temperature, length of sensor, and where it is mounted on the toe and shin of the athlete. Given that we cannot control these factors, it is essential to *normalize* f and g with a linear transformation such that:

$$\sum_{i=0}^{n-1} g(i) = \sum_{i=0}^{n-1} f(i) = 0 \tag{10}$$

$$\sum_{i=0}^{n-1} g(i)^2 = \sum_{i=0}^{n-1} f(i)^2 = 1 \tag{11}$$

Note that a perfect match between skater and model will yield

$$h(s,n) = 1 \tag{12}$$

when f and g are normalized this way.

3.3. Sonification

Once the phase is matched successfully the stride cycle can be sonified. We worked within the Pure Data (http://puredata.info/) environment to do the sonification. The model stride is divided arbitrarily into four equal sections. When the phase of the subject crosses over one of the boundary lines between a section the system plays a note. Figure 5 shows a depiction of a successful stride matching using Equations (8) and (9). We selected four sine tones from a C major chord as the notes. The frequencies of the four tones are: 261.6 Hz, 329.6 Hz, 391.9 Hz, and 523.2 Hz. This produces an arpeggio, helping the subject to naturally synchronize his stride with that of the model.

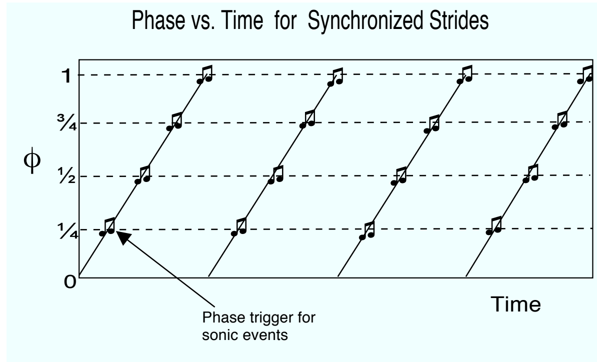

Figure 5: A successful synchronization between model and subject. ϕ ramps from 0 to 1 during each stride. Sound events are triggered as the skater progresses through the stride.

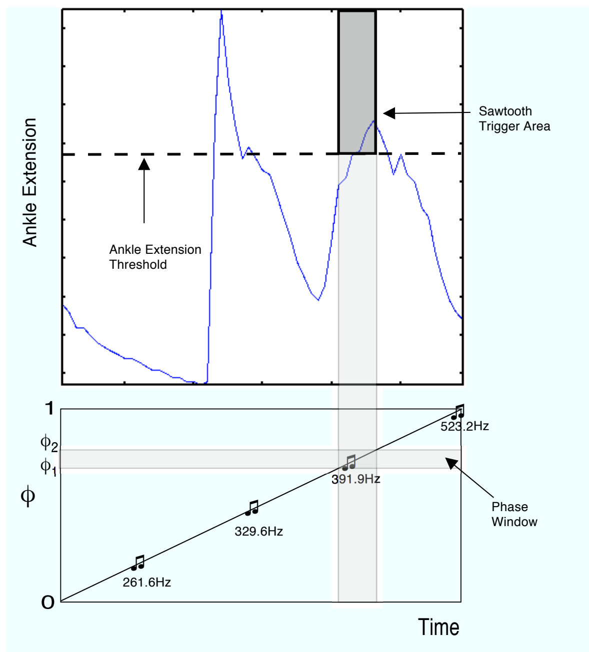

Figure 6: Phase is used to identify the window of time (highlighted rectangle) when we check if the subject is performing an incorrect movement. Phases between ϕ_1 and ϕ_2 form this window of time. Ankle extension exceeding the threshold, occurring during phases between ϕ_1 and ϕ_2 are considered to 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.

A reliable and accurate phase matching gives us the ability to focus on any part of the stride. We focus on the problematic area of the stride for our subject, the period of time immediately before the set-down. This is where we singled out variations between the model stride and the subject. We aimed to limit the amount of ankle extension allowed during this period. A threshold is set in the phase interval defined by ϕ_1 and ϕ_2 immediately preceding the set-down. Within this time interval, if the ankle extension of the subject surpasses the threshold, the system produces a corrective sound in the form of a sawtooth tone with harsh harmonics. Figure 6 shows a graphic representation of how phase information combined with ankle extension data is used to trigger corrective sawtooth tones. Our system is designed such that the threshold is adjustable and controllable from a base station via wireless network while the skater is skating.

The intensity of the sawtooth tone is directly related to the amount by which ankle extension surpasses the set threshold. In this way the subject can distinguish small deviations from the expected movement apart from large ones. Because our ankle extension measurements are relative rather than absolute, we scale the intensity of the sawtooth tone in proportion to the maximal readings from the sensor.

The resulting system produces a rhythmic arpeggio of consonant sine tones when the skater matches the model, but changes to a harsh sawtooth tone when the skater deviates at critical points in the stride. The intensity of the harsh sawtooth tone is proportional to the degree of deviation.

4. TESTS

We worked with our skating subject for a period of two months with approximately two one hour training sessions per week. The athlete also conducted his regular training regime and competed in a number of competitions during this time. We aimed to have the athlete use the system for as long a continuous period as was practical during a session. Ultimately we determined that fitting as many 3 - 4 lap repetitions in the one hour ice time was the most practical training method. Four laps last approximately 2.5 minutes total.

Speed Skating is physically demanding and we had to work within the abilities of the skater. Skating for 2.5 minutes and then taking a few minutes rest seemed to work the best. We had hoped to try training for continuous periods in the 10 minute range (15 - 20 laps) but that was not practical for our situation.

We progressed through three different training methods during the two months. We used our observations and feedback from the athlete to make necessary adjustments.

4.1. Corrective Feedback Training

The first training method we used was a corrective feedback set-up as described in detail in Section 3.3. Figure 7 shows the subject's skating stride before any training. We set up a threshold on the amount of ankle extension allowed in the period immediately before set-down as shown in Figure 6. Exceeding the threshold results in a sawtooth tone. The skater was instructed to try to avoid making the sawtooth tone. We began with a modest threshold, slightly less ankle extension than what the subject was already doing. We gradually decreased the threshold allowing less and less ankle extension until we reached a level that would result in a correct cross-over.

4.2. Awareness Feedback Training

The second training method we attempted required no alterations to the hardware or software that was used in the corrective feedback set-up described above. The skater however was given different instructions than what was given during corrective feedback training. We used the system and the sawtooth tone to create awareness about how much ankle extension was allowed. This time the skater was instructed to purposefully create the sawtooth tone. During Component B, labeled in Figure 2, when the right skate is in the air, the skater was instructed to extend his ankle pointing his toe towards the ice (creating the sawtooth tone) and then lift his toes back up until the sound stopped. After this the skater would attempt to finish his stride regularly by proceeding to set his right skate back to the ice. The skater did not skate normally doing this, it was a modified skating stride that allowed him more time with his right skate in the air. The skater went slower and was more upright to allow for this additional movement.

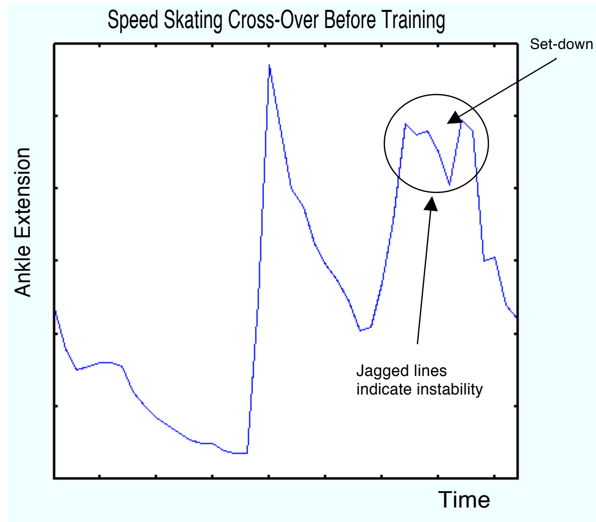

Figure 7: The skating stride of the subject before training. Notice the jagged movements at the set-down resulting from skater instability when the toe of the skate blade digs into the ice. In general the abrupt changes in direction on the graph and lack of smooth curves indicate a lack of flow in the skating stride.

The sawtooth tone was used to increase awareness about the expected movement. As the skater became comfortable with the movement, the threshold on the sawtooth tone was decreased. The aim was to reduce the threshold until the purposeful extension of the ankle was gone and the athlete, using his new found awareness of the correct amount of ankle extension, was left doing correct cross-overs.

4.3. Instruction Based Training

The final training method we used changed from a reactive system to a proactive system. Rather than giving feedback after the ankle extension exceeded the threshold, we provided a prompt telling the skater when we though he should extend his foot to meet the ice. We tried to manufacture the set-down point. The aim here was to not allow the athlete enough time to extend his ankle beyond the threshold. Instead we prompt the athlete to set-down before he has made the incorrect movement. There no longer was a corrective feedback aspect but rather we used the phase matching information to determine when we thought the skater should try to set down his foot.

We produced a bell tone at what we thought was the appropriate moment to start setting the right foot on the ice. The skater was instructed to extend for the ice with his right skate each time he heard the bell. We did not want to allow the skater enough time to extend his ankle pointing his toe to the ice. With enough training the manufactured set-down point would become the athlete's natural movement.

5. OBSERVATIONS

5.1. General Observations

The model stride, which is shown on the graph in Figure 2, from a speed skating perspective, is aesthetically pleasing. Focusing on the area around the set-down the model stride is smooth and devoid of abrupt changes in direction. Comparing this to the subject's stride before training, shown in Figure 7, we see the graph has plenty of abrupt changes in direction indicating inefficient on-ice movements and skater instability.

It is important to note that the subject had problems with his cross-overs during a continous 14 month span. During this time he repeatly executed incorrect cross-overs and that incorrect movement became ingrained into his motor pattern. Knowing that the subject had tried many different possible solutions to this problem without success, we entered into our training with moderate expectations. Contrary to those expectations, the athlete displayed improvements much sooner than we anticipated.

Upon training with the system the aesthetics of the athlete's stride quickly improved. The abrupt and extreme variations in ankle extension were muted and in some cases we achieved flawless set-downs. A flawless set-down was something the athlete was unable to achieve during the previous 14 months.

Common throughout testing were the arpeggio of background sine tones. One of the first improvements we noted with the athlete was an amelioration of the subject's cross-over. When we first started with the subject one of his cross-overs lasted approximately 1.3 seconds (42 samples at 33Hz). The duration of a typical cross-over from our model was closer to 1.5 seconds (50 samples at 33 Hz). The skaters were skating approximately the same speed. The model was covering more ground per cross-over than our subject. Almost immediately the subject modified his skating style to mimic that of the model in terms of stride duration. This improvement was persistent in all training methods. We attribute it to the subject using the arpeggio of background sine tones to maintain the rhythm of the different components of his stride. Our subject agreed: "this device was highly successful in helping me achieve a more efficient and fluid stride pattern while skating".

5.2. Corrective Feedback Training

Corrective feedback training produced a stride that was improved from what the skater was doing previously. However it seemed on par with what the skater was able to achieve using prior methods. During this training, the skater was attempting to pull his toes up to make the sawtooth tone go away. This was similar to his previous attempts at pulling his toes up before setting down. This time however the intensity of the sawtooth tone would predict how badly his toe was about to dig into the ice. He was not able to have a clean set-down but only mitigated the problem. It is evident at the set-down in Figure 8 by the jagged portion of the plot that the set-down was not ideal. It is also evident, by a reduction in the jagged portions of the plot, that this set-down is an improvement over the set-down seen in the untrained stride (Figure 7).

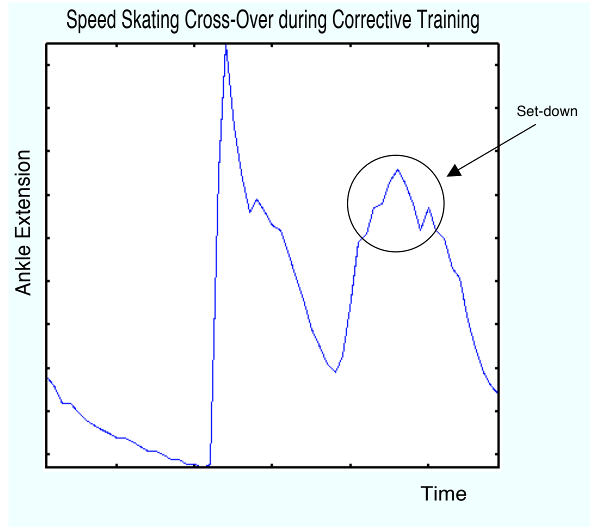

Figure 8: The skating stride of the subject during corrective training. The jagged lines during set-down indicate instability.

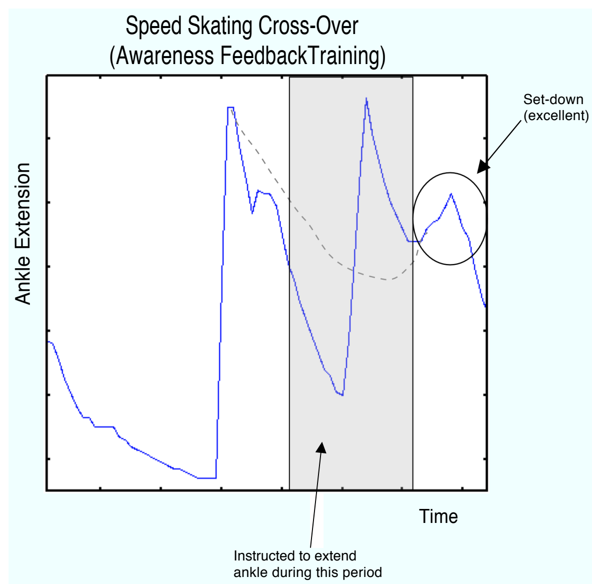

Figure 9: The skating stride of the subject during Awareness Feedback Training. Notice the smooth curves around the set-down indicating a flawless set-down. The dotted grey line represents a correct cross-over and what we hoped to achieve by reducing the purposeful ankle extension.

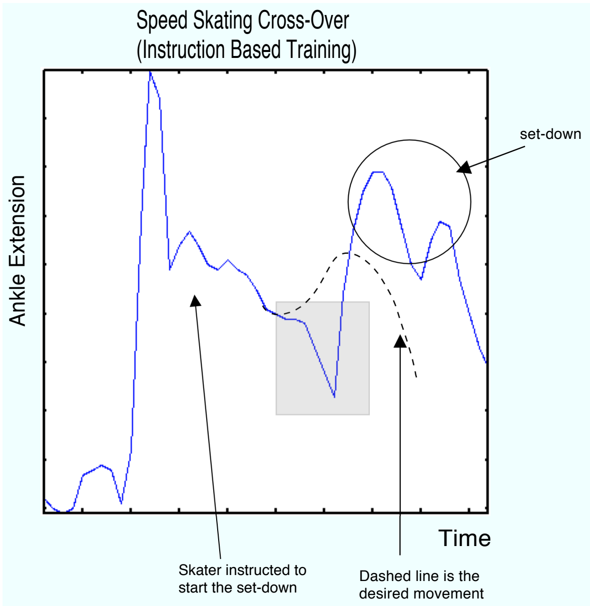

Figure 10: The skating stride of the subject during Instruction Based Training. The athlete is prompted to start the set-down process while the right skate is in the air. Notice that the athlete attempts to do this but reverts back to a more comfortable pattern, shown in the highlighted box. The dashed 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.

5.3. Awareness Feedback Training

Awareness Feedback training produced promising results. Using this training method the skater achieved some flawless set-downs, as seen in Figure 9. The skater could immediately tell that his set-downs were good and described it as the "first successful set-down in 14 months". The skater moved at a slower pace during this training to allow time for the deliberate ankle extension. Attempts at having him skate at a faster pace while doing these extraneous motions were unsuccessful. We were also not able to replicate the flawless set-down without first doing the purposeful ankle extension. During this training method two things became clear:

- this training method fixed the problems occurring at the set-down point, and
- reducing the amount of purposeful ankle extension while maintaining a flawless set-down required a long training period.

The introduction of changes into the middle of the cross-over (the purposeful ankle extension), provided awareness to the athlete about proper ankle extension. These additional movements being new to the athlete were hard for him to control. It became obvious that we would need more training time for him to become more comfortable with the extra movement and to eventually eliminate it. Ideally we would have continued to pursue these promising results, but it did not fit the training schedule of the athlete.

5.4. Instruction Based Training

During Instruction Based Training we attempted to manufacture a right foot set-down for the subject. We observed some near flawless set-downs using this training method. This was a very challenging movement for the athlete, as we were asking him to execute a critical part of the cross-over earlier than he was accustomed to doing it. We were asking him to execute the set-down before he felt he was ready to do it. This placed a large stress on the athlete to try to execute the movement when the system wanted but also to make adjustments so that he was able to execute the movement without crashing.

The plots during this movement varied greatly depending on how the athlete was reacting to the system. In some cases like the one shown in Figure 10 we see that the athlete attempted to start the set-down but reverted back to a more comfortable movement. Results were inconsistent during this training which is expected given the drastic changes we were making to the athlete's movements. More training time was necessary to fully evaluate this method as a solution to our subject's problem.

5.5. Discussion

Due to time constraints with the athlete, we evaluated and proceeded through the training methods very quickly. The skater had attempted many different solutions to the problem prior to our testing. We were familiar with the level of skating the athlete had achieved with other methods and if we determined our method did not produce better results than what we had previously seen we quickly moved on.

We are confident that if we had continued working with the athlete we would have continued to see improvements in the skater's cross-overs. The athlete tried many methods to correct his skating and about our system he commented "This device was the only thing that was able to improve my skating."

The athlete raced a number of times during the two months we were involved with him. The aesthetic improvements he was making did not show up as improvements in racing time. He did not wear the system during racing but did try to incorporate the same things he was working on during our training sessions. In the days leading up to a race we did not work with the athlete as he was busy with race preparations.

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