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Improving the Pedal Force Effectiveness Using Real-Time Sonification

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ABSTRACT The pedal force effectiveness, an important parameter in cycling performance, is rarely optimal. Decreased power is generally observed during the recovery phase (the cyclist does not pull enough). An essential part of training for cyclists consists in improving pedaling technique. Visual feedback can be useful but may not be feasible in real life, where the cyclist has to visually focus on the road. We propose auditive feedback as a better way to help cyclists improve their pedal force effectiveness in real-time. In this study, both competitive cyclists and non-cyclists tested different online sonification strategies of force effectiveness, comparing them to a silent control. The "Squeak" strategy, generating a squeak when torque was negative, had the most positive impact on Torque Effectiveness: some participants managed to eliminate any negative torque for a full minute.

INDEX TERMS Cycling ergometer, movement execution efficiency, torque effectiveness.

I. INTRODUCTION

Enhancing the performance of cyclists in competition depends on various parameters: physiological factors, nutritional strategy, bike design ([1], [2]) and, of course, pedaling technique [3]. The pedal stroke is a complex process consisting of 4 phases: pushing and pulling phases, high and low transitions (transitions which are also called top and bottom dead centres [4]). The most intuitive way to pedal is to transmit power mainly during the pushing phase, leading to loss of power during the pulling and transition phases. Pedaling technique is complex to analyze, forces applied with the feet may not reveal all this complexity [5]. However, measuring these forces is the easiest way to help the cyclist to improve his pedaling technique. This could explain why pedal force sensors are already available on the consumer market, as a solution for training. Analyzing pedaling technique with force sensors could be done through two different techniques. The first way is by examining pedaling efficiency, the ratio of tangential force to the total force applied on the pedal [3], [6]. It is maximal when the pedal is oriented in the same way as the crankset. The other way to evaluate pedaling technique is to analyze the total force applied on the pedal [7]. In a

mechanical point of view, this force should be distributed as evenly as possible during one pedal cycle. In particular during the pulling phase, this force could be negative due to the leg weight.

Effect of pedaling technique on overall performances is not yet proved [8], some authors highlight that the gross efficiency could be reduced if the cyclist modify his pedaling technique [8], [9]. However, we believe that improving pedaling technique will benefited from long-term use, and to proves this benefit it requires complex long-term studies, which is not the aim of this paper. Moreover, some authors [10] believe that an active pull may be beneficial for certain situations, like maximal power sprinting, justifying the need for a training tool.

One way to improve the pedaling technique is to provide information not usually available to the cyclist, using sensory feedback in an augmented reality process. Several studies showed that visual feedback helps to improve pedaling technique [6], [11], [12]. In [6], four different graphical interfaces reporting pedaling efficiency in real-time were tested, with results showing similar benefits for all of them. However, this kind of visual feedback requires the cyclist to focus almost continuously on the screen presenting the information, which seems incompatible with outdoor cycling, where the gaze needs to be on the "road-environment" system. For this

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reason, auditive feedback, usually called “sonification” [13], is proposed in this paper as an innovative way to help the cyclist improve pedaling technique in real-time. It is obvious than using headphones while cycling could be dangerous (even forbidden in some countries). However, alternative devices such as headphones with bone conduction exist and could be a solution. Moreover, since a lot of training takes place with a home-trainer, at the very least sonification could be used indoors even if the safety of cyclists using sonification is not proved. At this experimental step, standard headphones are used because there is no risk for the cyclist, this study only focus on the proof that sonification could be a training tool.

Sonification has already been shown to influence user movement execution. For instance, Thoret *et al.* [14] asked participants to draw a circle without being able to see their hands while a sound evoking an elliptical movement was played. The participants drew elliptical shapes, demonstrating that sound used in real-time could affect the movement. Sonification has also been used to enhance movement execution in sport, especially for rowing [15]–[17]. Sigrist *et al.* [17] studied different concurrent feedbacks in a rowing task, and showed that multimodal feedbacks (including audio) are more effective than visual feedback alone.

Some recent studies have attempted to improve pedaling technique using sonification [18]–[20]. In [18], the authors linearly mapped the crank moment to the frequency of a violin sound. The sound played through the right earphone corresponded to a “reference moment pattern” deduced from elite athletes’ performance, and the sound played through the left earphone corresponded to the pattern produced in real-time. This sonification strategy may have been too complicated for the participants: no clear effect was identified on six cyclists. In [19], [20], the force applied on the pedals was mapped to tones. A pilot study with four cyclists showed that they understood this sonification, but the authors did not clearly assess the beneficial effects of sonification on performances.

Given the encouraging results on sonification in sports and visual feedback in cycling, we aimed here to determine the efficacy of sonification in cycling training. This paper presents two experiments to test different sonification strategies in comparison to a silent control condition: 3 sound conditions were tested for 2-min sessions during the first experiment, and two sound conditions were tested for longer durations during the second experiment. Unlike previous studies [18]–[20] our experiments involved a large panel of participants (more than twenty participants for each experiment) and compared pedaling technique with and without sonification. In this study, only the effect of sonification on pedaling behavior is tested, since the effect of visual feedback have already been proven.

For both experiments, two categories of participants were involved, according to their practice of cycling. Participants of the first group practice a lot (including regular competitions), whereas the second group is composed of participants without any particular practice of cycling (student at the

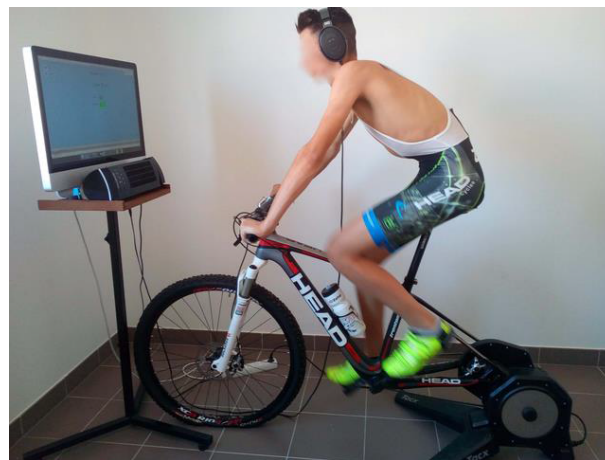


FIGURE 1. Experimental setup. The cyclist looks at the screen to obtain protocol information and cadence.

University or in the lab). Participants of the first group are called “cyclists” [21], and participants of the second group are called “non-cyclists” [22]. Terms proposed by [23] were not used, since most of “cyclists” are less than 18 years old.

II. FIRST EXPERIMENT

The goal of the first experiment was to test three different sounds and to evaluate their effect on pedaling technique. The sonification strategies were not explained to participants, in order avoid any kind of bias towards a strategy.

A. METHODS

1) PARTICIPANTS

12 young cyclists (aged between 16 and 20, mean age 17.6 ± 1.6) belonging to regional biking clubs took part in the experiment. Eight of them were mountain bikers and four were road bikers. All spent more than 5 hours per week cycling, including regular competitions. 16 non-cyclists (aged between 18 and 25, mean age 23.8 ± 3.0) were included in the same experiment. All participants signed an informed consent form in accordance with the Helsinki convention informing them about the conditions of the experiment and their right of withdrawal. The protocol was approved by the institutional review board of the Institute of Movement Sciences. The data were analyzed anonymously.

2) EXPERIMENTAL SETUP

This study was performed on an instrumented bike, a HeadCycle Trenton I-2015 (height 44 cm), using a Home-Trainer Tacx Flux to set the resistance. The crank was a Rotorbike Rex I, measuring the torque applied on the left pedal. The setup presented in Figure 1 was composed of the bike, the home-trainer, and a screen presenting the remaining time and the current cadence. Each participant adjusted the bike seat at his convenience.

The Rotorbike crank uses ANT+ transmission. The “fast-mode” of the Rotorbike crankset was selected to transmit

both angle position and torque applied on the left pedal at 50 Hz, both of which were used for sonification. The latency of the transmission of these data is estimated about 250 ms. The experiment interface was constructed on Mac OS using Max/MSP (a visual programming language), and the sound was played through headphones (Sennheiser HD650).

3) PROTOCOL

The protocol used for this experiment was similar to that used in [6]. The experiment began with a 5-min warm-up at 70 W, followed by a 3-min break. During the experiment itself, the resistance of the Home-Trainer was set to 120 W, and the participants had to pedal at 60 RPM. The screen placed in front of the participant informed the participant of real-time cadence and the remaining time in each session. At the end of the experiment, participants evaluated their perception of the effort on the Borg scale, with ratio properties [24] from 0 to 10 (0 meaning “nothing at all” and 10 meaning “very very strong”).

The experiment was divided into five 2-min sessions, separated by a 3-min break. The first and the last sessions were considered as control sessions and were performed with no sound, that is with no feedback on movement execution (although the participant still wore headphones). These sessions are respectively called “Silence” and “Silence2”. The three other conditions presented three sonification strategies in random order.

The first sonification strategy, called “Squeak”, used auditive feedback to inform the participant in real-time when his movement execution was not successful. As a first approximation based on mechanical consideration, negative torque applied on the pedal was considered as indicating non-optimal movement execution. When the torque was negative, a squeak was generated in real-time, lasting as long as the negative torque. Otherwise, a band-pass noise¹ was generated. Thus, if the pedal force effectiveness was optimal, only band-pass noise was generated. The squeak was synthesized based on a Coulomb Friction model, as presented in [25], [26]. A squeak was chosen because it is unpleasant to hear, so participant would like to suppress this sound. There was no difference in the intensity of the squeak, whatever the negative value of the torque. The band-pass noise had a central frequency of 300 Hz and a quality factor of 3.

The second sonification strategy, called “Dynamic”, aimed to influence the participant’s movement execution, similar to [14], where the sound influences the drawing of shapes. During the descending phase of the pedal, a band-pass noise with a central frequency of 300 Hz and a quality factor of 3 was generated. During the ascending phase, the central frequency exponentially increased from $f_0 = 300\text{Hz}$ to $f_M = 3\text{kHz}$ as a function of time. Just after the highest position was reached, the central frequency decreased more quickly from $f_M = 3\text{kHz}$ to $f_0 = 300\text{Hz}$. The central frequency $f(t)$ is

¹A band-pass noise is a sound with equal intensity at each frequency in a selected frequency band.

defined by the following equations:

$$\begin{cases} f(t) = f_0 * \exp^{\frac{(t-t_0)}{t_M-t_0} \log(\frac{f_M}{f_0})} & \text{if } t_0 > t > t_M \\ f(t) = f_M * \exp^{\frac{(t-t_M)}{t_e-t_M} \log(\frac{f_0}{f_M})} & \text{if } t_M > t > t_e \end{cases}$$

t_0 and t_e are the times corresponding to the lower frequency f_0 , and t_M the time corresponding to the higher frequency f_M . Times t_0 , t_M , t_e were respectively defined in such a way as to correspond to the beginning of the ascending phase (at 180), to the maximal angle (at 360), and to approximately the end of the next upper transition (at 90).

Due to the latency of the system and in order to match sound with angular position, it is necessary to “anticipate” the sound, taking into account a cadence of 60 RPM. According to the estimated latency (0.25 s) and the expected duration of a cycle (1 s), $t_0 = 0.50 - 0.25 = 0.25\text{s}$, $t_M = 1.00 - 0.25 = 0.75\text{s}$ and $t_e = 1.25 - 0.25 = 1.00\text{s}$. The time was reset at each new pedaling cycle.

The third strategy, called “Music”, did not employ full sonification. A song, “Gimme all your Lovin” by ZZtop was played through the headphones. The tempo of this blues song is 120 Beats Per Minute, double the imposed pedal cadence (60 RPM). Thus, the participant could synchronize one foot with the snare and the other with the bass drum. However, the music did not change with the participant’s movement execution, the aim of this strategy simply being to test the effect of a sound played without reference to the participant’s pedaling technique.

Instructions were read by the participants and orally explained by the experimenter before the warm-up. These instructions presented the experiment, stressing the fact that only the left foot could affect the sound and that it was pedaling technique that was being studied. The instructions did not detail the sonification strategies, allowing the pedaling technique to be intuitively adjusted to the sonication.

4) DATA ANALYSIS

The data recorded were sampled at regular time intervals, but this sampling did not enable each cycle or crank position to be analyzed independently of the speed rotation. Therefore, the torque was interpolated in such a way as to be sampled at regular angular intervals. The interpolation was performed in Matlab using the cubic interpolation of the function *interp1* with a 0.5° step.

To assess pedaling technique on each cycle, Torque Effectiveness TE was computed:

$$TE = 100 * \frac{T^+ + T^-}{T^+}$$

with T^+ the total positive torque over the cycle and T^- the total negative torque over the cycle (absolute value). Torque Effectiveness was thus considered 100% if there was no negative torque during the cycle. This indicator of pedaling technique was used in previous studies, such as [7]. Another way to evaluate pedaling technique is to compute Pedal Smoothness, which is the ratio of mean torque to maximal

torque over a cycle. Trends obtained with Pedal Smoothness both here and in the literature [7] were very close to those obtained with Torque Effectiveness; however, we chose Torque Effectiveness since a 100% value is consistent with the goal of this study (no negative torque).

Statistical analysis was conducted with Statistica, on the mean Torque Effectiveness over 30 s at the beginning (from cycle 10 to 40) and at the end (from cycle 80 to 110) of the experiment. Neither the first 10 nor the last 10 cycles were used (to avoid a border effect); nor did we use cycles in the middle (from 40 to 80, considered as an intermediate case between beginning and end). A repeated measures Analysis of Variance (ANOVA) was conducted at the significance level of 0.05, considering the factors “Condition” for the sonification strategy and “Cycles” for the selected period of cycles (beginning or end). “Expertise” was considered as a categorical factor. Post-hoc tests applying the Bonferroni procedure were conducted using a significance level of 0.05.

B. RESULTS

At the end of the experiment, participants gave their general impression and most of them considered that hearing a squeak was unpleasant, confirming the relevance of this sound. We analyze hereunder results on subjective evaluation of effort, cadence, evolution and mean Torque Effectiveness, and finally, average torque.

1) EFFORT: SUBJECTIVE EVALUATION

The effort induced by the experiment was subjectively evaluated at a mean score of 3.0 (“moderate”) for non-cyclists and 1.8 (almost “fairly light”) for cyclists. As the experiment was short (less than 15 min of pedaling), it can be assumed not to have been tiring even for non-cyclists. Participants also provided commentaries on the experiment: many cyclists said that a 60 RPM cadence was too slow and that they were more used to pedaling at 70 or 80 RPM at least.

2) CADENCE

The mean cadence did not significantly differ between the five conditions and two levels of expertise, according to a repeated measures ANOVA. The mean cadence for all conditions and all participants was 61 ± 1.2 RPM, meaning participants cycled a bit faster than specified in the instructions.

3) EVOLUTION OF TORQUE EFFECTIVENESS

The temporal evolution of Torque Effectiveness is shown in Figure 2. There was a settling time at the beginning of the experiment, especially for non-cyclists: Torque Effectiveness rapidly increased from cycles 0 to 10. For instance, Torque Effectiveness for the non-cyclists in the Squeak condition went from 86% to 93% during the first cycles. For cyclists, Torque Effectiveness in the Squeak condition was above 93% most of the time, whereas it was below 91% most of the time in the Silence condition. For non-cyclists, Torque Effectiveness was also generally highest in the Squeak condition.

TABLE 1. Results of ANOVA on mean Torque Effectiveness during the first experiment: Sum of Squares (SS), degrees of freedom (df), Mean Square (MS), F-value, p-value, partial eta-square (η_p^2). * mean a significant effect at level of 0.05.

	SS	df	MS	F	p	η_p^2
Exp	534	1	534	2.34	0.138	0.082
Cyc	87	1	87	11.62	0.002*	0.309
Cyc*Exp	34	1	34	4.51	0.043*	0.148
Cond	519	4	130	8.23	<0.001*	0.240
Cond*Exp	54	4	13	0.85	0.495	0.032
Cond*Cyc	13	4	3	0.69	0.602	0.026

However, unsurprisingly, pedaling technique varied more for non-cyclists than for cyclists with time: in all conditions, Torque Effectiveness decreased, meaning that the non-cyclist participants were unable to maintain their pedaling technique over time. Still for non-cyclists, the decrease was greatest in the Dynamic condition: Torque Effectiveness reached 93.5% at cycle number 10, and then fell to 86% by the end of the experiment.

4) MEAN TORQUE EFFECTIVENESS

Results of the ANOVA computed on the mean Torque Effectiveness are presented in Table 1. There was a significant effect of Condition ($F(4,104)=8.23$; $p<0.001$) and of Cycles ($F(1,26)=11.62$; $p=0.002$). There was a significant interaction between Cycles and Expertise ($F(1,26)=4.51$; $p=0.043$). The size of these three effects was “substantial according to Cohen classification ($\eta_p^2 > 0.14$). These results confirm the previous observations.

Detailed results are presented in Figure 3, reporting mean Torque Effectiveness by condition. Torque Effectiveness in the Squeak condition was significantly higher than in all the others except the Dynamic condition. Mean Torque Effectiveness was 93% for the Squeak condition, 89% for the two Silence conditions and 90% for the Music condition. Torque Effectiveness in the Dynamic condition was significantly higher only than in the Silence condition, with a mean value of 91%. The Squeak strategy therefore stands out as the best, with the Dynamic strategy helpful to the participants but to a lesser degree.

The right-hand side of the Figure 3 shows mean Torque Effectiveness according to Expertise and Cycles. The effect of Cycles is particularly visible for non-cyclists, with a significant difference between cycles 10 to 40 and cycles 80 to 110, best pedaling technique being reached during the first cycles. For cyclists, differences in mean Torque Effectiveness according to Cycles were not significant.

5) AVERAGE TORQUE

To illustrate the influence of the different sonification strategies, the average torque for cycles 10 to 40 for all participants is represented in Figure 4. We consider the first cycles as representing the best case, and group participants together since

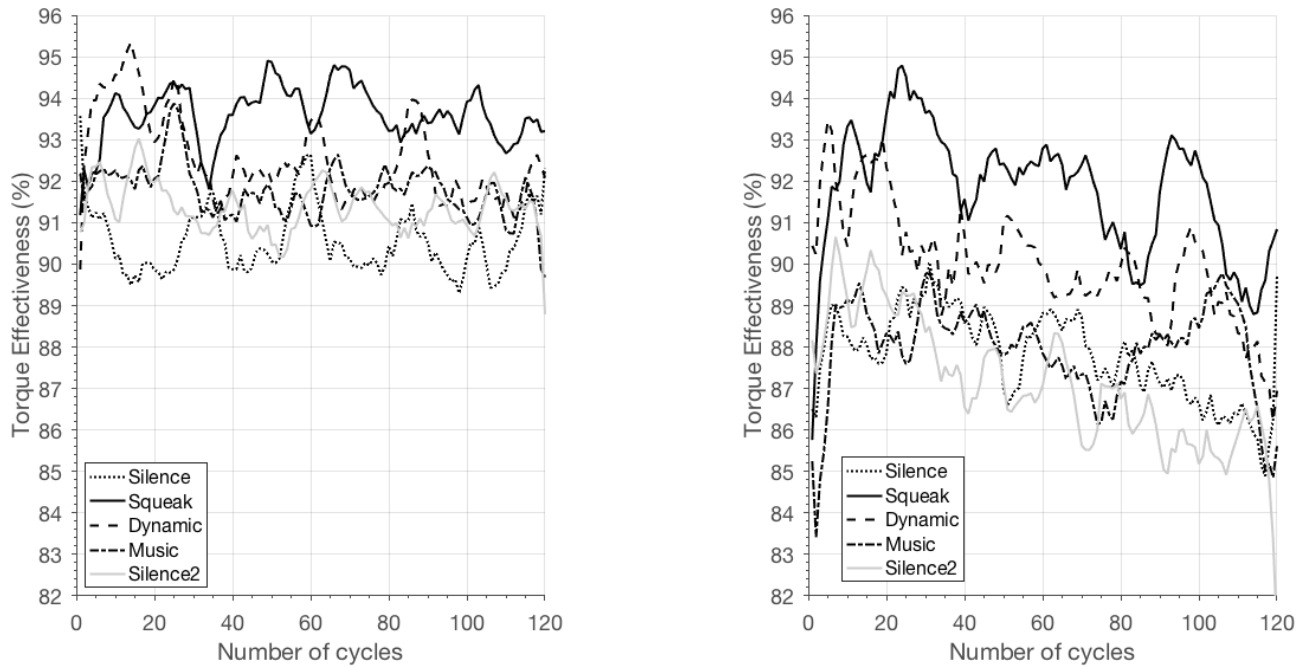


FIGURE 2. Evolution of Torque Effectiveness over 120 pedaling cycles according to the five sonification strategies, average over cyclist participants (left panel) and average over non-cyclist participants (right panel).

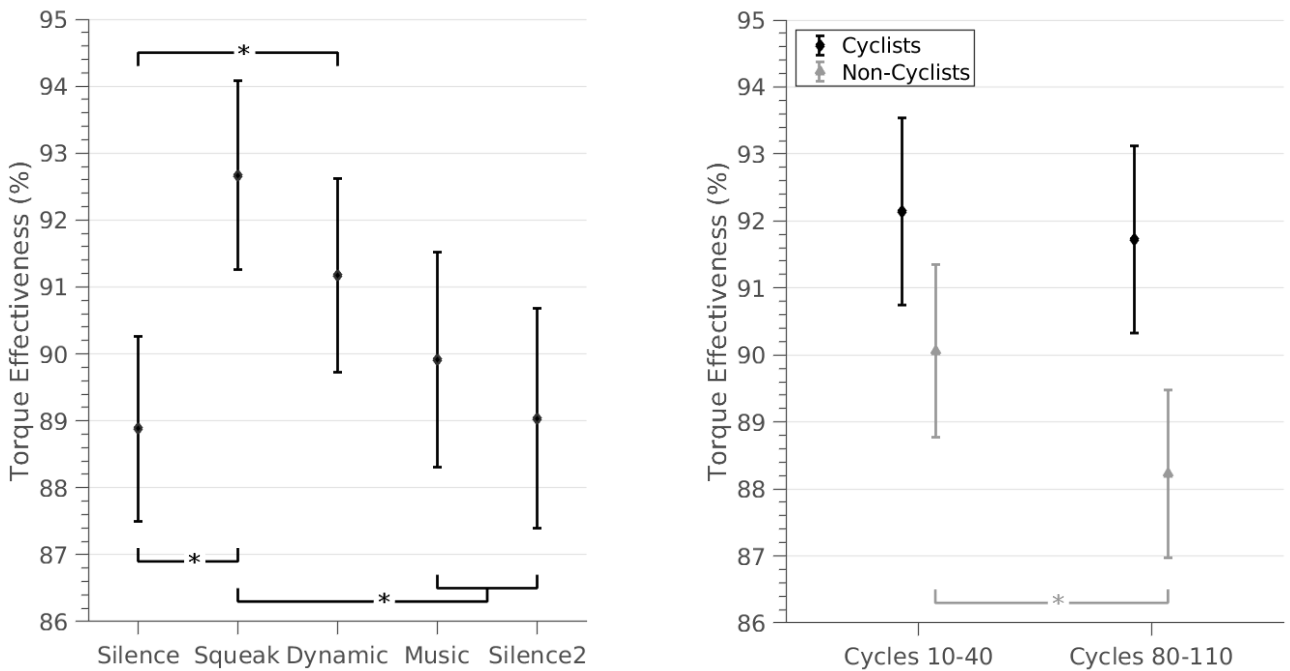


FIGURE 3. Mean Torque Effectiveness according to condition (left) and according to Cycles and Expertise (right). Error bars refer to a confidence interval of 95%. * means significant differences according to post-hoc tests with Bonferroni procedure, at a significance level of 0.05.

there were no significant differences according to Expertise. Cycle and Expertise effects have previously been presented; average torque is given here as a supplementary illustration.

Naturally, the torque during the pushing phase was far greater than the torque during the pulling phase. The torque was always greater than 35 Nm around 80°, and always less than

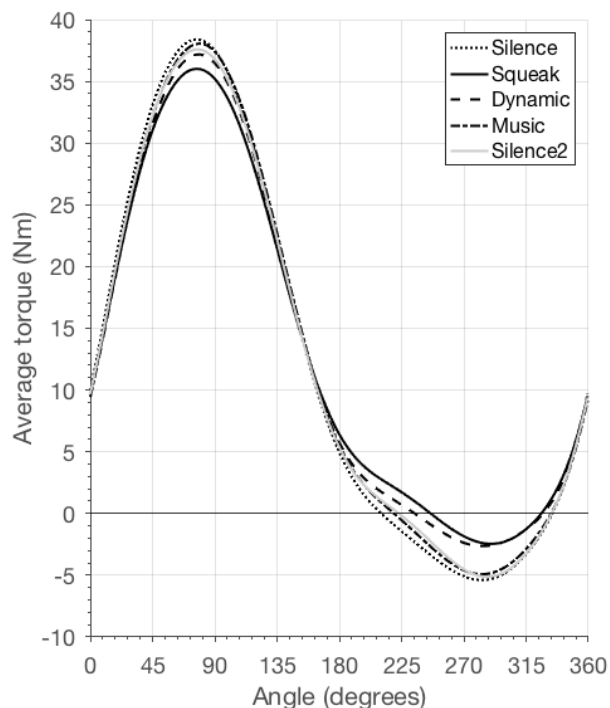


FIGURE 4. Average torque across cycles 10 to 40 and all 28 participants according to the angular position of the pedal.

−2 Nm around 280°. Analysis of average torque revealed the same trend as for Torque Effectiveness: the Squeak and Dynamic conditions produced similar results and outperformed the other three conditions. In the Squeak and Dynamic conditions, the minimum average torque value increased by 3 Nm. The average torque in the Squeak condition was, however, slightly higher than in the Dynamic condition, between 180° and 270°, making the Squeak strategy slightly better than the Dynamic strategy. Yet even with the best sonification strategy, torque was negative during the ascending phase, showing that sonification was not yet optimal.

C. DISCUSSION

The goal of this experiment was to test different sonification strategies while participants were given no explanation of the sonification procedure. Beginning with the participants' subjective evaluation, which shows that they did not find the experiment tiring, the specific effects of the different conditions can be assessed.

The major finding from this experiment is that sonification significantly modified pedaling technique whatever the degree of participants' expertise. Although the data are not the same, the evolution of results presents the same trend than in [6], indicating that our sonification strategy may be an effective way to improve pedaling technique.

The Squeak strategy worked best, increasing mean Torque Effectiveness by four percentage points compared to the no-sound conditions. This strategy provides almost in real-time information on potential error, allowing the participant to adjust his technique on the next pedal cycle. It is not clearly

“real-time”, since the latency of the setup is estimated to be about 250 ms. However, despite this latency results were very encouraging. Due to the repeatability of the rhythmic pedaling movement and the simplicity of the feedback, the latency of 250 ms was not decisive. Despite the latency, the sonification definitively allows the cyclists to detect errors and correct them during the next cycle. The choice of this strategy could have been the opposite (a pleasant sound for a successful movement execution), but we believe it wouldn't have been better. Indeed, this kind of “error sonification” previously yielded interesting results in another context, for body alignment in a gymnastic task [27].

The Dynamic strategy worked to a lesser extent, mean Torque Effectiveness increasing by two percentage points compared to the no-sound conditions. This strategy, based on the promising results of [14], provides information on how to execute the movement but not on its success. Thus, the participant may mistakenly think his movement execution was successful, and in the subsequent cycles may not try to improve his technique. Moreover, as only one foot is sonified, the participant may interpret the sound for the right foot, whereas it is dedicated to the left foot. A consequence of this interpretation is that the sound could induce a higher pushing phase of the right foot, whereas the initial goal was to induce a higher pulling phase of the left foot. Further refinement of this kind of sonification is needed before better results can be obtained.

Results for the Music strategy were close to those without sound, indicating that pedaling technique is only enhanced when the sound contributes relevant information. The music did indicate the pace, but participants already had this information on the screen, and repeating it through the music did not have a significant effect on mean cadence.

There were no significant differences according to participant expertise, which indicates that the information provided by the sonification was clear to everyone. It should be expected that cyclists would have a better pedaling technique, but our results did not prove it. Nowadays, little training is given on pedaling technique due to limited availability of the technical means required. Sonification might be an easy way to provide the training needed in the coming years.

A significant effect of Cycles and its interaction with Expertise were identified, Torque Effectiveness being higher at the beginning of sessions. A Torque Effectiveness decrease with time was particularly noted for non-cyclists. A similar observation was made in [6], where visual feedback helped naïve cyclists to improve their Instantaneous Efficiency index, but with a significant decrease over 2 min. As stated in [6], modifying pedaling technique is complex, and may tire people who are not accustomed to using specific muscles. In contrast, the Torque Effectiveness of our cyclists were stable over time: cyclists are better aware of their capacities than non-cyclists, and are more consistent in their effort.

These results raise the new question of the maximum possible duration of high Torque Effectiveness for cyclists, requiring a new protocol. Moreover, different Torque Effectiveness

was reached for cyclists and non-cyclists. Movement execution being linked to many parameters (such as level of expertise), we can assume that the threshold triggering the squeak needs to be individually set. One way of selecting this threshold is with reference to past movement executions.

III. SECOND EXPERIMENT

In our first experiment, sonification appeared to have a significant effect on participants' pedaling technique. The Squeak strategy worked best, but the effect was dependent both on skill level and on duration. Cyclists were able to improve their Torque Effectiveness for at least two minutes, unlike non-cyclists participants. The non-cyclists' decrease in Torque Effectiveness over time raises the question of the longer-term effect of sonification on cyclists. To test this, we performed a similar experiment involving longer cycling times. We also added an adaptive version of the Squeak strategy related to past values of Torque Effectiveness.

A. METHODS

1) PARTICIPANTS

Twelve cyclists aged from 16 to 50 (mean age 22.6) took part in the second experiment. Seven had participated in the first experiment, five were cross-country cyclists, five were road cyclists and two were triathletes. Twelve non-cyclists aged from 19 to 38 (mean age 25.8), five of whom had participated in the first experiment, took part in this experiment. All participants signed an informed consent form in accordance with the Helsinki convention informing them about the conditions of the experiment and their right of withdrawal. The protocol was approved by the institutional review board of the Institute of Movement Sciences. The data were analyzed anonymously.

2) PROTOCOL

The same experimental setup as for the first experiment was used. The protocol was similar, starting with a 5-min warm-up at 70 W, followed by a 3-min break. As cyclists had mentioned during the first experiment that the 60 RPM cadence was too slow, for this experiment the cadence was increased slightly, to 70 RPM. As shown in [3], pedal efficiency decreases with cadence, and increases with resistance. To try to minimize the predictable decrease of Torque Effectiveness due to increased cadence, the resistance was also increased slightly, from 120 W to 130 W.

To test the "long-term" effect of the sonification, sessions were longer than in the first experiment: 8 min for cyclists, with a 10-min break between sessions. However, some pre-tests indicated that this was too long for non-cyclists, who were unable to maintain power production.

Non-cyclists were therefore given a shorter version: only pedaling for 5 min per session, with a 10-min break between sessions. Thus, protocols and analysis differed according to participants' cycling expertise.

Three conditions were tested:

- "Silence": without any sound.
- "Squeak": as in the previous experiment, a squeak was generated when the torque applied on the left leg was negative. Unlike the first experiment, however, there was no sound otherwise.
- "Adaptive Squeak": a squeak was generated when the torque applied on the left pedal was below an adaptive level. This level was initialized at 0 Nm, increasing (respectively decreasing) by 0.5 Nm if, during the three previous cycles, the torque was above (respectively below) the level.

To minimize any possible ordering bias, the six possible permutations were presented the same number of times. As with the first experiment, instructions were read by the participant and orally explained by the experimenter before the warm-up. In contrast to the first experiment, however, participants were clearly instructed to adapt their cycling technique so as to avoid squeaking.

3) DATA ANALYSIS

The measured data are interpolated in the same way than for the first experiment. As for the first experiment, the statistical analysis is conducted on the mean Torque Effectiveness, but the mean is computed over a longer period of time (60 s). Mean Torque Effectiveness took into account the beginning (from cycle 10 to 70) and the end (from cycle 440 to 500 for cyclists and from cycle 260 to 320 for non-cyclists) of the experiment. For cyclists, we also used cycles from 260 to 320.

Two repeated measures Analysis of Variance (ANOVA) were conducted at the significance level of 0.05: one for cyclists, and one for non-cyclists. Both ANOVA considered factors "Condition" for the sonification strategy and "Cycles" for the selected period of cycles.

B. RESULTS

Data were processed in the same way as for the first experiment. The following analysis presents separate results for cyclists and non-cyclists, since the lengths of their experimental sessions were different.

1) EFFORT: SUBJECTIVE EVALUATION

As in the first experiment, the participants evaluated their perception of effort according to the Borg scale. The mean score was 5 ("hard") for non-cyclists and 3 ("moderate") for cyclists. Thus, the second experiment was slightly more tiring than the first, unsurprisingly given the greater pedaling time, cadence and resistance. It appeared particularly hard for non-cyclists to cycle longer.

2) EVOLUTION OF TORQUE EFFECTIVENESS

The evolution of Torque Effectiveness is represented in Figure 5. Once again, it differed according to level of expertise, being more variable for non-cyclists, in particular with the Squeak strategy. For non-cyclists, Torque Effectiveness

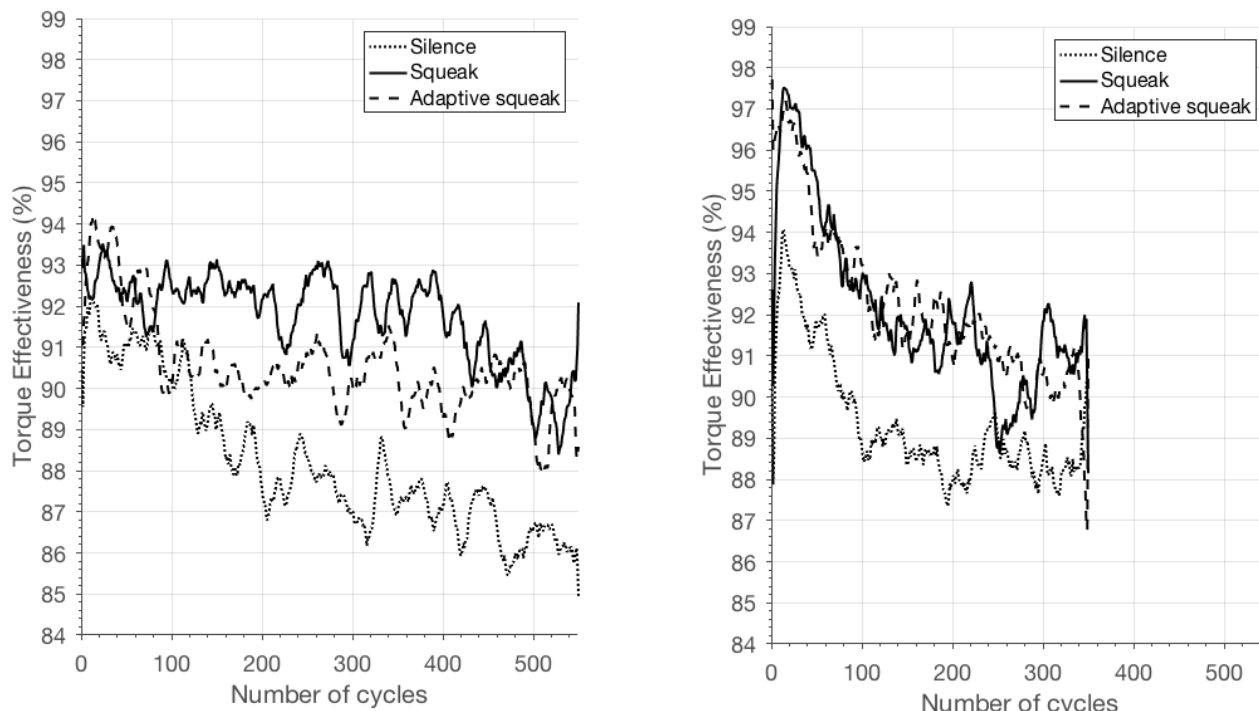


FIGURE 5. Evolution of Torque Effectiveness over the experiment: cyclists (left) and non-cyclists (right). Results are smoothed using a 15-point moving average.

reached 97% during the first cycles, then decreased and stabilized around 91% during the last cycles. For cyclists, Torque Effectiveness was less variable, between 89% and 94%.

3) MEAN TORQUE EFFECTIVENESS

TABLE 2 shows the results of the two repeated measures ANOVA (one for cyclists and one for non-cyclists). For both cyclists and non-cyclists, Cycles had a significant effect (respectively $F(2,11)=14.62$ and $F(1,11)=45.31$, $p<0.001$), and Condition had a significant effect (respectively $F(2,22)=6.13$, $p=0.008$ $F(2,22)=6.32$, $p=0.007$) too. Moreover, the interaction between Condition and Cycles had a significant effect for cyclists ($F(4,11)=2.64$, $p=0.046$), but not for non-cyclists ($F(4,11)=0.38$, $p=0.687$). For the five cases which were significant, the size of the effect was substantial according to the Cohen classification ($\eta_p^2 > 0.14$).

Figure 6 shows the results, representing mean Torque Effectiveness for the three conditions and the different periods of cycles.

For cyclists, post-hoc tests revealed significant differences between the Silence condition during cycles 440 to 500 and all other configurations (condition / period), with the exception of the Silence condition during cycles 260 to 320. Mean Torque Effectiveness was lowest in the Silence condition during cycles 440 to 500, at 86.5%. The effect of longer-term cycling is thus particularly visible with the Silence condition: cyclists were able to improve their pedaling technique as

TABLE 2. Results of ANOVA on mean torque effectiveness for the second experiment with the same notation than table 1.

Cyclists	SS	df	MS	F	p	η_p^2
Cycles	196	2	98	14.62	<0.001*	0.571
Cond	250	2	125	6.13	0.008*	0.358
Cond*Cycles	50	4	13	2.64	0.046*	0.193
Non-cyclists	SS	df	MS	F	p	η_p^2
Cycles	384	1	384	45.31	<0.001*	0.805
Cond	124	2	62	6.32	0.007*	0.365
Cond*Cycles	7	2	13	0.38	0.687	0.034

instructed, but found it difficult to maintain this improvement without sonification. For cycles 10 to 70, there were no significant differences between conditions, but sonification led to a two percentage point improvement in mean Torque Effectiveness, which reached over 93% in the Adaptive Squeak session.

For non-cyclists, the ANOVA did not yielded a significant effect of the interaction, but it is represented in Figure 6 to be consistent with cyclists. Still for non-cyclists, post-hoc tests revealed that mean Torque Effectiveness is higher during cycles 10 to 70 than during cycles 260 to 320, and mean Torque Effectiveness is higher during the Squeak and Adaptive Squeak than during the Silence condition. In particular, mean Torque Effectiveness during the Squeak condition from cycles 10 to 70 is 96%.

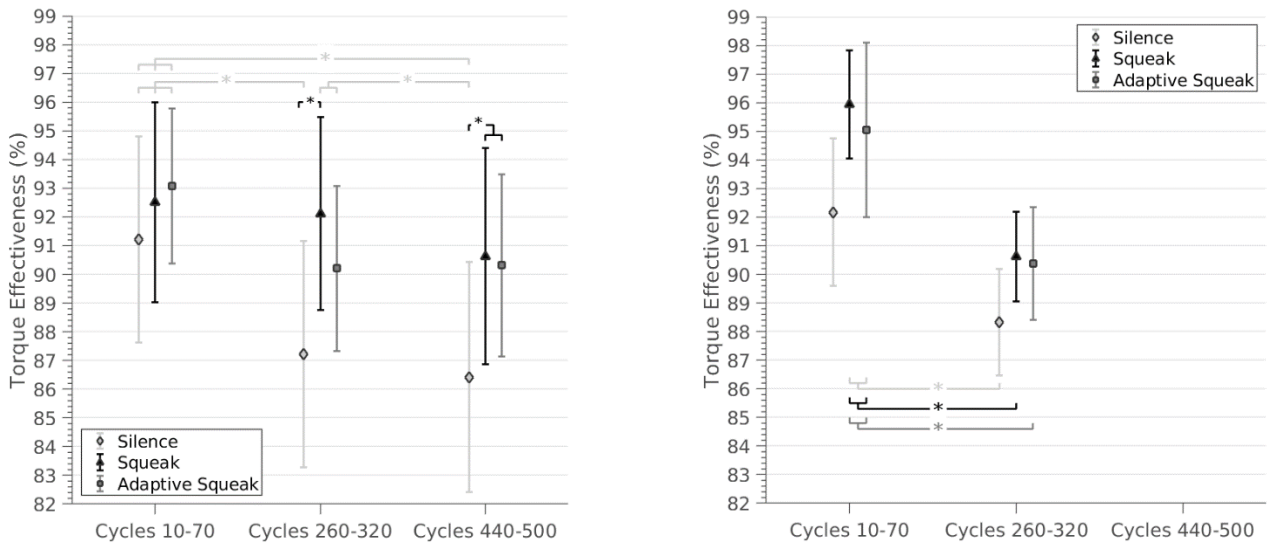


FIGURE 6. Mean Torque Effectiveness over 60 cycles according to condition: cyclists (left) and non-cyclists (right). Error bars refer to a confidence interval at 95%. * means significant differences at 0.05 level according to post-hoc tests with Bonferroni procedure. Both figures show the interaction between Cycles and Condition, but the ANOVA did not yielded a significant effect of this interactions for non-cyclists.

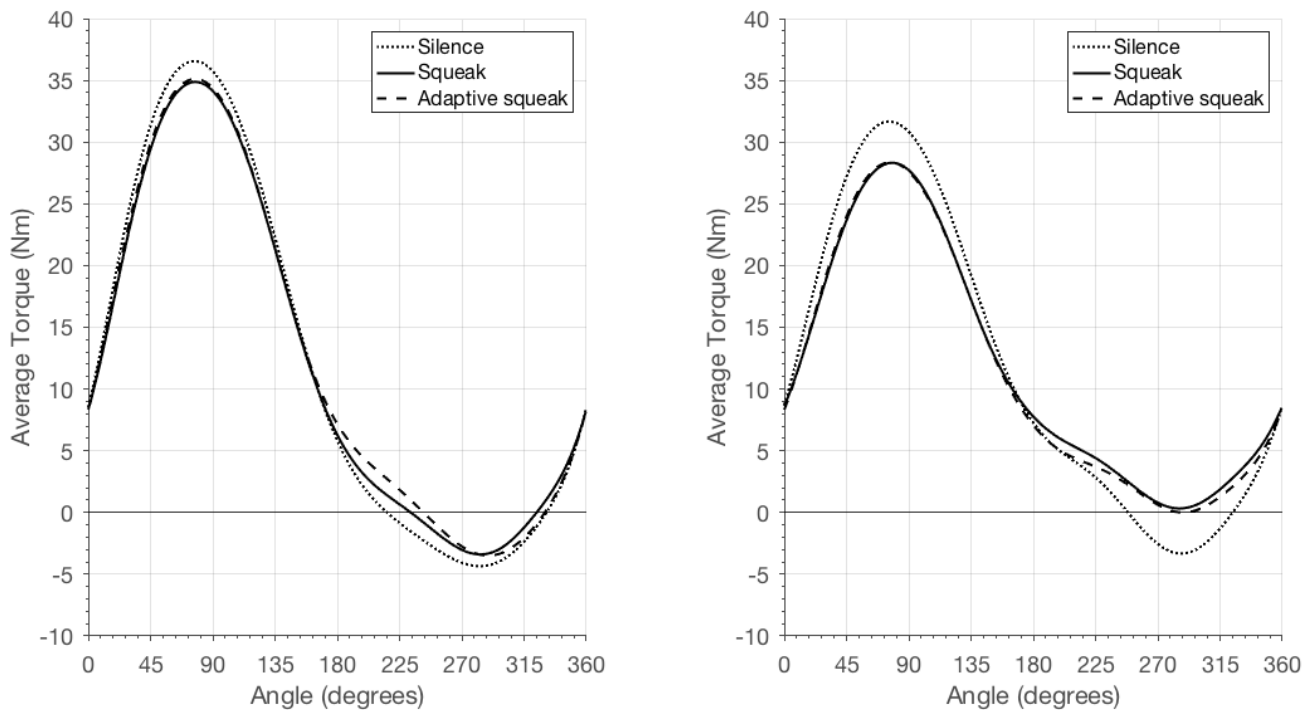


FIGURE 7. Average Torque across cycles 10 to 70 for 12 cyclists (left) and 12 non-cyclists (right) according to the angular position of the pedal.

4) AVERAGE TORQUE

Since Torque Effectiveness was the highest during cycles 10 to 70, Figure 7 shows the mean torque from cycles 10 to 70 alone. As previously, only slight differences between conditions were observed for cyclists: maximum torque was 37 Nm during the Silence condition and 35 Nm during the sonification conditions. The differences according to condition were more marked for non-cyclists: maximum torque was higher for the Silence condition than for the sonification

conditions, respectively 32 Nm and 28 Nm. Similarly, minimum torque was lower for the Silence condition than for the two others, respectively -3 Nm and 0 Nm, suggesting that sonification is an effective strategy for avoiding negative torque.

C. DISCUSSION

The goal of this experiment was to test the effect of the Squeak sonification strategy on pedaling technique when

sessions were longer than in the first experiment, as well as to test an adaptive sonification strategy. The beneficial impact of sonification was once again demonstrated. The effect on cyclists differed slightly from that on non-cyclists; however, the difference in length between the two groups' experimental sessions may explain this.

For cyclists, the effect of the sonification was mainly visible at the end of the session. For cycles 440 to 500, Torque Effectiveness was significantly higher in sonified sessions (90.5%) than in the Silence session (86.5%). However, during the first cycles, contrary to the first experiment, the Torque Effectiveness improvement was not significant, while Torque Effectiveness in Silence (91%) surpassed the one of all participants in the first experiment (89%). It is true that cadence and resistance were different for the two experiments, which could be expected to lead to different degrees of improvement in pedaling technique [3]. Yet Torque Effectiveness in the silent control condition appear to have been better from the outset in the second experiment. One possible explanation may be a learning effect: more than half the participants were involved in the first experiment, and could have memorized an effective movement execution. Moreover, the Silence condition was randomly presented, thereby possibly benefiting from an order effect. A participant beginning the experiment under sonification would have had the opportunity to learn a pedaling technique and memorize it, so as to be able to reproduce it even without sound and thus start the Silence condition session with high Torque Effectiveness.

For non-cyclists, the Squeak and Adaptive Squeak strategies yielded a mean Torque Effectiveness exceeding 96% during the first 60 cycles, with average torque always positive: the initial goal was reached. Surprisingly, the Torque Effectiveness surpassed those of the cyclists. The different lengths of time the two groups pedaled should, however, be borne in mind when comparing their results. As the required movement execution may be unnatural, cyclists, who should be better aware of their capacities may not try something they will not be able to maintain. Moreover, cyclists who have been training several times a week for many years are used to pedaling in a specific way, which may not be the best one. Having automatized and stabilized their movement execution, it is not easy for them to rapidly change their way of pedaling. They may need more time to learn how best to modify their technique. So the use of longer session than the first experiment and than [6] is limited to train cyclists to pedaling technique. Maybe a repetition of short sessions should be a preferable approach.

The non-cyclists' Torque Effectiveness quickly worsened, indicating that they could not maintain this movement execution. This way of pedaling is not intuitive and could be more tiring or attention-demanding than the standard technique. This was confirmed by the subjective evaluation, where the RPE was 5 ("hard" effort) although the experiment was quite easy (130 W, 70 RPM for 3 × 5 min).

For both cyclists and non-cyclists, mean Torque Effectiveness under the Adaptive Squeak strategy did not differ

TABLE 3. Summary of the main parameters of both experiments.

	1 st Experiment	2 nd Experiment
Power	120 W	130 W
Cadence	60 RPM	70 RPM
Sessions length	2 min	5 min / 8 min (cyclists)
Number of sessions	5	3
Cyclists	12	12
Non-Cyclist	16	12

significantly from that under Squeak. Setting the level adaptively therefore had no influence on movement execution, possibly because this adaptive setting allowed the participant to remain in his "comfort zone", without having to try harder. One way of inciting participants to greater effort might be to choose the adaptive setting differently (for example, increasing the level after only one successful cycle). Another possibility would be for a third party (for example, the coach) to fix the adaptive level based on previous values of Torque Effectiveness.

This experiment (and the first one) highlighted differences between "cyclists" and "non-cyclists" which is a very basic cyclist categorization (as example, more groups are used in [23]). In particular, one can expect differences between road bikers and mountain bikers, as in [28].

Finally, both experiments focus on improving mechanical aspects of the pedaling technique. As mentioned in the introduction, the link between overall performances and pedaling technique has not yet been established, and was not the goal of this study. Further works should be necessary, in particular to assess the muscular consequences of the sonification process. As shown in [10] with a visual feedback, an effective pedaling technique increases the activity of Biceps Femoris long head, Gastrocnemius Medialis, Rectus Femoris and Tibialis Anterior.

IV. CONCLUSION

This paper presented two experiments assessing the use of sonification to improve pedaling technique. TABLE 3 summarizes the main parameters of both experiments. During the first experiment, both sonification strategies led to improved Torque Effectiveness, the Squeak strategy working best. As a further step, a second experiment was performed, focusing on the Squeak strategy and adding an adaptive version. Results for non-cyclists at the beginning of the second experiment were excellent, with average torque always positive. For cyclists, Torque Effectiveness in the sonified sessions was significantly higher than without sonification during the later cycles. Cyclists have their own pedaling habits that it would probably take longer than the time allowed in the experiment to change. Long-term training could be useful for both cyclists and non-cyclists, and will be explored as an extension of this work.

It would also be necessary to compare overall performances using this technique, as well as to apply sonification under real-life conditions. Indeed, modifying pedaling technique implies a different use of muscles than for a basic pedaling, and could induce more fatigue.

Moreover, since we observed differences according to the basic cyclist's level (cyclists vs non-cyclist), in further works it could be interesting to compare the influence of the sonification according to cyclist practice (such as a comparison between road cyclists and mountain bike cyclists).

The proposed tool could be useful to improve sprints, but we used slow cadences (60 and 70 RPM), whereas cadences during maximal power sprinting could be much higher. However, our setup did not allow us to test high cadences: the latency of the setup was about 250 ms, which is a quarter turn at 60 RPM. At higher cadences, the delay between the leg position and the emitted sound could be too high to be understood by cyclists. Another study should be conducted with another setup with less latency, to assess the influence of the latency.

Finally, to validate the hypothesis that sonification is an interesting *in-situ* real-time solution, auditive and visual feedbacks should be compared both in terms of change in pedaling behavior and cognitive load. Both feedbacks could also be combined, to take advantage of both. While this *in-situ* validation is not conducted, this solution should only be used indoors.

As a general conclusion, this paper presents an innovative training tool to influence the cyclist's movement execution, but there are some limitations and should be fixed in further studies.

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