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# Developing an Integrated VR + Musical Feedback System for Stationary Biking in Endurance Training

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Stationary biking is a common endurance training activity in the motor rehabilitation of neurological patients. Regular and intense training is crucial to eventual patient outcomes, but the activity itself is traditionally a monotonous one. In recent years, the potential of interactive virtual reality (VR) and musical feedback to enhance motor performance and motivation has been established, but there is a lack of proven training paradigms that optimally combine them to benefit patients. In this work, we iteratively developed an integrated multimodal interactive system to provide individualized VR and musical feedback in real time with the goal of boosting motivation and modulating pedaling intensity over a training session. The concept was initially realized by coupling two independent systems for VR and musical feedback on cumulative and instantaneous pedaling intensity respectively. The coupled systems were tested in a pilot study with 11 participants, and the overall paradigm was found to be usable and motivating with room for technical and design-specific improvement. In a second iteration of development, the systems were robustly integrated and the feedback design was streamlined to primarily inform on a single variable - cumulative pedaling intensity. With this new system built for individualized feedback delivery, the efficacy and clinical potential of the concept and system will be systematically evaluated in future work. The eventual results will, in our estimation, contribute to a growing body of knowledge on how best to leverage the potential of multimodal interactive systems in motor rehabilitation.

CCS Concepts: • **Do Not Use This Code → Generate the Correct Terms for Your Paper**; *Generate the Correct Terms for Your Paper*; Generate the Correct Terms for Your Paper; Generate the Correct Terms for Your Paper.

Additional Key Words and Phrases: Rehabilitation, VR, Music, Multimodal, Interaction, Cycling

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## 1 INTRODUCTION

For several patient groups, exercise-based motor rehabilitation methods are known to be beneficial in enhancing balance, strength, flexibility and coordination [15]. Functional improvements are maximized when exercise practice is meaningful and involves repetition, sufficient intensity, and task-relevant feedback [5, 24]. A common activity in lower limb rehabilitation and endurance training is stationary biking as involves a controllable physical workload and employs safe equipment [2]. It can facilitate a large number of flexion and extension repetitions in the lower limbs [2] while contributing to maintaining and regulating specific balance coordination patterns [15]. In recent decades, the adoption of low-cost computer technologies for monitoring movements and creating realistic environments for personalized activities has been on the rise [10]. *Virtual reality (VR)* training is a specific type of intervention for therapeutic purposes that incorporates training protocols and visual feedback to deliver an interactive and immersive experience [3, 13]. Recent studies have shown how VR-based cycling paradigms can improve balance [25], reduce quadriceps pain [22], and increase motivation [11] relative to conventional training. At the same time, the positive effects of music during exercise have been well documented; while even passive music listening can reduce perceived exertion and enhance enjoyment [16], it has been shown that interactive real-time engagement with musical stimuli during exercise can help motivate, monitor, and modify movement [14] while also reducing perceived exertion and pain [6]. The auditory route is well-suited to providing real-time feedback on movement due to its temporal resolution [7] as well as strong neural connectivity between the auditory and motor areas [12]. The combination of musical and VR-based feedback for promoting physical activity is therefore an interesting proposition. Studies have found that integrating traditional music therapy with VR results in enhanced motor performance in patients [1, 4, 8], in line with with existing knowledge of the benefits of multimodal learning [19] and the potential of congruent crossmodal stimuli to elicit stronger internal representations of physical phenomena including bodily movement [20]. Even so, there have not been many cycling-specific VR + musical feedback paradigms developed, which raises questions as to how these paradigms should be optimally designed and implemented as technological systems for real-world use. The goal of this work was to develop an intuitive and motivating VR + musical feedback design concept and implement it into an integrated system for the delivery of individualized real-time feedback on PI.

## 2 ITERATION 1 - PROTOTYPING AND PILOTING

### 2.1 Design Concept

The interaction design objective was to display instantaneous and cumulative PI as a real-time combination of crossmodal stimuli in order to promote motivation and modulate PI as per clinical goals. Leveraging the positive relationship between PI and translational speed in real-life cycling, we decided to map instantaneous PI during stationary biking to the speed of a virtual bike on a track circuit. The setting was a picturesque virtual environment experienced from a first-person perspective with pre-recorded music in the background. User PI was modulated through the enforcement of a *target* PI represented by a rabbit hopping in front of the virtual bike, whose translational speed and displacement respectively represented instantaneous and cumulative target PI. The defined user goal was to pedal so as to stay close to the rabbit for the training duration without overtaking it. Additional real-time feedback on instantaneous PI was provided to encourage consistent sustained maintenance of the desired PI, and this was done as follows:

- Visual Changes: The colour of the sky changed depending on whether the user cycled too fast (yellow), too slow (dark blue), or within an acceptable PI range (light blue).
- Musical Changes: The playback rate of the pre-recorded music reflected whether the user cycled too fast (sped-up music and raised pitch), too slow (slowed-down music and lowered pitch), or within range (normal-sounding music) based on a straightforward *speed - tempo* metaphor.

### 2.2 Prototype System

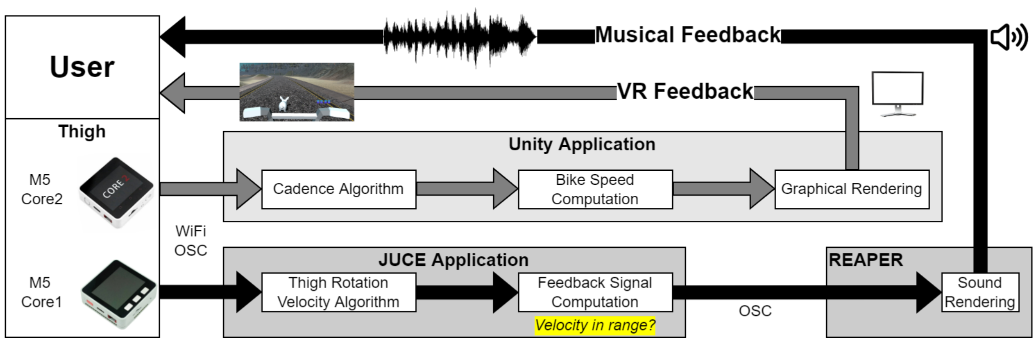


Fig. 1. Overview of the system combination used in Iteration 1.

We combined two independent systems responsible for generating the VR-based and musical feedback loops, depicted in Fig. 1 with grey and black arrows respectively. As shown, two thigh-mounted inertial sensors transmitted via *Open Sound Control (OSC)* to separate PC applications that generated the respective feedback stimuli and delivered them to the user as follows:

- VR Feedback Loop: An M5Stack Core2[1] sensor transmitted 3D accelerometer and gyroscope data to *PedaleoVR*, a Unity3D application [18]. PI, as captured by average cycling cadence was computed using peak detection on the sagittal gyroscope reading and linearly mapped to the speed of the virtual bike. The speed of the rabbit was fixed at a value corresponding to a target cadence of 60 RPM.
- Musical Feedback Loop: An M5Stack Core1[2] sensor transmitted its own 3D accelerometer / gyroscope data to a JUCE-built application for real-time movement sonification [9], where PI was computed as an aggregated thigh rotation velocity signal by applying half-wave rectification, low-pass filtering, and envelope following to the raw sagittal gyroscope reading. The output was compared to a range corresponding to the target cadence in the VR loop and sent to REAPER[3] to control the playback rate of a pre-imported music track.

### 2.3 Pilot Test and Findings

We conducted a short pilot test to assess the basic working of the system combination and the usability of the combined sensory feedback. A convenience sample of 11 individuals (7 women, 4 men, mean age 26.3 ± 5.5 years) consented to participate. With the M5Core1 and M5Core2 sensors respectively placed on the lateral and anterior thigh of the same leg, each participant was instructed to closely follow the rabbit and subsequently cycled for 3 minutes while receiving

[1]https://shop.m5stack.com/products/m5stack-core2-esp32-iot-development-kit?variant=35960244109476
[2]https://shop.m5stack.com/products/grey-development-core?variant=16804796006490
[3]https://www.reaper.fm/

the VR and musical feedback (selected song - *Barbie Girl* by Aqua) from a monitor screen and loudspeaker respectively. Following this, the participants filled out a questionnaire containing basic demographic information followed by the Presence Questionnaire [23] combined with items covering usability and motivation (scale-based and long-form).

The median Presence Questionnaire rating was relatively high (109.5/133, interquartile range 102.5 - 114), in particular for the sub-items *realism*, *possibility to act* (i.e. perceived agency), *sound*, and *self-evaluation of performance*. In terms of overall satisfaction, a median of 5/5 (interquartile range 4.5 - 5), was obtained.. Additionally, the feasibility of using the system for a 20-30 min training session received a median rating of 4.0/5. The participants generally felt that the main sources of motivation and most useful feedback sources for PI maintenance respectively were (1) performing the exercise correctly, (2) following the rabbit and (3) the musical feedback. From the long-form responses, participants were seemingly divided on which feedback modality they found most useful, and they expressed that finding the right PI to maintain could be difficult until they were accustomed to the feedback. Relating to the use of independent systems for VR and music, we noted some issues and potential improvements:

- The short-term cadence (mapped to virtual bike speed) and the thigh rotation velocity (music playback rate) were not always strongly correlated, sometimes leading to incongruent crossmodal feedback.
- The feedback on cumulative and instantaneous PI sometimes contradicted each other, for instance speeding up to catch up with the rabbit led to negative musical feedback being triggered (sped-up music) and vice versa.
- The virtual bike speed could not be individualized to suit different user PI baselines, and the rabbit speed (target PI) was static over the entire session.

## 3 ITERATION 2 - INTEGRATED SYSTEM DEVELOPMENT

In Iteration 2, we developed an integrated system to address the discovered issues and flexibly allow individualized training sessions to be conducted by a professional (e.g. physiotherapist) using a lightweight setup.

### 3.1 Modified Design Concept

The interaction concept remained largely intact, but one crucial change was made. Aside from the bike speed (perceptible through changes in optic flow), all PI feedback (music, sky colour) was based on a single computed variable - the *position* of the bike relative to the rabbit, corresponding to cumulative PI over a session. As such, lagging by a certain distance led to slowed-down music and a red sky, while overtaking the rabbit led to sped-up music and a yellow sky, with a navy sky and normal-sounding music when within range. The rabbit speed was also made variable so as to modulate PI dynamically within a session.

### 3.2 System Features

The system is depicted in Fig. 2. The JUCE application aims to maximize flexibility and usability by providing the following main features, some of which are shown in Fig. 3:

- Step-by-step tutorials on sensor interfacing and placement.
- User-specific PI baseline calibration before training.
- Graphical interface to define target PI evolution over a session.
- Inbuilt music player to load and play user-selected tracks.
- Difficulty adjustment through modification of maximum permissible distance from rabbit.
- Real-time monitoring of bike / rabbit speed and relative position.

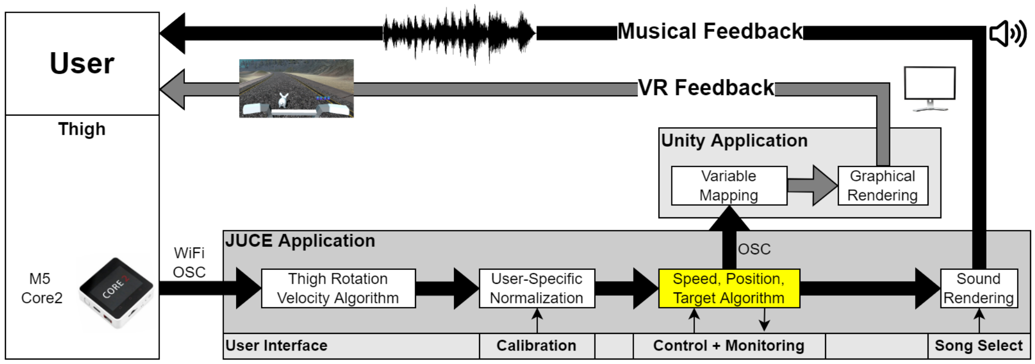


Fig. 2. Overview of the system built in Iteration 2.

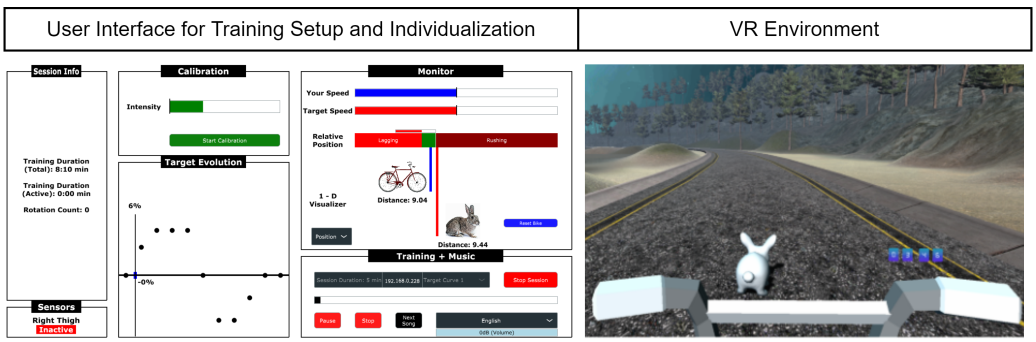


Fig. 3. The interface for training setup and individualization (left) and the virtual environment (right). Each of these will be displayed on a separate monitor, with the therapist operating the former and the patient viewing the latter.

- Detailed session logging at a sampling rate of 100 Hz.

As shown, the system now uses a single inertial sensor and a single application for sensor signal processing, individual calibration, computation of speed and position of the bike / rabbit, and sound rendering. The Unity application receives the speed information of the bike and rabbit via OSC, internally maps it, and renders the virtual environment. The JUCE and Unity applications can run in tandem on a single Windows laptop with two screens (one for each) or be distributed across two machines on the same local area network. In its envisioned clinical use case, the physiotherapist will perform a rapid one-time setup on the JUCE interface, following which the patient will cycle for the specified duration while engaging with the virtual environment and musical feedback (*not* the JUCE application). At the end of the session, an on-screen report will present the total and active training durations as well as the pedal crank rotation count. A short video demo showcasing the overall user experience and key interface elements is provided here[4].

## 4 GENERAL DISCUSSION

In this work, we conceptualized, built, and tested an interactive system to modulate pedaling intensity during endurance training in a motivating and intuitive fashion through real-time musical and VR-based feedback. In Iteration 1, we

[4]https://drive.google.com/file/d/19lb0I2fx3wyB-LiaKVQupKGrcuwU2Ztx/view?usp=drive_link

demonstrated the feasibility of concurrently providing musical and visual feedback on cumulative and instantaneous PI. The pilot test provided initial evidence of the intuitiveness of the PI mappings to bike velocity and music playback speed respectively. However, this result should be interpreted with caution as the users were young and cognitively unimpaired, which may not be the case with, for instance, neurological patients, especially when multiple streams of information are concurrently presented. Moreover, the use of different variables to represent PI between the modalities (cadence and aggregated thigh rotation velocity) proved problematic, and this was addressed in Iteration 2 to ensure crossmodal congruence, an important requirement for multisensory integration during motor rehabilitation [17]. In Iteration 2, both the interaction and the system were considerably streamlined to encourage users to focus on various convergent sources of information on bike position relative to the rabbit to more effectively leverage multisensory integration [20]. The developed interface will also make it possible to adapt the training to the needs and capacities of diverse individual users, which is an important feature of technology-based rehabilitative interventions at large [21]. Planned future work aims to assess the combined feedback paradigm as well as its individual modalities in terms of usability and efficacy in modulating PI and enhancing motivation during training through a combination of feasibility tests and effect studies with healthy and patient populations. In addition, the user interface for therapist use will be iteratively improved through user-centered focus group activities with physiotherapists.

## 5 CONCLUSIONS

Overall, we believe this work is a useful preliminary demonstration of the feasibility of applying combined musical and VR-based feedback in the ubiquitous context of stationary biking, both in terms of interaction design and system development. Through the iterative process documented in this work, we were able to build a solution designed to play to the strengths of each modality and exploit multisensory redundancy to saliently and intuitively convey exercise intensity during cycling. With the functionally robust new system built for individualized feedback delivery, the efficacy and clinical potential of the feedback paradigm will be systematically evaluated. The eventual results will, in our estimation, contribute to a growing body of knowledge on how best to design and leverage the potential of multimodal interactive systems for motor rehabilitation.

## 6 ACKNOWLEDGEMENTS

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