VibRacket: Designing and Experiencing Embodied Vibrotactile Feedback on a Badminton Racket

Nihar Sabnis
Max Planck Institute for Informatics
Saarbrucken, Germany
nsabnis@mpi-inf.mpg.de

Gabriela Vega
Max Planck Institute for Informatics
Saarbrucken, Germany
gvega@mpi-inf.mpg.de

Valentin Martinez-Missir
Max Planck Institute for Informatics
Saarbrucken, Germany
val.martinez.missir@gmail.com

Paul Strohmeier
Max Planck Institute for Informatics
Saarbrucken, Germany
pastrohm@mpi-inf.mpg.de

Abstract

Racket sports such as badminton and tennis are played globally and are popular in virtual sports experiences. Although commercial systems and research prototypes have looked at improving the sensation of impact for virtual sports, movement guidance remains essential to improve the stroke quality. Existing vibrotactile feedback strategies provide extrinsic vibrations to guide movements, which can feel unnatural and increase cognitive load. In contrast, motion-coupled vibrations are perceived as self-generated, intrinsic and have shown promise in creating embodied tactile experiences. However, their role in motor learning is not yet understood. We present *VibRacket*, a prototype mountable on rackets that provides extrinsic and intrinsic vibrotactile feedback for controlled and ballistic movements. *VibRacket* integrates an IMU and vibration actuator to deliver guiding, error-enhancing, and embodied vibrotactile feedback. *VibRacket* also includes a graphical interface for customizing orientation-based vibrotactile patterns. We outline the design and implementation of *VibRacket* and discuss its potential for motor learning.

CCS Concepts

• **Human-centered computing → Haptic devices**.

Keywords

racket, haptics, embodied vibrotactile feedback, movement guidance, motor learning

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1 Introduction

Racket sports like Tennis, Badminton and Table-Tennis are among the most common sports played in the world and are turned into common virtual experiences. For example, Wii Sports, which features both tennis and table-tennis, and Eleven Table Tennis VR, which focuses only on table-tennis, are among the best-selling games [24]. One aspect of the sport is to provide realistic experiences of hitting the ball or shuttle, which these games achieve using controller vibrations. But these controller vibrations are abstract and need to be interpreted by the user, increasing their cognitive load [7] and hence research has looked at designing custom devices using compressed air propulsion jets [24], fingertip skin deformation [9], impedance type kinesthetic feedback [5], tendon-based robots [13], and multimodal feedback [11] to provide force sensations similar to those of balls or shuttles hit with the racket.

Another important aspect to improve the impact of the racket with the shuttle is that of performing high quality strokes. Trainers typically improve stroke quality by physically guiding novice players. However, physical feedback can interfere with the movement being performed. Vibrotactile feedback is one way of providing movement guidance for motor learning, which primarily uses *extrinsic* feedback strategies like constructive and error-enhancing feedback [1, 12, 20]. Constructive (or guiding) feedback provides vibrotactile cues that assist users in performing the correct movement or trajectory, thereby reducing errors and supporting early skill acquisition [1]. In contrast, error-enhancing feedback exaggerates errors, encouraging users to actively correct their performance and thereby promoting deeper learning and better retention [3, 23]. Vibrations on the body are used to indicate these errors [26]. However, these vibrations are not generated by the person performing the movement (low sense of agency) [19] and hence are probably perceived as extrinsic to the person.

On the other hand, when we explore textures or material properties (e.g., crushing a piece of paper), the vibrations at the fingertips are perceived as more intrinsic and embodied, contributing to the creation of the material experience [18]. One explanation could be that these vibrations are coupled to user motion, and thus are perceived to be embodied, intrinsic and self-caused [15, 17]. Research shows that artificially generated vibrotactile pulses coupled to user motion are still capable of eliciting embodied material and textural experiences [17]. These motion-coupled vibrations have been used to induce a sensation of movement in the absence of it [8]; simulate texture experiences in air and on smooth sliders [17, 21, 22]; and create compliance experiences on rigid objects by coupling vibration with user applied pressure [10, 27, 28]. Recent research shows that the perceptual mechanisms of sense of agency [14] and sensory attenuation [4] contribute to motion-coupled vibration feeling more intrinsic [15, 16]. Specifically, motion-coupled vibrations are perceived to be self-caused (higher sense of agency), and since they are perceived to be self-caused, the vibrations are attenuated, leading to an intrinsic experience of feedback. However, motion-coupled vibrations, which are perceived to be embodied, have not been explored as a feedback strategy to provide movement guidance.

Therefore, we present *VibRacket*, a first prototype capable of providing embodied vibrotactile feedback on a badminton racket. *VibRacket* is a mountable system with an IMU sensor as well as electronics to render vibration feedback on rackets. With *VibRacket* we demonstrate three different strategies of rendering vibrotactile feedback, namely: guiding, error-enhancing and embodied feedback. *VibRacket* can also be integrated with a GUI, which can help users create their own vibrotactile patterns for different racket orientations. *VibRacket* demo's primary aim is to showcase embodied vibrotactile feedback through its implementation, and potentially influence the perceived racket movement with and without the feedback. The embodied feedback unlike the guiding and error-enhancing feedback does not need to be interpreted and aims at changing racket movements. The demo also serves as a proof-of-concept for future motor-learning studies to investigate if embodied vibrotactile feedback can enhance stroke-learning outcomes for novice badminton players. The following sections describe the design rationale, the implementation details, the demos which will be presented and the future scope and bigger questions this research aims to investigate.

2 Design Rationale

Vibrotactile feedback for movement guidance can take various forms, including guiding (assistive), error-enhancing (perturbing), corrective (reactive error signaling), embodied (intuitive), and terminal knowledge-of-results, each supporting different stages and goals of motor learning. Out of these, terminal knowledge-of-results feedback is provided after the intended action and is not often used for teaching badminton strokes to novice players since they need deliberate feedback by moving their hand in the intended trajectory during the movement [1].

On the other hand, the other forms of feedback are usually provided when the trainee is performing the movement. Extrinsic feedback (guiding, error-enhancing and corrective) is shown to be useful for reducing errors, supporting early skill acquisition, and promoting deeper learning for motor tasks. However, with extrinsic vibrotactile feedback–where vibrations are decoupled from a user's actions–often suffer from disconnection and abstraction that limit their utility in motor skill learning. Moreover, research shows that while external vibration can momentarily improve accuracy, its continuous and frequent use may lead to guidance dependency and diminishing performance once feedback is withdrawn [25]. Furthermore, extrinsic signals can impose additional cognitive load, as users must consciously interpret artificial cues that lack natural integration with their movements [7].

In contrast, intrinsic or embodied vibrotactile feedback for motor learning—where vibrations are motion-coupled and perceived as self-generated—holds significant promise. Such feedback leverages sensory attenuation mechanisms [16] while improving the sense of agency [15]. This alignment with natural sensorimotor processes can enable richer, more intuitive learning experiences and open new opportunities for embodied interaction designs for motor-learning in racket sports where embodied action and feedback are tightly interwoven. Hence, we created *VibRacket* to enable users to compare different types of feedback while using a badminton racket. Although the initial goal of VibRacket is to demonstrate the implementation and highlight the perceptual differences between extrinsic and embodied feedback, the larger goal is to investigate whether embodied vibrotactile feedback is able to influence stroke-learning outcomes for novice badminton players.

3 VibRacket

We present *VibRacket*, which can render guiding, error-enhancing and embodied vibrotactile feedback on a badminton racket. We briefly explain the algorithm, the graphical user interface, the hardware, and the communication protocol used to augment the movement experience. [2]

3.1 Firmware

Coupling vibrotactile pulses to user action has shown to elicit embodied material experiences [17]. A 9-degree of freedom inertial measurement unit (IMU) is placed on the racket to measure its orientation in the X, Y, and Z axes as the racket moves in air or makes impact with a shuttle. This orientation on each axis is divided into a discrete number of bins. When the orientation changes sufficiently that the sampled sensor value enters a new bin, an AC pulse is generated, as shown in Figure 1-left. Based on the changes in the measured orientation, pulses are generated. That is, if the orientation changes fast, pulses are generated rapidly, whereas if the orientation changes slowly, the pulses are generated proportionally slowly. The orientation of each axis is sampled individually, and specific vibrotactile pulses can be rendered based on that axis only. Each vibrotactile pulse can be configured using the GUI parameters.

3.2 Graphical User Interface

We modified a two-window Graphical User Interface (GUI) used in Sabnis et al. [18] with Processing version 4.0, as shown in Figure 2. Participants used the Racket Tactile Symbol Designer window of the GUI to design sequences of vibrotactile effects perpendicular to each axis of the IMU. A racket with the three axes is visualized in the GUI to assist with the orientation of the design. The other window of the GUI, called the vibrotactile pattern designer, which provides control over a set of vibration parameters. The vibration design parameters of the GUI screen can help designers to understand and assist them in designing motion-coupled as well as continuous vibrations effectively. These continuous vibrations are similar to

[1] N. Sabnis mentions reflecting on 5 years of teaching badminton professionally.

[2] The GUI and M5 Echo Dots sensing + actuation pipeline can be found here: https://github.com/sensint/VibRacket

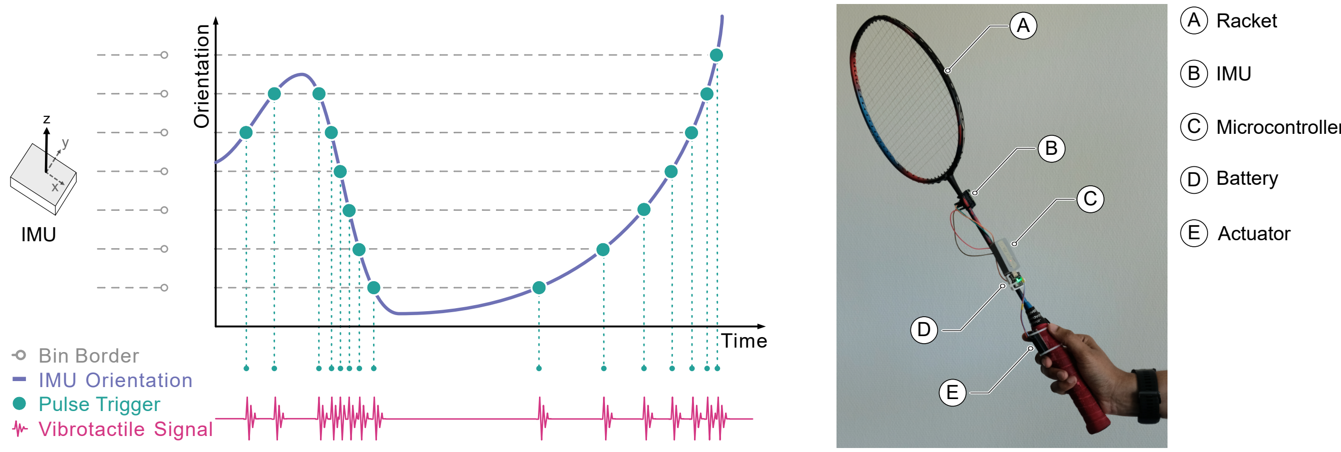

Figure 1: The left figure visualizes the binning algorithm in which the vibrotactile pulses are generated based on the orientation changes of the IMU (*pitch: x-axis, yaw: y-axis, roll: z-axis*). The right figure shows *VibRacket* with the IMU sensor and the M5 Atom Echo vibration pipeline.

the vibration feedback used to provide constructive or destructive movement guidance, whereas the motion-coupled vibrotactile feedback has been shown to induce a more embodied experience of movement [21]. We also added the functionality of using asymmetric vibration which has shown to induce sensations of pulling (also known as pseudo forces) to be a design element for the vibrotactile augmentation on the rackets [2, 6, 16]. The motion-coupled and continuous asymmetric vibrations enable experimenting with two ways of rendering pseudo forces. Participants can create their desired vibrotactile effects and can switch to the Racket Tactile Symbol Designer window to assign these effects to slot(s) in the sequences, where each sequence represents the absolute orientation range of each axis. The upload button sends the vibrotactile patterns to the hardware mounted on the racket. Saving and Loading buttons help to save and load a previously saved design, respectively. The clear all button stops the augmentation of the racket and the vibrotactile pattern is removed.

3.3 Hardware

We used a commercially available badminton racket (Yonex Astrox) and added the sensing and actuation pipeline as shown in Figure 1-right. BNO085 is used as an IMU to measure the orientation, while the 'Hapcoil one' by Actronika as the actuator to render the vibration patterns.

We use three different pipelines to trigger vibrations, each with its own peculiarity:

- Haptic Servos [17]: Haptic Servos are shown to keep the delay below 5 milliseconds, which can be crucial to give a perception of real-time embodied feedback. We use Teensy 4.1 with pt8211 digital to analog converter and voltage amplifier (PAM8403, Visaton) to generate the audio signals before feeding into the actuator. This pipeline will be used to interface with the GUI.
- M5 Atom Echo: M5 Atom Echo (esp32) platform enables a compact form factor with Wi-Fi and Bluetooth connectivity options and has an onboard amplifier.
- SEEED XIAO sense nrf52840: This pipeline provides a compact form factor since it uses the onboard IMU (LSM6DS3TR) along with an amplifier (MAX98357) and can be connected using Bluetooth.

All three systems will be demonstrated during the demo. The current locations of the sensor, microcontroller, and actuator are based on the preferences of the authors, however they are not fixed and hence we will bring modular mounts for participants to try different configurations and elaborate on which works best for them. To provide feedback, we will define a range of movement trajectories for the badminton serve (under-arm) which would be used as baseline to compare the user trajectories with and render the desired vibrotactile augmentation.

3.4 Interfacing Between GUI and VibRacket

For a part of our demo, we enable participants to experience the designed vibrotactile patterns as well as design their own patterns during different racket movements. The communication protocol (inspired from Sabnis et al. [18]) is used to interface the GUI with the electronic system mounted on the racket to design the vibrotactile patterns. The electronic system receives messages from the GUI via a serial interface and assigns them to the respective orientations of the IMU. These messages are ASCII strings and control-messages to modify the system's state and data-messages to transfer the vibrotactile effects and effect sequences to the corresponding axes of the inertial measurement units. The IMU axes are configured accordingly to render the vibrotactile patterns as and when a movement around that axis is detected. The microcontroller assigns the orientation along the three individual rotation axes, and the actuator renders vibrotactile pulses according to the selected effect sequence and parameters that were assigned.

4 VibRacket Demo

We propose to demonstrate *VibRacket* in three parts. The demo is targeted towards sports enthusiasts who are familiar with racket

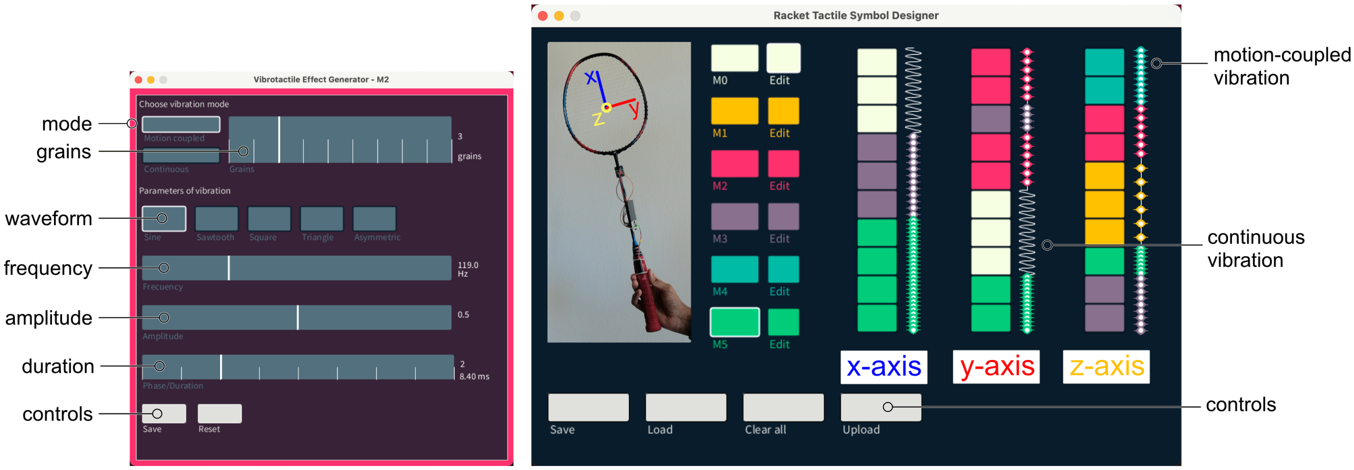

Figure 2: The Graphical User Interfaces with two screens is shown. The left screen is a vibrotactile effect generator which can be used to switch between modes of continuous (extrinsic) and motion-coupled (intrinsic) vibrotactile feedback. Further, the vibration parameters of waveform, frequency, amplitude, and duration can be customized as desired. The right screen (Racket Tactile Symbol Designer) is used to apply the effects to the desired axis orientation (*pitch: x-axis, yaw: y-axis, roll: z-axis*). Different effects can be assigned to different sensor ranges.

sports, haptic experts and other HCI researchers. The first part is targeted at the overall audience to show the effects of vibrotactile augmentation on perceived racket movement, while the second part is targeted towards designing your own vibrotactile patterns and how different vibration patterns and parameters affect the perceived racket movement. The final part will show three different feedback strategies: constructive, error-enhancing and embodied. We expect the demo parts to be performed in order, but reversing this order or doing other tasks is not an issue. All the parts together would need around five to ten minutes per participant.

Procedure. A presenter will be physically presenting the demo at the assigned booth. There would be two/ three badminton rackets so that multiple people can experience the demo in parallel. We will also bring some shuttles for participants to experience hitting a shuttle with and without vibrotactile augmentation.

Part 1: VibRacket with and without vibrotactile augmentation. In this part, participants will move a badminton racket in multiple directions, as they would typically move a badminton or tennis racket. Then, the system will automatically render vibrotactile augmentation to enable users to experience their movement in more detail. They can perform different movements and experience how they feel different vibrotactile feedback moving in different directions. They can also hit a few shuttles with and without vibrotactile feedback to experience the differences made by haptics in movement perception. When experimented within authors, the vibrotactile pulses using the algorithm described above, felt like it is resisting the movement and induce a feeling of moving the racket through rough and bumpy materials. Users also felt that the racket feels heavy with vibrotactile augmentation.

Part 2: Design your own Augmentation on VibRacket. In the second part, participants can create their own material experiences along different axes of the racket movement using the GUI and feel them by moving the racket. They can also experience some pre-defined symbols to experience what helps semi-professional badminton players to train during shadow practice and for novice users to learn the serve movement in Badminton. Presenters will encourage participants to design as many experiences as they wish to, mostly to demonstrate how different vibration parameters shape the overall experience of moving the racket.

Part 3: Experiencing different feedback on VibRacket. The final part will present three feedback strategies on a predefined movement. Guiding feedback will continuously indicate participants' deviation from the predefined movement, with vibration amplitude increasing proportionally to the degree of deviation. In contrast, the error-enhancing feedback will increase the amplitude of continuous vibration as the error is reduced (i.e., doing the right movement would have the strongest vibrotactile feedback) and vice versa. The final feedback strategy is of providing intrinsic (embodied) vibrotactile feedback using motion-coupled vibrations. We believe that intrinsic feedback would interfere less with the desired movement of the participants while providing the necessary correction.

5 Future Scope and Bigger Questions

VibRacket opens up several directions for future exploration in the design and application of vibrotactile feedback for racket sports. A key question is how different feedback strategies—guiding, error-enhancing, and embodied—can be effectively combined or provided in sequence to support motor learning across varying levels of expertise. Additionally, how can embodied vibrotactile feedback reinforce immersion in VR racket sports while combining more realistic simulations of ball or shuttle impact? Furthermore, understanding how different feedback strategies influence the sense of agency, and how embodied vibrotactile feedback could extend to other movements, and sports, is an interesting research area.

Future work includes designing algorithms capable of generating perceivable vibrotactile cues during ballistic movements (like badminton smash or tennis serve), where the duration of pulses of the motion-coupled vibration can fall below perceptual thresholds. Investigating optimal actuator and IMU placement on the racket, as well as designing actuation patterns and metaphors that convey meaningful information (e.g., stroke quality or impact force), could further enhance training outcomes. Finally, empirical studies in the lab (using motion-capture systems) and also on the court for different levels of expertise of players, will be essential to evaluate and optimize these feedback strategies.

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