

Controlling Musical Parameters in Neurorehabilitation with a Haptic Finger Tracker

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ABSTRACT

Patients in neurorehabilitation often face not only severe motor impairments, but also associated psychological problems. Music therapy can make a valuable supplement to purely verbal psychotherapy, but its use is limited as patients often cannot play conventional musical instruments due to motor skill limitations. This can hinder the psychological recovery, where musical expression is essential. To address this, the Haptic Finger Tracker was developed, emerging from a project at the ligeti zentrum, Hamburg, a collaborative initiative where researchers and artists work on interdisciplinary projects. This paper describes a prototype that translates minimal finger movements into congruent sound and haptic sensations. Technically, the device uses flex sensors and an inertial measurement unit (IMU) to capture a range of small-scale finger movements. Using the Open Sound Control (OSC) protocol, these captured gestures are then translated to control musical elements such as pitch, volume and arpeggios. Simultaneously, a vibrotactile actuator provides haptic feedback aimed at enhancing the user's sense of engagement and embodiment. The resulting portable prototype provides patients with a creative outlet, fostering self-efficacy. This work establishes a technical foundation for future neurorehabilitative tools that utilize multisensory feedback to improve patient outcomes.

1. INTRODUCTION

This project aims to overcome the challenges in experiencing self-efficacy among individuals with severe physical and neurological impairments through the application of a novel therapeutic tool. The theoretical foundation for this work is provided from several distinct fields:

Neuroplasticity

The human brain consists of several hundred million nerve cells that form functional networks. These networks are not static, they undergo modifications in response to injury or learning processes, a phenomenon known as neuroplas-

ticity. This continuous reorganization of the nervous system involves the formation of new synaptic connections. Modern neurological rehabilitation uses this inherent ability for therapeutic treatments. Even in cases of significant damage to the peripheral or central nervous system, intensive and targeted neurorehabilitation can increase cortical representation and improve function. This approach is typically more effective than compensatory plasticity of the uninjured hemisphere. [1, 2]

For instance, studies involving intensive, structured training of primate fingers have demonstrated that the corresponding central representations can be selectively enlarged. This activity-dependent neuroplasticity is associated with improvements in the execution of motor functions and sensory processing. [3, 4]

Psychological Distress

Following an acquired brain injury, individuals may develop comorbid psychiatric disorders. Among the most common are depressive disorders, anxiety disorders, stress and adjustment disorders, and addictions [5, 6, 7]. The risk of developing a mental health condition is highest during the first year after post-injury but remains elevated throughout the individual's life [8]. Gauggel shows that in the field of neuropsychological therapy, inventions and treatment goals are predominantly focused on function-related and behavioral approaches [9]. According to Klein and Guthke, brain damage can result in impaired awareness of the disorder, a deficit that severely restricts the ability for self-exploration, which is crucial for conversational psychotherapy. Consequently, it is often necessary to adapt therapeutic methods to the specific needs and characteristics of patients with acquired brain injury [10].

Music Therapy

Music plays an important role in modern healthcare. Music therapy is a psychotherapeutic intervention aimed at activating a patient's psychological and social resources to support their recovery process. This therapeutic approach involves active musical engagement through various activities, all conducted within the framework of a therapeutic relationship. Improvisation on musical instruments serves as a nonverbal medium for self-expression. It enables feelings and emotional issues that arise during therapeutic conversations to be experienced directly and processed more effectively [11]. However, for patients with significant mo-

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tor impairments, the use of music therapy in early rehabilitation has been severely limited [12].

Haptic Feedback

Haptic feedback, essential for playing analog instruments, is key for human-machine interaction, enhancing immersion and engagement [13, 14]. It serves three primary functions: increasing realism in virtual environments [15], transmitting information [16] and evoking emotions [17]. These functions improve user engagement, user experience and the sense of embodiment.

In neurorehabilitation, haptic feedback provides tactile cues (e.g. vibrations, force feedback) to guide movement and link a therapeutic task to the user's sensory experience [18, 19]. Integrating haptic feedback with auditory information, particularly music, can create a rich, multisensory experience that may benefit therapeutic outcomes [20]. Vibrotactile feedback synchronized with music can heighten a user's sense of immersion and social connection [17], crucial for engagement in long-term rehabilitation [1, 21].

Patients, who are often unable to use traditional musical instruments or interfaces, could benefit immensely from the motivational advantages of music therapy. But in the current landscape of therapeutic tools is a lack of adaptable, customizable and accessible haptic systems designed for the specific needs of patients with severe motor impairments. This paper aims to address this gap by introducing a novel system that integrates high-resolution finger tracking with customizable auditory and vibrotactile feedback, designed specifically for a therapeutic context. The aspect of inducing targeted neurophysiological change forms an important foundation for the rehabilitative and therapeutic processes that the newly developed tool is intended to facilitate.

2. RELATED SOLUTIONS

Commercially available haptic devices have limited usability for our specific therapeutic application.

The design of novel interfaces for musical expression has a long history, with pioneering work by researchers like Machover [22] and Sonami [23] establishing the mapping of human gestures to musical control. While these systems demonstrated the potential of gestural control, they were often designed for large, expressive movements of performers.

Most critical, available systems today are typically designed for e.g. gaming to track larger, rapid movements of healthy individuals and lack the sensitivity required to accurately capture the **small-scale, slow movements** characteristic of patients with neurological impairments. Maggioni et al. stated systems like *MediaPipe* or *Leap Motion* as systems with approximately 2 to 3 mm spatial error [24]. The most accurate motion tracking systems are marker-based optoelectronic devices, which have a long setup and calibration time, high costs, and are bulky to transport between different hospital rooms [24]. Additionally, haptic feedback in existing models is often absent or improperly positioned, such as on the fingernail, which is not an optimal location for simulating the tactile sensation of playing an instrument and could be uncomfortable [25]. An-

other limitation is that many of these systems are designed as complete gloves, which restricts their use to hands of a specific size and shape; anatomical variations such as deformations or swelling can render the glove unusable [26]. Finally, for clinical use, these devices must be easily disinfected, and the common alternative of wearing a secondary glove often compromises usability and tactile sensitivity [27, 28, 29].

3. OUR HAPTIC FINGER TRACKER

Developed with a music therapist, the system is designed for single-finger operation to support patients with severe movement restrictions. A primary technical requirement was the ability to detect movements with a resolution below 1 mm. The integration of haptic feedback at the fingertip was an essential feature, considered fundamental for enhancing patient engagement and providing a tactile connection to the process of virtual tone generation. The key design criteria also included a mobile and lightweight construction (< 50 g), along with ergonomic features to ensure that the device did not impose additional restrictions on patient movement.

The system's interface utilizes the Open Sound Control (OSC) protocol, which facilitates straightforward a future integration with existing musical production and control tools like PlugData. Finger flexion and extension control the volume of a generated tone, while abduction and adduction in the vertical plane control the pitch. Horizontal abduction and adduction respectively trigger ascending and descending arpeggios.

Other requirements were considered for high accuracy, fast responsiveness, user comfort and wearability, robustness to noise, ease of integration, low cost, and low power consumption. These criteria were incorporated into a weighted decision matrix to evaluate sensor technologies for joint angle measurement (volume/pitch) and linear displacement (arpeggio). Following a comparison between flex sensors, strain gauges, inertial measurement units (IMU) and Leap Motion technology for joint angle measurement, the flex sensor was selected. For linear displacement sensing, the IMU was chosen.

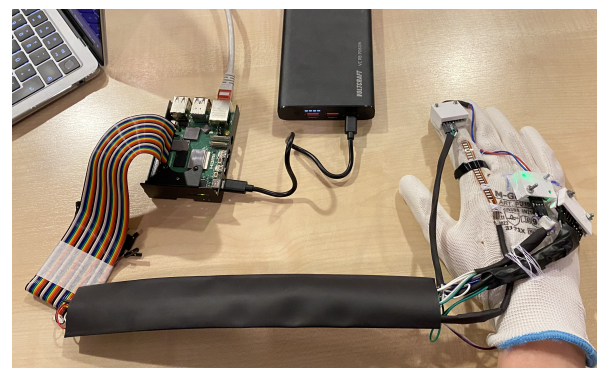


Figure 1. The Haptic Finger Tracker Device, showing the sensor glove, microcontroller, and connection to a computer.

For haptic feedback, a linear resonant actuator (LRA) was selected over an eccentric rotating mass (ERM) due to its superior control over distinct vibration patterns and the faster response time.

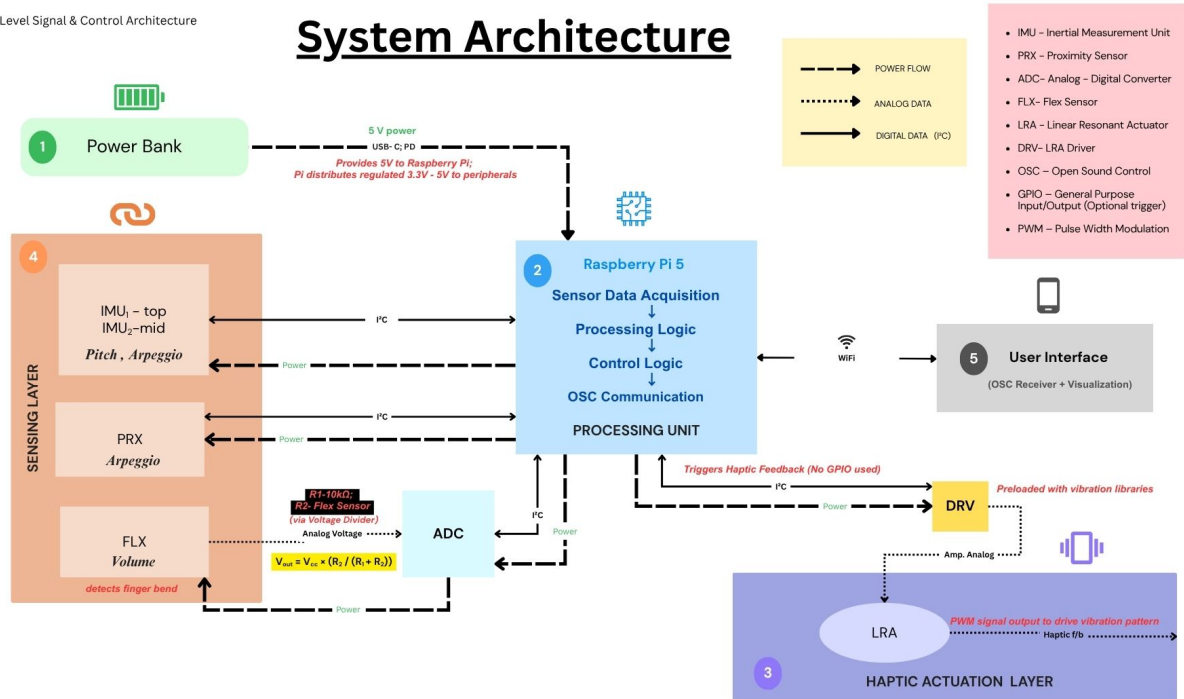


Figure 2. The system architecture of the Haptic Finger Tracker Device.

The system's architecture (Fig. 2) uses a Raspberry Pi 5 to manage data acquisition, processing and communication. It provides significant computational power for real-time processing while creating a path toward a fully embedded, standalone device in future iterations.

4. RESULTS AND DISCUSSION

The primary goal was to develop a system enabling patients to interact with a virtual instrument a music therapy context. The system was specially designed for use in the neurological rehabilitation, targeting patients with a severely restricted range of motion to facilitate their engagement in musical expression.

The current prototype underwent a preliminary qualitative evaluation of the collaborating music therapist who has experience in neurorehabilitation. The evaluation consisted of a session where the therapist used the device while employing verbal feedback. The primary goal was not to measure clinical outcomes, but to assess the usability of the core audio-haptic feedback loop and confirmed the prototype as a mobile, lightweight, and ergonomic solution. The assessment also identified opportunities for further improvement. Its design, which includes a disinfectable glove, promotes clinical hygiene and enables an inclusive and emotionally engaging experience for patients. Volume modulation was implemented using a flex sensor positioned on the ventral position of the index finger, while pitch control was achieved via a second flex sensor located on the dorsal side. Control over arpeggios was achieved using an inertial measurement unit (IMU). The haptic feedback was provided by a linear resonant actuator (LRA).

The system enables simultaneous control of auditory (OSC) output and haptic feedback via single-finger movement.

This provides an intuitive and highly accessible interface for patients with significant motor impairments.

This work presents a haptic finger tracker that successfully enables musical expression from minimal gestures, providing a tool for self-efficacy in neurorehabilitation. While initial feedback confirms the prototype's ergonomic design, its current high latency and timing inconsistencies are key limitations. Future work will prioritize optimizing system response time, developing a more robust sensor fixture, and creating an mobile application for therapists to customize the audio-haptic feedback. These steps will move the prototype towards a therapeutic tool validated through user studies.

Acknowledgments

This research was funded under the Program "Innovative Hochschule" (innovative university) by the Federal Ministry of Research, Technology and Space (BMFTR) of Germany (Grant No. 13IHS232C) and the City of Hamburg

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